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Aspects of the economics of transformation : harvesting productivity, a case study of different intervention types in the conversion of Welsh sitka spruce to continuous cover forestry

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Aspects of the Economics of Transformation

Harvesting Productivity: a case study of different intervention types in the conversion of Welsh Sitka spruce to continuous cover forestry

A thesis submitted in candidature for the degree of

Philosophiae Doctor

by

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ABSTRACT

An increased interest in continuous cover forestry (CCF) and a national policy change in Wales has generated a demand for knowledge of operational productivity in transformation relative to conventional working.

This study took place within Coed Trallwm, a privately owned upland woodland in Mid Wales. The site is one of three study sites in Wales used by the UK Forestry Commission to study operational aspects of the transformation to CCF.

A total of eight 0.5 ha buffered plots were installed in uniform areas of Sitka spruce (*Picea sitchensis*). Treatments consisted of low thinning (paired plot), frame tree (paired plot), group system (paired plot), spatially-moderated creaming (single plot) and premature clearfelling (single plot).

Harvesting removed 20% of the standing basal area in the transformation plots and 100% in the clearfell plot. Harvester and forwarder working was recorded through a time and work study in order to identify time differences in cyclical and non-cyclical operations and felling outputs between the different interventions. Relative brash mat production, rack usage and area coverage were also studied. Models for work phase time consumption and total productivity were developed for both machines.

Harvester cyclic time consumption was found to be most related to tree size, spacing and morphology, and non-cyclic time consumption to the regularity of the racking system. Forwarder cyclic time consumption was most influenced by thinning type through its effect on assortment, and thinning intensity, through its effect on volume cut. Non-cyclic work was less strongly influenced by these factors. The productivity of both machines increased with mean felled tree diameter. Models for volume recovery, relative product assortments and volumes were also developed for intervention type. Volume recovery, proportion of log material and mean piece size all increased with mean felled tree diameter.

Keywords: Harvester, Forwarder, Shortwood, Productivity, Sitka spruce, Transformation, Continuous cover forestry, Frame tree, Group shelterwood, Low thinning, Clearfell, Creaming, Time study, Assortment, Wales, UK.

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LIST OF SYMBOLS USED

STAND

d	diameter at breast height measured at 1.3m from ground [cm]
$\bar{d}_{pre}$	mean tree diameter before thinning [cm]
$\bar{d}_{post}$	mean diameter of retained trees [cm]
$\bar{d}_{thin}$	mean diameter of felled trees [cm]
$\bar{D}_{thin}$	plot mean diameter of felled trees [cm]
$\bar{D}$	stand arithmetic mean diameter [cm]
$\sigma_{\bar{D}}$	standard deviation of diameters before thinning [cm]
D_g	stand quadratic mean diameter [cm]
D_o	quadratic mean diameter of the largest 20% of trees per hectare [cm]
D_{100}	quadratic mean diameter of the 100 trees of largest diameter per hectare [cm]
$d_{1/8}$	diameter of stem at 1/8 height [cm]
$d_{4/8}$	diameter of stem at 4/8 height [cm]
$d_{7/8}$	diameter of stem at 7/8 height [cm]
d^{UB}	diameter under bark [cm]
d^{OB}	diameter over bark [cm]
d_{-10}	diameter at breast height ten years previously [cm]
d_q	diameter of mean cross-sectional area [cm]
d_{tc}	thinning cell diameter [m]
z_d	ten-year diameter growth [cm]
BDq	basal area : diameter q ratio (*after* Buongiorno *et al.*, 2000)
g	stem cross-sectional area at d [m^2]
g_q	stem cross-sectional area at d of tree of d_q [m^2]
g_{q-10}	stem cross-sectional area at d of tree of d_{q-10} [m^2]
g_{tc}	stem cross-sectional area at d of a tree of d_{tc} (m^2)
G	basal area [m^2/ha]
G_{pre}	stand basal area before felling [m^2/ha]
G_{post}	stand residual basal area [m^2/ha]
G_{thin}	removed basal area [m^2/ha]

G_{tr}	plot basal area target reduction (m^2/ha)
h	tree height [m]
h_{-10}	tree height 10 years previously [m]
h_0	height of d_q from point of cutting [m]
h_{0-10}	height of h_0 ten years previously [m]
h_{-10}	tree height ten years previously [m]
H_{100}	height of a tree of D_{100} [m]
H_f	stand form height (*after* Edwards & Christie, 1981) [m]
H_g	height of tree of D_g [m]
H_o	height of a tree of D_o [m]
H_t	stand top height (*after* Edwards & Christie, 1981) [m]
z_h	ten-year height growth [m]
$\bar{h}_{thin}$	mean felled tree height [m]
$\bar{h}_{post}$	mean retained tree height [m]
$\bar{h}_{thin}$	mean thinned tree height [m]
v	tree volume [m^3]
$\bar{v}_{pre}$	mean tree volume before thinning [m^3]
$\bar{v}_{post}$	mean retained tree volume [m^3]
$\bar{v}_{thin}$	mean felled tree volume [m^3]
z_v	ten-year volume growth [m^3]
V	stand volume [m^3]
ff	form factor
A	plot area [ha]
n_{cells}	number of thinning cells
N	number of trees per hectare
N_{pre}	total number of stems before felling
N_{post}	number of residual stems
N_{thin}	number of removed stems
N^{ha}_{pre}	plot trees per hectare before felling
N^{ha}_{post}	plot retained trees per hectare
N^{ha}_{thin}	plot trees cut per hectare
RS	relative spacing [m] (*after* Gadow & Hui, 1999)

RS_{thin}	relative spacing of felled trees [m]
t	present time
t_{-10}	ten years previously
$\overline{CH}_{thin}$	mean crown:height ratio of felled trees
$\overline{HD}_{thin}$	mean height:diameter ratio of felled trees
S_1	separation parameter (*after* Gadow & Hui, 1999)
SG	SG ratio (*after* Gadow & Hui, 1999)
H'	Shannon-Weiner index
D	Simpson's index of diversity

RACKS, TRACK AND BRASH

$L_{total}^{brashmat}$	total length of brash mat [m]
$L_{rack}^{\%brashmat}$	proportion of rack brash-mat coverage
L_{total}^{track}	total length of track [m]
$L_{used}^{rack+track}$	total length of used rack and track [m]
L_{used}^{rack}	length of rack used [m]
L_{total}^{rack}	total length of rack [m]
$L_{\%used}^{rack}$	proportion of rack used

HARVESTER

(cmin is the abbreviation used for centiminutes; 0.01minutes)

T_{tree}^{A0}	per tree movement time consumption [cmin]
T_{total}^{A0}	total plot movement time consumption [cmin]
T_{tree}^{C0}	per tree felling time consumption [cmin]
T_{total}^{C0}	total plot felling time consumption [cmin]
T_{tree}^{C2}	total plot inspection time consumption [cmin]
T_{total}^{C3}	total plot move between racks time consumption [cmin]
T_{total}^{C9}	total plot manoeuvre time consumption [cmin]
T_{total}^{D5}	total plot prepare route time consumption [cmin]

T_{mean}^{D7} mean stack log element duration [cmin]

T_{total}^{D7} total plot stack logs time consumption [cmin]

T_{tree}^{E0} per tree processing time consumption [cmin]

T_{tree}^{E1} per tree 495cm log processing time consumption [cmin]

T_{tree}^{E2} per tree 315cm log processing time consumption [cmin]

T_{ree}^{E1+E2} per tree combined 495cm & 315cm log processing time consumption [cmin]

T_{tree}^{E3} per tree 375cm bar processing time consumption [cmin]

T_{tree}^{E4} per tree 254cm bar processing time consumption [cmin]

T_{tree}^{E5} per tree 300cm pulp processing time consumption [cmin]

T_{tree}^{E6} per tree 172cm stake processing time consumption [cmin]

T_{total}^{F0} total plot aside & cut up top time consumption [cmin]

T_{tree}^{A3} per tree trim butt time consumption [cmin]

T_{tree}^{total} total per tree time consumption [cmin]

$T_{tree}^{-A\&G}$ total per tree time consumption less movement A & G [cmin]

$T_{tree}^{process}$ total per tree processing time consumption [cmin]

T_{tree}^{fell} total per tree felling time consumption [cmin]

R_{tree}^{total} total per tree work rate [m^3/cmin]

$R_{tree}^{-A\&G}$ total per tree work rate less movement A & G [m^3/cmin]

$R_{tree}^{process}$ total per tree processing work rate [m^3/cmin]

R_{tree}^{fell} total per tree felling work rate [m^3/cmin]

ASSORTMENTS AND PRODUCE

$P_{v}^{495+315}$ plot combined percentage by volume of 495cm & 315cm logs

$P_{n}^{495+315}$ plot combined percentage by number of 495cm & 315cm logs

$P_{v}^{300+172}$ plot combined percentage by volume of 300cm pulp & 172cm stakes

$P_{n}^{300+172}$ plot combined percentage by number of 300cm pulp & 172cm stakes

P_{v}^{375} plot percentage by volume of 375cm bar

P_v^{254}	plot percentage by volume of 254cm bar
P_v^{300}	plot percentage by volume of 300cm pulp
P_v^{127}	plot percentage by volume of 172cm stake
${}_{dclassY}P_v^{productX}$	plot percentage by volume of product X in diameter class Y
$\bar{v}^{495+315}$	plot mean volume of 495cm and 315cm logs [m³]
$\bar{v}^{x}$	plot mean volume of product x [m³]
$v_{total}^{allproducts}$	plot volume of all products removed [m³]
CR%	cubic recovery percentage (*after* Stevens & Barbour, 2000)

FORWARDER

$\overline{F}_{move}^{C\&F}$	mean forwarder movement distance for moving in (C) and moving out (F) rack [m]
$F_{total}^{C\&F}$	total forwarder movement distance for moving in (C) and moving out (F) rack [m]
$\overline{F}_{speed}^{C\&F}$	forwarder mean speed for moving in (C) and moving out (F) rack [m/s]
$\overline{F}_{load}^{all}$	mean forwarder movement distance for per load cycle [m]
$\overline{F}_{load}^{extract}$	mean forwarder extraction distance for per load cycle [m]
l^n	number of forwarder load cycles
$\bar{l}^v$	mean bunk (load) volume [m³]
$\overline{GL_v}$	mean grapple loading volume [m³]
$\overline{GU_v}$	mean grapple unloading volume [m³]
$\overline{GL_n}^{mixed}$	mean number of pieces per grapple load – all product types
$\overline{GU_n}^{mixed}$	mean number of pieces per grapple unload – all product types
$\overline{GL_T}^{mixed}$	mean time per grapple load – all product types [cmin]
$\overline{GU_T}^{mixed}$	mean time per grapple unload – all product types [cmin]
T_{total}^{C+F}	total within plot movement time consumption [cmin]
T_{total}^{L}	total plot loading time consumption [cmin]
T_{total}^{U}	total plot unloading time consumption [cmin]

T^{L}_{piece}	plot mean loading time consumption per piece [cmin]
T^{U}_{piece}	plot mean unloading time consumption per piece [cmin]
T^{L}_{m3}	plot mean loading time consumption per cubic metre [cmin]
T^{U}_{m3}	plot mean unloading time consumption per cubic metre [cmin]
T^{K}_{total}	total plot manoeuvre within wood time consumption [cmin]
T^{A2}_{total}	total plot move to unload time consumption [cmin]
T^{A5}_{m3}	stacking time consumption per cubic metre [cmin]
T^{A5}_{total}	total plot stacking time consumption [cmin]
T^{A6}_{total}	total plot stow / un-stow grapple time consumption [cmin]
T^{A8}_{m3}	load adjust time consumption per cubic metre [cmin]
T^{A8}_{mean}	mean load adjust element duration [cmin]
T^{A8}_{total}	total plot load adjust time consumption [cmin]
N^{A8}_{m3}	number of load adjusts per cubic metre forwarded [cmin]
T^{C4}_{total}	total plot aside brash time consumption [cmin]
T^{C4}_{m3}	plot aside brash time consumption per cubic metre [cmin]
T^{D2}_{total}	total plot aside produce to load time consumption [cmin]
T^{C2}_{total}	total plot inspect & consider time consumption [cmin]

LIST OF FIELDWORK COMPLETED

TASK	DETAILS	COMPLETED BY
Original plot layout	Positioning, numbering, treatment allocation & surveying	TSU Tal-y-bont; Forest Research
Inner plot numbering and dbh measurement	Initial numbering of inner plot.	TSU Tal-y-bont
Outer plot numbering and dbh measurement	Initial numbering of outer plot.	Author
Plot re-survey	Theodolite survey of plot corners and features	DMS mapping; Author
Tree height	Measurement with Vertex	Author; TSU Tal-y-bont scribe
Mark frame tree plots 1 & 4	Mark frame trees and removals	Author; Dr. Arne Pommerenning (UWB); Carl Foster (TSU Tal-y-bont)
Mark group plots 2 & 6	Mark groups, shelter building trees & removals	Author; Carl Foster (TSU Tal-y-bont)
Mark low thinned plots	Mark removals	George Johnstone
Mark creaming plot	Mark removals	Author; Carl Foster (TSU Tal-y-bont)
Rack survey	Initial survey of rack network & re-survey for use	Author; Duncan Ireland (Technical Development)
Harvester time study		Author
Forwarder time study		Duncan Ireland (Technical Development)
Destructive sampling	Felling & cutting discs	Author
Destructive sampling	Tree measurement & calculation of disc position	Steve Murphy (Forest Research)

CHAPTER 1: GENERAL INTRODUCTION

1.1 BACKGROUND TO THE PROJECT & STUDY

The commissioning of the wider project and the research detailed in this study by Forestry Commission Wales (FCW) can be traced to the renewed interest in continuous cover forestry (CCF) leading from international and national policy changes.

1.1.1 Forest Policy Change

1.1.1.1 International Forest Policy

Forest policy change can be seen to stem from a series of international conferences on forest policy, most notably the United Nations Conference on Environment and Development (UNCED) that took place in Rio de Janeiro in 1992

At this conference delegate countries signed up to Agenda 21: the outline for sustainable development to the year 2000 and beyond, and to conventions on biological diversity, climate change, desertification and on the conservation and sustainable development of forests (FAO, 1992).

The next year in Helsinki saw the Ministerial Conference on the Protection of European Forests take place which followed up on the previous ministerial conference in Strasbourg in 1990 and the UNCED meeting in Rio (EU, 1993 (a)).

As an outcome of this conference, two resolutions were produced; Resolution 1: General Guidelines for the Sustainable Management of Forests in Europe; and Resolution 2: General Guidelines for the Conservation of the Biodiversity of European Forests. In particular, reference is made to the encouragement of silvicultural practices emulating nature e.g. continuous cover forestry (EU, 1993 (b)).

1.1.1.2 National Forest Policy

As a national response to international agreements the UK Forest Standard (Forestry Commission, 1998) was published. In particular the standard states that forests should be managed for the increase of species diversity, felling coupe size should be reduced and areas suitable for continuous cover management should be identified.

The rise of forest and forest product certification has also provided impetus for the use of CCF management. The most widely used certification system in the UK is the

UK Woodland Assurance Standard which is accredited by the Forest Stewardship Council (FSC) (UKWAS steering group, 2000).

The UK Woodland Assurance Standard (UKWAS) is the interpretation of the FSC principles and criteria to fit UK laws and circumstances. The standard was developed through negotiations between the FSC, Forestry Commission (FC), Timber Growers' Association (TGA) and the World Wide Fund for Nature (WWF) and was ratified in 1999. CCF management is favoured both directly and indirectly by the UKWAS certification standard.

The prominence of FSC certification was heavily influenced by the decision of a large proportion of domestic UK timber outlets to convert to selling only FSC certified timber by the year 2000. This collective, known as the WWF 95+ Buyers Group included such prominent names as B&Q and Sainsbury and by 1999 comprised more than 90 companies and around 20% of the UK market share (Goodall, 2000).

Although entry into the certification process is voluntary, the decision by the 95+ group had the net effect of pushing the Forestry Commission to become certified by the year 2000 in order to continue to sell its timber. The shift in the demand for certified timber has also had the knock-on effect of forcing many privately managed forests to become certified albeit through group certification schemes. Certification is generally seen as necessary in order to maintain access to timber markets, not necessarily to gain any price premium, but to maintain market share.

1.1.1.3 Forest Policy in Wales

The Welsh National Assembly increased national commitment to continuous cover forestry in publishing "Woodlands for Wales" the Welsh Woodland Strategy in 2001 (Forestry Commission, 2001). In the document the Assembly made a target of converting at least half of public forest land (managed by Forestry Commission Wales) to CCF by 2020. In addition to public sector woodlands, the use of CCF in private forests is heavily promoted through the grant scheme structure of Better Woodlands for Wales (Forestry Commission Wales, 2006). The grant scheme provides funding for CCF assessments and also pays higher rates, Woodland Improvement Grants (WIG) up to 75% of costs, for operations such as infrastructure improvement, uneconomic thinning and natural regeneration establishment work. Conventional plantation management attracts lower rates of 25 to 50%.

1.1.2 Rationale for the Project

It was acknowledged within "Woodlands for Wales" (Forestry Commission, 2001) that research and training were needed to implement the Assembly's CCF targets. One of the priorities was seen as identifying costs associated with CCF management. Mason *et al.* (1999) noted that there was little UK experience from which to derive costing examples.

A research project, of which this study is a part, was initiated to gain operational data from differing transformation approaches on which economic models could be based. The project aims to provide a rational framework for the discussion of grant aid for CCF management by estimating the difference in revenues between conventional clearcutting and different CCF management regimes. A key question to be answered by the project was the level of financial incentive appropriate for encouraging transformation toward CCF in the private sector.

The research plots at Trallwm were also envisaged as adding to the Forestry Commission demonstration areas as examples of operational CCF working.

The project is a partnership between Forestry Commission Wales, Forest Research and Bangor University (formerly the University of Wales, Bangor).

1.1.2.1 Rationale for the Study

This study covers the operational aspects of transformation harvesting, providing productivity and output data for typical harvesting scenarios of harvester and forwarder thinning of Sitka spruce (*Picea sitchensis* (Bong.) Carr.) in Welsh upland forest. The choice of this stand type was due to it being the most commonly encountered type in commercial plantations in Wales, and so likely to be frequently targeted for transformation to CCF.

The study aim was to produce time consumption and productivity models for different thinning approaches. The models could then be used as inputs to further economic modelling in the wider project.

1.1.2.2 Limitations of the Study

The study carried out at Trallwm is limited by the fact that it is a case study of one site and machine/operator combination only, and as such, the results cannot be generalised without further validation. The constraints of plot size and layout also restricted the statistical validation of analysis (discussed further in 2.3.1). The study should therefore be taken as a demonstration of transformation working and the productivities and outputs as examples, not necessarily applicable to all stands or machine combinations.

1.2 STUDY AIMS

- Install plots marked with transformation approaches likely to be used in commercial conditions to be compared against a conventional "control"
- Provide values of productivity for transformation approaches through time study on harvester and forwarder
- Provide data on the relative yields of transformation approaches
- Provide data on the silvicultural effects of transformation approaches
- Provide sufficient data to the wider project to enable the investigation of the economic implications of transforming a forest, presently under a clearfelling regime, to one under a continuous cover regime, particularly during the process of transformation.

1.3 RESEARCH SITE; COED TRALLWM

1.3.1 Location and General Description

1.3.1.1 Geographical Location

Coed Trallwm is located in mid-Wales, approximately 15 km west of the town of Builth Wells centred on grid OS SN 880 540 as shown in Figure 1.1.

Figure 1.1 Location of Coed Trallwm

Ownership boundary shown in red in right hand map.

1.3.1.2 Topography

Coed Trallwm is situated in the valley of the watercourse Nant Bach-helyg where its course turns from travelling east to south. The woodland is divided into northern and southern portions by the watercourse; the northern portion in turn divided by the combining watercourses Nant Tŷ-coch and Nant Eithaf which flow from the north into the Nant Bach-helyg. The larger block of the woodland to the north of the Nant Bach-helyg rises to meet Forestry Commission planting at the ridge and has a south-westerly aspect, the smaller having an easterly aspect. The portion to the south of the Nant Bach-helyg is steep with a northerly aspect.

1.3.1.3 Elevation

Coed Trallwm is an upland woodland, the planting ranging in elevation from 260m above sea level in the valley to 427m at the highest part of the ridges.

1.3.1.4 Climate

Met Office station summaries indicate that Coed Trallwm experiences c.1800mm precipitation per year and has a mean annual temperature of c.7°C.

The upland nature of the site means that it is exposed, wind hazard class (WHC) varying from high in the WHC 3 band in the valley bottom to low in the WHC 6 band on the ridges and DAMS scores ranging from 9 to 22 (Gardiner *et al.*, 2004).

1.3.1.5 Underlying Lithology and Soils

Coed Trallwm has soils typical for the local area; acid upland complexes overlying Lower Ordovician shales. Soils are generally upland brown earths and intergrade brown earths of varying depths with areas of gleying occurring in wetter parts and variable depths of peat build-up in the O horizon.

1.3.1.6 Coed Trallwm Management History

The woodland consists of 161.6 ha of mainly coniferous (98%) plantation established in 1967.

Sitka spruce makes up the vast majority of planting covering 63%, with Norway spruce (*Picea abies* (L.) Karst.), Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco) and western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) the more numerous minor species, covering 16%, 7.5% and 6.8% respectively.

The area was planted on upland grazing land by the Economic Forestry Group (Tilhill precursor) and was subsequently bought by George Johnson in 1980 and has been managed by him and his family since.

The Sitka spruce crop within the study area was 37 years old at the beginning of the study and had been thinned three times before in 1988/89, 1993/94 and 1997/98. The first thinning systematically removed every fifth row with some selective thinning of the matrix whilst successive thinnings were purely selective low thins.

The woodland is one of three sites in Wales used by the Forestry Commission to study the operational aspects of transformation to continuous cover forestry, the others being Clocaenog (Coed y Gororau FD) and Cym Berwyn (Llanymyddfri FD).

1.4 STRUCTURE OF THE THESIS

The structrure of the thesis is as follows.

Chapter 2: Plot Layout, Surveying and Measurement

The initial layout of the plots is described and baseline pre-thinning stand parameters including diameter, basal area, height, volume, site index, racking density and increment are presented. This information allows initial description and comparison of the plots and provides the base data for further work.

Chapter 3: Silvicultural Application

This chapter describes the intensity and type of the interventions applied to the plots and investigates the marking decisions made. Post thinning stand parameters and mean felled tree parameters are presented to describe interventions and, as variables, to analyse vehicle working. Stand stability and structural diversity indices are also investigated.

Chapter 4: Shortwood Harvesting and Time Study Literature Review

This chapter describes the shortwood harvesting system and its origins and reviews the current literature pertinent to the study. A review of time and work study is also made.

Chapter 5: Harvester Study

Harvester working is investigated and summarised. Time consumption is analysed and related to treatment and stand effects. The accuracy of the harvester head is confirmed and the volume and proportions of products cut are assessed. Rack use and brash mat creation by the harvester is also analysed.

Chapter 6: Forwarder Study

Forwarder working is investigated and analysis made of movement, loading and unloading, and other work.

Chapter 7: Comparison of Vehicle Productivity & Future Plot Growth

The final chapter brings together work from chapters 2, 3, 5 and 6. Harvester and forwarder productivities achieved in the study are first presented and compared with those achieved in other studies. Due to limitations in direct comparison, interventions are applied to a normalised stand for comparison and assortment outputs and vehicle productivities calculated for each plot. The effect of interventions on future growth of the stand is then investigated with particular regard to volume loss through growing oversize. The study is then summarised with comment made on the implications of findings.

CHAPTER 2: PLOT LAYOUT, SURVEYING AND MEASUREMENT

2.1 INTRODUCTION

This chapter covers the initial layout and measurement associated with setting up the eight plots, and discusses the findings of the process.

The study at Trallwm deals with four different approaches to transformation compared to a control of maintaining a low thinning regime until rotation-end.

The initial survey and assessment acts as a base-line from which to analyse thinning marking and harvesting operations.

The fundamental stand measures of diameter, basal area, height and volume will be covered as knowledge of them is integral to further work.

The inclusion of increment measurement is also important as it forms the basis of any modelling. Knowledge of increment can be used to predict how diameter distributions develop between treatments; of particular relevance if the percentage of crop that exceeds sawlog butt-diameter limits is to be calculated or estimates of future diameter distributions and stand volumes to be made.

2.1.1 Aims

- Describe and present results of the initial survey of the plots
- Identify key plot mensuration parameters
- Assess homogeneity of plots
- Gain measures of plot increment

2.2 LITERATURE REVIEW

2.2.1 Diameter

Of the simple variables, the description of diameter is the most powerful and most commonly used method of presenting stand properties (Husch *et al.*, 2003; Bailey & Dell, 1973). Diameter at breast height (d), due to its ease of measure, is often included in forest survey data in the form of diameter distributions (Gadow & Hui, 1999). Knowledge of diameter and hence basal area (g) allows a wide range of stand parameters to be calculated due to it closely correlating with stem volume, conversion cost, product output and hence value (Husch *et al.*, 2003; Gadow & Hui, 1999; Philip, 1994; Bailey & Dell, 1973).

2.2.2 Projecting Diameter Distributions

2.2.2.1 Distributions

A number of functions exist for describing diameter distributions and include the normal, exponential, binomial, poisson, Charlier, Fournier series, normal logarithmic, Johnson's SB, Pearl, Reed, Schiffel, gamma, beta and Weibull functions (Husch *et al.*, 2003; Schreuder *et al.*, 1993).

Bailey & Dell (1973) suggest that when selecting a function to describe a unimodal diameter distribution, a number of attributes are desirable. Since distribution shapes can vary from negatively exponential to a bell-shaped curve with varying amounts of positive or negative skewing, the function should be able to describe the full range. The utility of the function is also increased if the form and parameters are easily related to the form of the distribution. Lastly, the function should be easily fitted to the observed distribution and provide a base for further development.

2.2.2.2 Parameterisation

Approaches to parameterising distribution functions can be allotted to one of three categories; the parameter prediction approach, the parameter recovery approach and percentile estimation (Husch *et al.*, 2003; Gadow & Hui, 1999).

The parameter prediction approach estimates parameters of a future distribution from current stand variables such as dominant height (H), mean diameter ($\overline{D}$), age and density.

The parameter recovery approach estimates the rate of change in distribution moments or percentile values using known distribution moments or percentile values at time t, as well as some other known stand variable such as H.

The parameter recovery approach is generally thought to yield better results than the parameter prediction approach (Reynolds *et al.*, 1988). Gadow & Hui (1999) note, however, that the parameter prediction approach is the more common.

2.2.2.3 The Weibull Distribution

Of all distribution functions, the Weibull has been the subject of the greatest amount of work (Husch *et al.*, 2003), probably because the function displays more desirable characteristics than any of the other functions (Bailey & Dell, 1973) and as noted by Husch *et al.* (2003) can be parameterised through parameter prediction, parameter recovery or percentile methods.

Hafley & Schreuder (1977) state that the Johnson's SB and the beta function are more flexible in fit than the Weibull as well as several other functions. Rennolls *et al.* (1985) note however that the goodness of fit comes at the expense of calculating a fourth parameter in comparison to the Weibull's three.

The goodness of fit of different functions varies with the distribution they are applied to and the methods of parameterisation and calibration (Maltamo *et al.*, 1995; Reynolds *et al.*, 1988; Hafley & Schreuder, 1977).

For example, Puumalainen *et al.* (2002) compared uncalibrated Weibull and percentile distributions to empirical data from unmanaged irregular pine stands. It was found that the percentile distribution performed better with the exception of describing an inverse-J structure. The poor performance of the Weibull distribution was attributed to the inability of the Weibull to describe multi-modal distributions. When calibrated using empiric data such as stocking density (N), stand basal area (G) and diameter of tree of mean basal area (D_g), the ability of both approaches to describe the distributions was generally increased and became equal, although in the case of the Weibull the increase in ability was greater.

To describe bimodal distributions, the Charlier A and the Pearl-Reed functions are suggested by Gadow & Hui (1999) as being suitable.

The Weibull probability density function (p.d.f.) is commonly seen in two forms: the three parameter function and the two parameter function.

The three parameter function is defined as:

$$f(x) = \frac{c}{b}\left(\frac{x-a}{b}\right)^{c-1} \exp\left\{-\left(\frac{x-a}{b}\right)^{c}\right\}$$

$$a \geq 0, b > 0, x > c$$

The a parameter controls the location of the curve by dictating a minimum variable value

The b parameter controls the scale of the curve by describing the range of the variable

The c parameter controls the shape of the curve by altering the skewness. The effects of different values of c on the curve shape are presented below.

c < 1	inverse J-shape
c = 1	exponential decreasing
1 < c < 3.6	positive asymmetry (skewness)
c = 3.6	symmetric
c > 3.6	negative asymmetry (skewness)
$c \to \infty$	spike over a single point

(Husch *et al.* 2003)

The two parameter Weibull is parameterized using the assumption that the minimum value (a) is 0 or the smallest value possible or sampled (Husch *et al.*, 2003) and is expressed as:

$$f(x) = (c/b)(x/b)^{c-1} \exp\{-(x/b)^{c}\}$$

$$x \geq 0, b > 0, c > 0$$

(Bailey & Dell, 1973)

The Weibull cumulative probability distribution function can be derived through a change of variables and expressed for the three parameter function as:

$$F(X) = P(x \leq X) = 1 - e^{-\left(\frac{X-a}{b}\right)^{c}}$$

(Husch *et al.* 2003)

and for the two parameter function as:

$$F(X) = P(x \leq X) = 1 - e^{-\left(\frac{X}{b}\right)^c}$$

(Bailey & Dell, 1973)

Where for characterising a diameter distribution:

x = diameter at breast height

X = DBH, for which the probability is calculated that x assumes a smaller value

F(X)= $P(x \leq X)$ = cumulative probability of the random variable x = probability that a random DBH is smaller that X

a, b, c = location, scale and shape parameters

(Bailey & Dell, 1973)

The Weibull model has also been used to predict diameter distributions after thinning by estimating the change in parameters. Álvarez González (1997, in Gadow & Hui, 1999), used the proportion of stems and proportion of basal area removed to convert pre-intervention b and c parameter values to post-intervention values for stands of pure *Pinus pinaster*.

$$b_{after} = -4.7067 + 1.0205 \cdot b_{before} + 85.35 \frac{N_{removed}}{N_{total}} - 73.617 \frac{G_{removed}}{G_{total}}$$

$$c_{after} = -1.059 + 1.178 \cdot c_{before} + 8.170 \frac{N_{removed}}{N_{total}} - 5.255 \frac{G_{removed}}{G_{total}}$$

Where:

b_{before}, b_{after}, c_{before} and c_{after} = Weibull parameters b and c before and after thinning

$N_{removed}$, N_{total} = stems per hectare removed and before thinning

$G_{removed}$, G_{total} = basal are per hectare removed and before thinning

2.3 PLOT LAYOUT

2.3.1 Plot Layout Method

2.3.1.1 Original Plot Layout

Layout of plots within Trallwm and the experimental design was tasked to Forest Research Technical Services Unit (TSU) at Tal-y-Bont and negotiations between Forest Research, Forestry Commission Wales and University of Wales, Bangor. The plot positions and treatment type were decided before the involvement of the author as part of the demonstration area setup.

As the plots were to become permanent 0.5 ha buffered sample plots, a total plot area of 1 ha was required (see 2.3.1.3). Plots were installed in the most homogeneous areas of pure Sitka spruce possible. Plot corners were marked with tree-tube stakes and no edge demarcation was made. Due to the topographical constraints of the field site, there was only space for the low thinning, group shelterwood and frame tree treatments to be replicated twice and the premature clearfell and creaming treatments were not replicated.

The inclusion of the group shelterwood treatment (see 3.3.1.3) precluded the subdivision of plots to gain more replicates as the spatial diversity of the treatment required a larger minimum area than the other treatments.

Plots were originally surveyed using a walktax (also known as a string-box or logger's string) and sighting compass from known points identified on a map. Information was transferred to and processed in ArcView.

2.3.1.2 DMS Survey

Concern was raised over the accuracy of the original plot layout and the implications for mensuration and area-derived data. A theodolite survey of the corner points of the plots was contracted to Digital Mapping Services of Conwy.

Survey data was co-ordinated with the OS National Grid by post-processing comparison of a temporary reference station against OS active network control points at Blackpool, Daresbury, Northampton and Nottingham.

Six stations were fixed relative to the temporary reference station and seven traverses around the plots were carried out using the stations as reference.

The survey recorded the inner and outer plot corner points (see 2.3.1.3) and notable features within the plots. Portions of the Trallwm mountain bike track within the plots were recorded as well as the banks left within the forest by historic field boundaries. Points on racks were also recorded to enable further survey of plot racking infrastructure. Plot corner marker posts were repositioned at the time of survey and survey points on racks, bike tracks and banks were recorded with coloured marker sticks.

Point co-ordinates and data were made available in spreadsheet format and were subsequently imported into ArcView and converted into point and shape files.

2.3.1.3 Plot Shape

All plots possess a square inner 0.5 ha plot, designated as being retained as a permanent sample plot, and an outer buffer which would only be marked for the duration of the study. Initially, all buffers were to be 0.5 ha in size, a hollow square of 100 m sides with the inner plot centred within it. The total available area and distribution of homogeneous Sitka spruce at Trallwm limited plot layout and required that some buffers would differ from those planned.

Plots 2 and 3 overlapped and so plot 2 was retained as a square and the buffer of plot 3 was reduced by the area of overlap. This also occurred with plots 5 and 6, the buffer of plot 5 being reduced and plot 6 remaining square.

Plot 4 was originally positioned so that two sides ran along forest roads. The number of edge-trees included in the plot due to this placement was a concern as it might create bias in the study. The buffer was moved to the west whilst maintaining parallel edges so that edge trees were excluded whilst maintaining the original position of the inner plot and the desired 0.5 ha area of the outer buffer (see Appendix 1).

The clearfell, plot 7, was irregularly shaped as it was defined by forest edges on three sides. The inner plot was positioned centrally within this area but a square buffer could not be fitted around this. Using the entire remaining area as a buffer posed problems in terms of edge trees and edge effects. Two areas bordering the inner 0.5 ha plot were identified to increase total plot area to 0.68 ha. The two areas were defined by racks and the mountain bike trail (see Appendix 1).

2.3.1.4 Defining Edges

The delineation of plot boundaries was carried out after the theodolite survey.

Equipment carried by the surveyor included a Suunto KB-14/360 R sighting compass, 4 sighting poles made from yellow painted 1.3 m tree-tube stakes, marking paint and a plot map for taking notes.

Bearings along plot edges were identified from the theodolite survey and were measured using the Suunto compass, allowing for a declination of 2° West of grid North. A bearing was taken from a plot corner post and a point identified that lay on the plot edge. The surveyor walked to the point and fixed a sighting post at that point. Back-bearings were used to adjust and confirm initial sightings. Care was taken that posts remained upright so that compass readings occurred directly over surveyed points and parallax errors were minimised.

When the positioning of the initial sighting post was confirmed it was used to sight and position another sighting post further along the plot edge. The process was repeated until the corner post was reached with the plot boundary marked by a series of sighting poles.

Where the plot boundary passed through trees the points at which the boundary intersected the trunk were identified and marked with paint. Trees were identified as included or excluded from the plot by whether the centre of the trunk at breast height, lay inside the boundary.

The plot edge was finally marked by painting dashes in line with the plot edge on prominent stumps and other features and across the centre of racks crossing the boundary.

Sighting poles were recovered and another edge surveyed.

2.3.1.5 Rack Mapping Method

The rack network in and around plots was mapped by a two-person team by breaking racks into a series of "legs"; straight lines connecting nodes.

Using known points from the DMS survey, a spreadsheet was used to calculate the grid references of nodes by using trigonometry to convert the bearing and length of legs into eastings and northings which were added to the known grid reference of the known points.

A table of point grid references and their identification codes was imported into ArcView and a rack map constructed from them using the sketch-map and notes as reference.

A fuller description of the method is given in Appendix 2.6.

2.3.2 Plot Layout Results

2.3.2.1 Relative Plot Positioning

The relative positioning of the eight plots is shown in Figure 2.1.

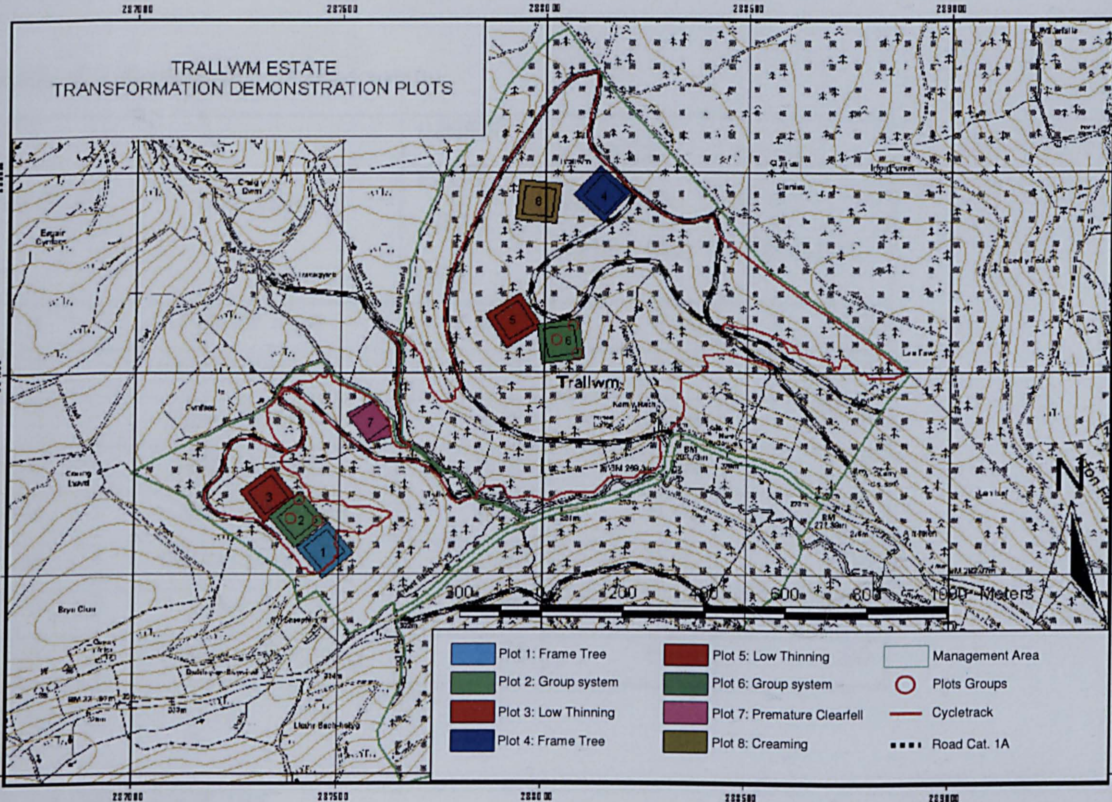


Figure 2.1 Map of Trallwm Estate showing positions of all plots

2.3.2.2 DMS Survey

Comparison of the temporary reference station against the OS network resulted in finding its 3D position to within 0.0071 m.

The 3D coordinates of the six stations fixed from the temporary reference station were derived to between 0.0135 m and 0.0150 m.

Accuracy of points surveyed in the seven traverses ranged from 1 in 25051 to 1 in 118506.

The Digital Mapping Services report can be found in full in Appendix 2.4.

The raw coordinate data provided by DMS can be found in Appendix 2.5.

2.3.2.3 Plot Shape

The changes to the shapes of some of the plots can be seen in Appendix 1. The areas of the plots after repositioning are shown in Table 2.1. Part of the buffer areas of plots 3 and 5 were lost to retain the full 1 ha areas of plots 2 and 6 respectively. Plot 7 can be seen to consist of the 0.5 ha inner plot and two smaller areas to increase total area. It should be noted that no plot area was lost through the displacement of the buffer in plot 4.

Table 2.1 Summary of plot areas

PLOT	SYSTEM	INNER PLOT AREA (ha)	OUTER BUFFER AREA (ha)	TOTAL PLOT AREA (ha)
1	Frame Tree	0.50	0.50	1.00
2	Group System	0.50	0.50	1.00
3	Low Thinning	0.50	0.44	0.94
4	Frame Tree	0.50	0.50	1.00
5	Low Thinning	0.50	0.49	0.99
6	Group System	0.50	0.50	1.00
7	Clearfell	0.50	0.18	0.68
8	Creaming Thinning	0.50	0.50	1.00

2.3.2.4 Rack Mapping

Maps showing the numbered rack network existing in the plots before harvesting and the tracks added by the harvester and forwarder during harvesting can be found in Appendix 2. Coordinates of the nodes derived through the rack survey are provided in Appendix 2.7.

Table 2.2 presents the total rack length recorded in each plot and the value adjusted per hectare to provide values for rack density as not all plots were 1 ha in area.

Table 2.2 Rack length and density within plots

	Frame Tree plot 1	Group System plot 2	Low Thinning plot 3	Frame Tree plot 4	Low Thinning plot 5	Group System plot 6	Clearfell plot 7	Creaming plot 8
Plot Area	1.00	1.00	0.94	1.00	0.99	1.00	0.68	1.00
Total Rack Length	1284.0	1080.0	1192.0	1124.0	1037.0	1109.0	760.0	1133.0
Total Rack Length per ha.	1284.0	1080.0	1266.1	1124.0	1047.4	1109.0	1117.2	1133.0

2.3.3 Discussion of Plot Layout

2.3.3.1 Plot Positioning

Coed Trallwm covers a total of 161 ha of which 63% is Sitka spruce. The area covered by Sitka spruce, however, is not homogeneous but occurs on a range of slopes, soils, aspects and elevations. The layout of plots was further limited by the positioning of watercourses, roads, areas of check, windblow and to some extent the landowner's objectives.

The heterogeneity within the stands of Sitka spruce at Trallwm, therefore, will be reflected in the data produced from them and this should be borne in mind during analysis.

2.3.3.2 Mapping Accuracy

The accuracy of surveying was such that the maximum error incurred over a 100 m boundary would be 4 mm. This error is negligible especially when considered against the method of corner marking. The shape and area of plots as mapped can therefore be used and considered with confidence.

The spatial referencing of the plot shapes is also very accurate, the maximum 3D error being 0.015 m. This value is the maximum a plot shape as recorded could be displaced from its true coordinates.

The error therefore incurred on any marked point in the plots is under 2 cm.

2.3.3.3 Rack Mapping

The rack network in and around the plots was created by the systematic removal of every fifth row of trees in the first thinning. Assuming a distance between planting rows of 1.8 m (derived from the site cultivation of ploughing with a six foot separation between furrows), rack spacing should be nine metres between centres.

Assuming a constant separation of nine metres between straight racks, a racking density of between 1100 m and 1200 m per hectare would be expected; with racks running parallel with the plot edge, either 11 or 12 racks 100 metres long could be held within the plot area.

If the racks pass through the plot at an angle of 45 degrees, 15 or 16 racks with a total length of 1113 m or 1110 m respectively would be held within the plot area.

The closest approximation of this ideal occurs within plots four, six and seven where the racks are generally parallel and running with the plot boundary. As such the rack density within these plots is close to 1100 m.

The racking density within plot 1 is the highest of all the plots at 1284 m/ha. This is due to the plot being a pinch-point for extraction. Extraction from the areas to the northeast to the road-head must pass through the plot. To facilitate this movement racks 1.2 and 1.7 (see appendix 2) are used as main extraction routes or skid-roads. Both racks travel with the cultivation direction for only part of their length, the remainder of the length travels across the cultivation direction and hence other racks. This extra length of rack has increased plot density. In addition, areas of the plot are prone to bogginess, particularly in the southwest, causing racks to follow firmer ground.

The racking density within plot 3 is the second highest and is due to the topography of the plot. The plot is not positioned on a slope that bends into a small drainage hollow. The cultivation has followed the slope and so the racks are also curved, so increasing racking density.

Plot 2 has the lowest racking density of the plots due to the presence of a field boundary running through the plot. The field boundary stopped cultivation through the middle of the plot so creating a planting break. Racks do not cross the field boundary and there is a resultant loss of rack length and hence density due to this area.

The rack density within plot 5 is also a little lower than expected. Plot 5, as plot 3, is situated on a curved slope. Ploughing in this area remained in straight lines unlike the curves in plot 3. This has caused the plot network to consist of straight branching racks which are slightly wider spaced, so causing a drop in rack density.

Rack density within plot 8 is close to expected levels. Although there is a change in cultivation direction in the plot the racks remain generally straight and evenly spaced at around 9 metres.

2.4 TREE NUMBERING AND MEASUREMENT

The enumeration and mensuration of the plots allows the characterisation of the stands and the later silvicultural analysis of interventions by acting as a baseline. The numbering of trees allows mensuration data to be combined with other data sources such as time study files and vehicle data logs for analysis of vehicle working and production. Stand parameters are also used as variables in the analysis of vehicle working.

2.4.1 Tree Numbering and Measurement Method

2.4.1.1 Numbering and dbh Measurement

Numbering of trees within the inner plots was carried out by TSU, Tal-y-Bont. Trees were marked in series starting from 1 with marking generally progressing between racks.

A horizontal mark was made on all trees to indicate 1.3 m where dbh was measured to the nearest millimetre with a diameter tape.

Trees within the plot buffers were numbered and measured for dbh by the author. The number series used was not started from the last integer used in the inner plot but from a higher integer, starting from a multiple of one hundred, so that numbering changes could occur as necessary.

Marking was carried out using aerosol paint, separate colours being used between inner and outer plots to aid visual differentiation.

2.4.1.2 Height Measurements

Height measurements were taken using a Häglof Vertex 2 to the nearest 0.1 m. The Vertex transponder was placed on the tree to be measured at the marked dbh level (1.3 m) and the Vertex adjusted to calculate from this height. All heights were measured by the author with TSU aid acting as scribe and transponder positioner.

Tree height was measured to the tip of the tallest leader and crown depth to the lowest live branch contiguous with the crown. Both heights were measured three or more times and the mean recorded.

All trees within the inner 0.5 ha plot were measured. Trees within the outer 0.5 ha buffer areas were measured if they were to be felled, were a shelter building tree (see 3.3.1.2), or selected by a random one-in-ten sample of retained trees.

The Vertex was calibrated at 10 m twice daily, and as weather conditions dictated to maintain accuracy.

2.4.1.3 Permanent Sample Plot Marking

Trees within the inner 0.5 ha plots which were not to be felled were marked by TSU Tal-y-Bont with a more permanent white paint after being prepared by wire-brushing.

2.4.1.4 Numbering to Aid Time Study

Trees to be felled were marked with their number at two or three points around their circumference to aid identification during time study. Numbers were painted as large as possible and so as to be read vertically.

2.4.1.5 Dead and Dying Trees

A number of standing, fallen and leaning dead and dying trees were encountered. Although the trees were not of value in terms of timber production and were to be left if possible for dead-wood habitat, they were measured and numbered so as to be identifiable if they were processed by the harvester. Several trees had one or more snapped sections and these were measured and recorded. Whilst these trees were recorded with the other plot mensuration data they were not included in stocking or crop attribute calculations. Dead and dying trees can be found listed in Appendix 2.1, denoted with a "Fell Code" of 4.

2.4.2 Tree Numbering and Measurement Results

A summary of pre-intervention mensuration data for the plots is presented below in table 2.3. Values are presented for inner 0.5 ha permanent sample plots, the 0.5 ha buffer and the plots as a whole. Full raw mensuration data for all plots can be found in appendix 2.1 and full summaries by plot in appendix 4.

Owing to not all the heights of the trees in the outer plots being available, top height was calculated as the mean height of the 50 trees of greatest diameter (100 trees per hectare) from the inner plot (Philip, 1994; Hamilton, 1975).

General yield class, an estimation of maximum average yearly increment, was derived through yield model top height curves (Edwards & Christie, 1981).

2.4.2.1 Stocking Density

Table 2.3 shows the stocking density (N) varying between plots. Values range between 465 tree per hectare in plot 4 and 719 trees per hectare in plot 3. The mean stocking density throughout the plots is 548 trees per hectare with a standard deviation of 79.7.

2.4.2.2 Basal Area

Table 2.3 shows varying basal area (G) between plots from a minimum of 39.3 m^2/ha in plot 8 to a maximum of 45.8 m^2/ha in plot 6, the mean being 43.16 m^2/ha with a standard deviation 2.18 m^2/ha.

Table 2.3 Summary of plot mensuration data

	Frame Tree plot 1			Frame Tree plot 4			Clearfell plot 7		
	INNER	OUTER	TOTAL	INNER	OUTER	TOTAL	INNER	OUTER	TOTAL
Area (ha)	0.5	0.5	1.0	0.5	0.5	1.0	0.5	0.2	0.7
Total Trees	272	284	556	225	240	465	238	100	338
Trees per hectare	544	568	556	450	480	465	476	555	497
Basal Area per hectare (m2/ha)	42.6	43.8	43.2	41.1	43.3	42.2	38.8	49.2	44.0
General Yield Class (m3/ha/year)			22			20			26
Top Height (m)			25.0			22.6			29.3
DBH (cm)	INNER	OUTER	TOTAL	INNER	OUTER	TOTAL	INNER	OUTER	TOTAL
Min	19.8	19.0	19.0	21.4	14.8	14.8	19.0	20.7	19.0
Max	45.8	46.0	46.0	45.9	46.8	46.8	55.6	49.9	55.6
Mean (arithmetic)	31.2	30.9	31.0	33.8	33.5	33.6	31.5	33.1	32.0
Standard Deviation	5.1	5.1	5.1	4.6	5.3	5.0	6.7	5.9	6.5

	Group plot 2			Group plot 6			Creaming plot 8		
	INNER	OUTER	TOTAL	INNER	OUTER	TOTAL	INNER	OUTER	TOTAL
Area (ha)	0.5	0.5	1.0	0.5	0.5	1.0	0.5	0.5	1.0
Total Trees	279	298	577	245	250	495	249	259	508
Trees per hectare	558	596	577	490	500	495	498	518	508
Basal Area per hectare (m2/ha)	40.8	42.1	41.4	45.4	46.2	45.8	40.3	38.2	39.3
General Yield Class (m3/ha/year)			22			24			16
Top Height (m)			25.1			25.9			20.1
DBH (cm)	INNER	OUTER	TOTAL	INNER	OUTER	TOTAL	INNER	OUTER	TOTAL
Min	17.1	16.3	16.3	21.7	19.9	19.9	9.5	13.4	9.5
Max	44.3	45.0	45.0	50.7	53.4	53.4	47.0	48.1	48.1
Mean (arithmetic)	30.1	29.5	29.8	34.0	33.7	33.9	31.6	30.2	30.9
Standard Deviation	4.9	5.2	5.1	5.3	6.1	5.7	5.6	5.4	5.5

	Low Thinning plot 3			Low Thinning plot 5		
	INNER	OUTER	TOTAL	INNER	OUTER	TOTAL
Area (ha)	0.5	0.4	0.9	0.5	0.5	1.0
Total Trees	363	314	677	282	280	562
Trees per hectare	726	711	719	564	571	568
Basal Area per hectare (m2/ha)	44.8	46.5	45.7	42.7	44.6	43.7
General Yield Class (m3/ha/year)			22			20
Top Height (m)			24.9			23.2
DBH (cm)	INNER	OUTER	TOTAL	INNER	OUTER	TOTAL
Min	13.4	16.1	13.4	16.1	13.8	13.8
Max	39.5	45.4	45.4	53.8	52.9	53.8
Mean (arithmetic)	27.6	28.3	27.9	30.5	30.9	30.7
Standard Deviation	5.1	5.7	5.4	5.8	6.3	6.1

2.4.2.3 Top Height

Pre-intervention plot top height (H_t), the arithmetic mean height of the 100 trees of largest diameter per hectare, (Philip, 1994; Hamilton, 1975) is shown in Table 2.3. Values range from a minimum of 20.1 m in plot 8 to a maximum of 29.3 m in plot 7. The mean of the plot top heights is 24.5 m with a standard deviation of 2.6 m.

2.4.2.4 General Yield Class

Plot general yield class, the value of maximum mean annual increment (m^3/ha/year) (Edwards and Christie, 1981), is represented by Table 2.3, value ranging between 16 for plot 8 and 26 for plot 7.

2.4.3 Discussion of Tree Numbering and Measurement

2.4.3.1 Pre-intervention Stocking Density Within Plots

With the exception of plot 3, all plots have values of between 465 trees per hectare (plot 4) and 577 trees per hectare (plot 2). This spread is roughly equivalent to the standard deviation of 79.7 from the mean of all plots of 548 trees per hectare.

Plot 3 shows a high stocking density of 719 trees per hectare and if treated as an outlier and excluded, the value for the stocking mean decreases to 524 with a standard deviation of 46.4 and decreases the coefficient of variation from 14.5% to 8.9%.

Variation in plot stocking illustrates the degree of heterogeneity inherent in the stands that the plots were installed in.

2.4.3.2 Pre-intervention Plot Basal Area

Basal area (G) is a useful measure by which to compare stocking in stands of the same species, age and height (Philip, 1994) and also as a rough indicator of below-canopy light levels when managing for natural regeneration (Hale, 2004).

Although stand top height varies between plots, basal area is still a useful indicator of comparative stocking. In all but plot 8, the standing basal area, and hence stocking, lies within 1.2 standard deviations from the mean of the plots.

G in plot 8 is noticeably lower, differing from the mean by 1.77 standard deviations. The low value of G in plot 8 is due to a combination of the plot stocking density being similar to that found in plots 6 and 7 (relatively low at 508 tree/ha) but having a lower $\overline{D}$, more similar to that of plot 1 (plot 8 $\overline{D}$=30.9cm). If plot 8 had the stocking density equivalent to plot 1, its value of G would increase by 3.7 m^2 to 43.0 m^2, only 0.07 standard deviations from the mean.

The basal areas found in all plots are higher than the threshold of 30 m^2/ha suggested by Hale (2004) below which natural regeneration would be more likely to occur in suitable Sitka spruce stands.

2.4.3.3 Pre-intervention Plot Top Height and General Yield Class

Top height (H_t) is a stand variable that is little affected by thinning regimes (Philip, 1994) and is well correlated with cumulative volume production and site quality and hence general yield class (Edwards & Christie, 1981; Hart, 1994; Philip, 1994).

Plots 1, 2 and 3 are evenly matched in terms of site quality as might be expected from their immediacy. Soils in the plots are generally upland brown-earths with some minor variation due to poor drainage. The plots are at an altitude of between 340 m and 370 m and due to having a north-easterly aspect are somewhat sheltered from the prevailing wind.

Plots 4, 5, 6 and 8 are spatially close, although site conditions and quality vary more between plots.

Plot 8 has a noticeably lower top height that is probably derived from its poorer soils and more exposed position. The soils consist of intergrade brown-earths on the upper slope which change rapidly to shallow peaty gleys on the lower slope. The plot is also situated on a south-west facing slope and at an altitude of around 410 m, so is considerably more exposed.

Plot 4 is situated on the highest point of the estate at 420 m and so is very exposed. The soils in the plot are well drained intergrade brown earths and so the site is of a better quality than its neighbouring plot 8, hence a greater top height and yield class.

Plot 5 occupies similar soils to plot 4, has an exposed south-westerly aspect and is only slightly lower at 390 m. Top height and yield class are therefore similar to plot 4.

Plot 6, conversely, shows a higher top height and yield class probably due to its better quality soils and more sheltered position. The soils change with the slope from intergrade brown-earths in the north to upland brown-earths in the south. It should be noted however that the plot is "low" within yield class 24 and so there is greater similarity with plots 1, 2 and 3.

Site conditions in plot 7 are dissimilar to those in other plots and account for the very high growth found. The plot is the lowest at 300 m and is sheltered. The soils are flushed peaty-gleys and peats which have provided good growing conditions for the Sitka spruce.

2.5 ANALYSIS AND DATA PROCESSING

Analysis of plot diameter, height and volume is used to investigate the validity of direct plot comparison as well as to further characterise the plots and interventions. Weibull curves are used to describe diameter distributions, their changes due to interventions and as a base for further stand modelling efforts.

2.5.1 Diameter

2.5.1.1 Analysis of Differing Plot Diameter Distributions

Plot diameter distributions are displayed by 4 cm diameter classes in Appendix 5. Analysis of normality through normal probability plots (normal Q-Q) (Pallant, 2005) is carried out in Appendix 2.8.

A one-way between-groups analysis of variance was conducted to explore the observed differences in the diameter ranges of the plots (Pallant, 2005; Wheater & Cook, 2000; Fowler *et al.*, 1998). Diameter differences between plots were found to be statistically significant at the p=0.000 level [$F(7,4170)=70.0$, $p=0.000$]. The effect size as calculated through eta squared was 0.1 which suggests a medium to large effect. The results of post-hoc comparison using the Tukey HSD are presented in Table 2.4.

Table 2.4 Summary of post-hoc comparison of plot diameters using the Tukey HSD

		Subset for alpha = .05				
plot	N	1	2	3	4	5
3	677	27.917				
2	577		29.810			
5	562		30.716	30.716		
8	508			30.886		
1	556			31.045	31.045	
7	338				31.994	
4	465					33.625
6	495					33.851
Sig.		1.000	.152	.981	.112	.998

Means for groups in homogeneous subsets are displayed.

(a) Uses harmonic mean sample size = 503.590.

(b) The group sizes are unequal. The harmonic mean of the group sizes is used. Type I error levels are not guaranteed.

2.5.1.2 Calculation of Quadratic Mean Diameter (Dg)

The diameter of the tree of arithmetic mean cross-sectional area (Husch *et al.*, 2003; Hamilton, 1975) was calculated for all plots and is presented in Table 2.5.

Table 2.5 Comparison of pre-felling plot quadratic mean diameters

	Frame 1	Group 2	Low 3	Frame 4	Low 5	Group 6	Clearfell 7	Creaming 8
D_g pre-felling (cm)	31.46	30.23	28.43	33.99	31.30	34.32	32.64	31.37

2.5.1.3 Estimation of Weibull Parameters

To describe the diameter distributions found in the plots, the Weibull distribution was employed.

The two parameter Weibull was used instead of the three parameter owing to its comparative ease of calculation although this required an assumption in the threshold value (the *a* parameter).

Plot mensuration data were sorted by diameter into 4 cm classes. A SPSS file was created that summarized the diameter class information for the plots, including the number of trees within each class, the mean diameter for each class, and the cumulative count and proportion for successive classes.

A non-linear regression was run for each plot for:

$$F(dbh) = 1 - e^{\left(\frac{d_{\min}}{b}\right)^c} \cdot e^{\left(\frac{dbh}{b}\right)^c}$$

Starting values of b=30, c=5 and 1<b,c<100 were used. The value of d_{min}, the threshold value, was taken as 7 cm as this was the smallest diameter that would have been measured.

A maximum likelihood regression was then run using the parameter estimates and the original dataset:

$$F(dbh) = \int_{d\,\min}^{dbh} \frac{c}{b} \cdot \left[\frac{dbh}{b}\right]^{c-1} \cdot e^{\left[\frac{d^c - dbh^c}{b^c}\right]} \cdot dt$$

2.5.1.4 Calculated Weibull Parameters

The two calculated parameters, b and c, are presented for all plots in Table 2.6. Weibull curves describing diameter distributions for all plots are presented together in Figure 2.2 and are overlaid on 4 cm diameter class distributions in Appendix 5.

Table 2.6 Calculated Weibull parameters for all plots before the intervention

	Frame 1	Group 2	Low 3	Frame 4	Low 5	Group 6	Clearfell 7	Creaming 8
b pre felling	33.2161	31.9492	30.1484	35.7708	33.2282	36.2908	34.6620	33.1451
c pre felling	6.4235	6.2615	5.4707	7.2623	5.0849	6.1110	5.1039	6.2140

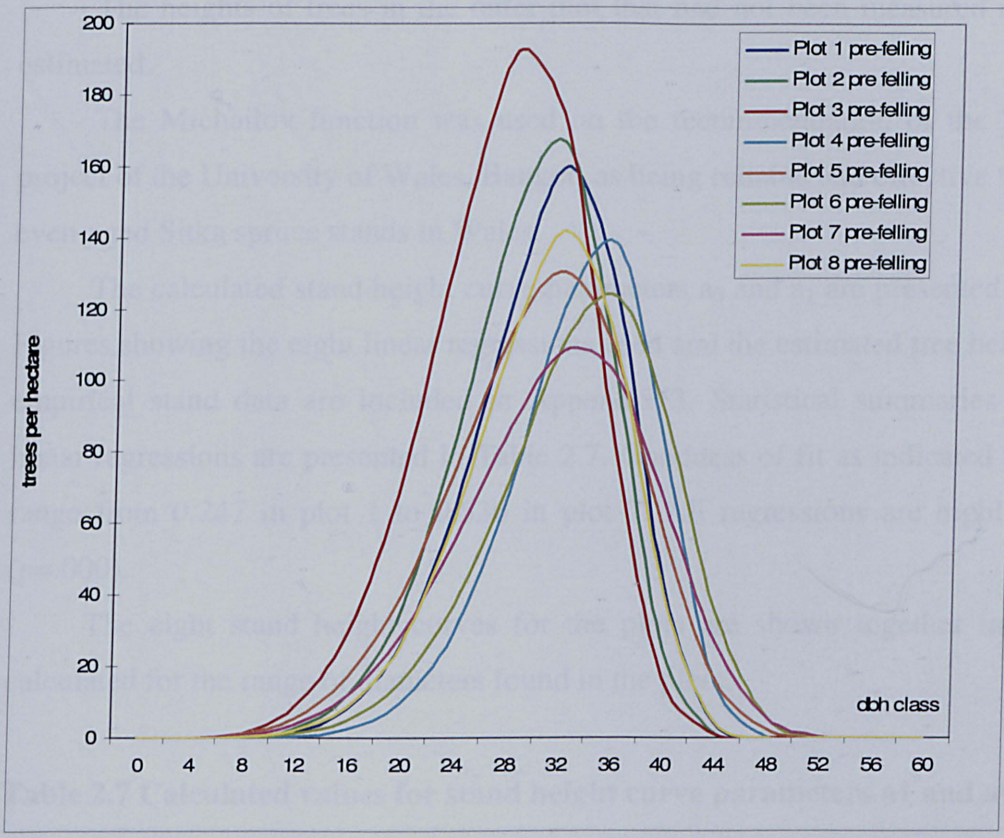


Figure 2.2 Plot diameter distributions described through Weibull curves

2.5.2 Height

2.5.2.1 Fitting of a Stand Height Curve

A stand height curve was fitted to all the plots using a function described by Michailov (1943):

$$h = 1.3 + a_0 \cdot e^{\frac{-a_1}{d}}$$

Where:

h = tree height

d = diameter at breast height

a_0 & a_1 = parameters calculated for the stand

The constants a_0 and a_1 were derived through a linear regression of stand height and diameter data using the expression:

$$\ln(h-1.3)=\ln a_0 + a_1 \cdot \frac{1}{d}$$

The heights of trees in the outer plot that had not been measured could then be estimated.

The Michailov function was used on the recommendation of the Tyfiant Coed project of the University of Wales, Bangor, as being reliable and effective for describing even-aged Sitka spruce stands in Wales.

The calculated stand height curve parameters a_0 and a_1 are presented in Table 2.7. Figures showing the eight linear regressions used and the estimated tree heights fitted to empirical stand data are included in Appendix 3. Statistical summaries of the eight linear regressions are presented in Table 2.7. Goodness of fit as indicated by R^2 values range from 0.247 in plot 1 to 0.536 in plot 7. All regressions are highly significant (p=.000).

The eight stand height curves for the plots are shown together in Figure 2.3, calculated for the range of diameters found in the plots.

Table 2.7 Calculated values for stand height curve parameters a1 and a0

Plot	a1	a0	Dependent variable	R^2	F-test	Term	Constant / Coefficient		t-test	
							Estimate	Std. Error	t-value	p
Plot 1: Frame	9.635	30.747	ln(h-1.3)	0.247	[F(1,382)=125.175, p=.000]	Constant	-9.635	0.861	-11.188	0.000
						1/d	3.426	0.028	120.244	0.000
Plot 2: Group	8.293	29.925	ln(h-1.3)	0.346	[F(1,400)=211.928, p=.000]	Constant	-8.293	0.570	-14.558	0.000
						1/d	3.399	0.020	168.922	0.000
Plot 3: Low	10.349	31.334	ln(h-1.3)	0.457	[F(1,483)=405.907, p=.000]	Constant	-10.349	0.514	-20.147	0.000
						1/d	3.445	0.020	171.085	0.000
Plot 4: Frame	10.975	28.008	ln(h-1.3)	0.457	[F(1,326)=274.377, p=.000]	Constant	-10.975	0.663	-16.564	0.000
						1/d	3.333	0.020	165.403	0.000
Plot 5: Low	9.440	27.555	ln(h-1.3)	0.460	[F(1,372)=317.029, p=.000]	Constant	-9.440	0.530	-17.805	0.000
						1/d	3.316	0.019	176.880	0.000
Plot 6: Group	9.258	30.683	ln(h-1.3)	0.405	[F(1,341)=232.430, p=.000]	Constant	-9.258	0.607	-15.246	0.000
						1/d	3.424	0.019	181.483	0.000
Plot 7: Clearfell	13.806	38.617	ln(h-1.3)	0.536	[F(1,243)=280.504, p=.000]	Constant	-13.806	0.824	-16.748	0.000
						1/d	3.654	0.028	130.850	0.000
Plot 8: Creaming	9.739	24.242	ln(h-1.3)	0.507	[F(1,325)=334.672, p=.000]	Constant	-9.739	0.532	-18.294	0.000
						1/d	3.188	0.018	177.083	0.000

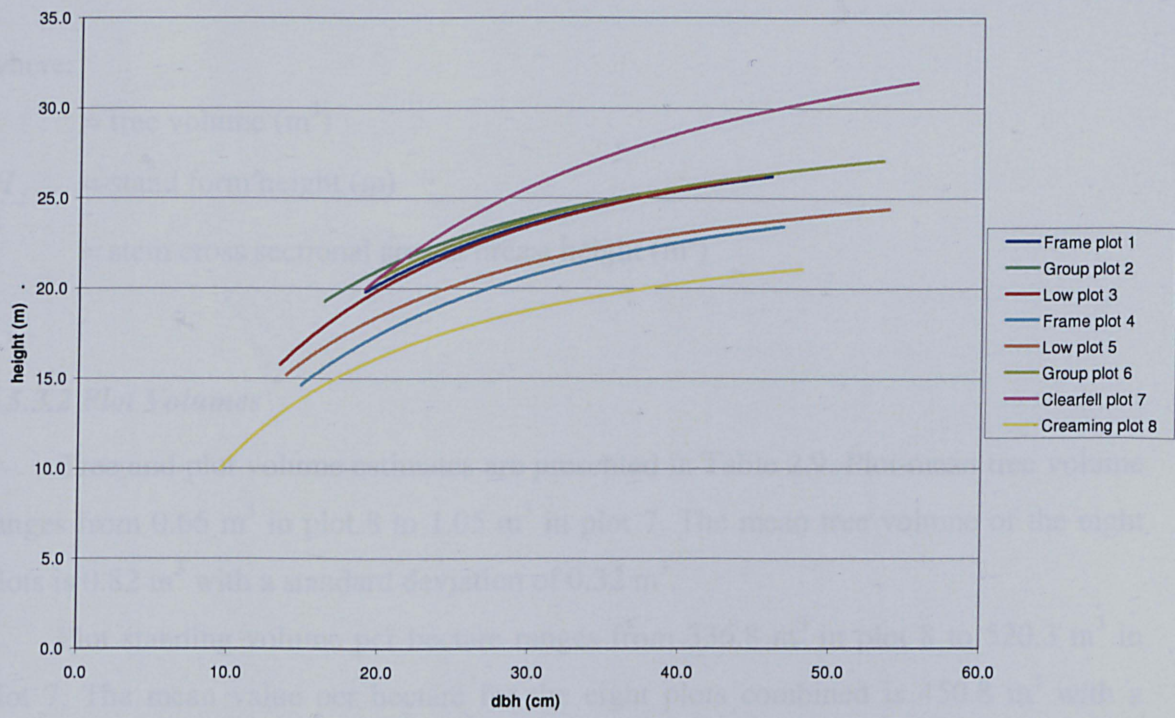


Figure 2.3 Comparison of Plot Stand Height Curves

2.5.2.2 Calculation of Hg

The plot values for the height of the tree of quadratic mean diameter (H_g) were calculated using the values of D_g (section 2.4.1.2) and the stand height curves (Loetsch *et al.*, 1973). Values for H_g are provided in Table 2.8.

Table 2.8 Calculated values for Hg; the height of the tree of quadratic mean diameter

	Frame 1	Group 2	Low 3	Frame 4	Low 5	Group 6	Clearfell 7	Creaming 8
H_g pre-felling (m)	23.94	24.05	23.07	21.58	21.68	24.73	26.60	19.07

2.5.3 Volume Calculation

2.5.3.1 Form Height

Volume was calculated using tree basal areas and stand form height derived from main crop form height tables through stand top height (Hamilton, 1975; Matthews & Mackie, 2006). Volume values are therefore estimated for over-bark live-stem volume to 7 cm top diameter. Volume was calculated using:

$$v = g \cdot H_f$$

where:

v = tree volume (m^3)

H_f = stand form height (m)

g = stem cross sectional area at breast height (m^2)

2.5.3.2 Plot Volumes

Tree and plot volume estimates are presented in Table 2.9. Plot mean tree volume ranges from 0.66 m^3 in plot 8 to 1.05 m^3 in plot 7. The mean tree volume of the eight plots is 0.82 m^3 with a standard deviation of 0.32 m^3.

Plot standing volume per hectare ranges from 336.8 m^3 in plot 8 to 520.3 m^3 in plot 7. The mean value per hectare for the eight plots combined is 450.8 m^3 with a standard deviation of 61.49 m^3.

Table 2.9 Summary of tree and plot volume values

Volume (m^3)	Frame plot 1	Group plot 2	Low plot 3	Frame plot 4	Low plot 5	Group plot 6	Clearfell plot 7	Creaming plot 8
N	556	557	677	465	562	495	338	508
Mean	0.84	0.78	0.69	0.88	0.76	1.04	1.05	0.66
Median	0.81	0.76	0.65	0.85	0.69	1.00	0.98	0.64
Std.Deviation	0.27	0.26	0.27	0.26	0.31	0.36	0.43	0.23
Minimum	0.31	0.23	0.15	0.17	0.15	0.35	0.36	0.06
Maximum	1.80	1.75	1.79	1.67	2.25	2.52	3.05	1.56
Volume per ha.	467.0	452.3	498.0	408.7	433.0	515.3	520.3	336.8

2.5.3.3 Individual Form Factor

Volume was also calculated using an individual tree form factor. Form factor was calculated for each tree using the function described by Bergel (1974).

$$ff = a_0 + \frac{a_1}{h \cdot d + d} + \frac{a_2}{d} + a_3 \cdot \log d^2 + \frac{a_4}{h \cdot d}$$

The form factor was used on the recommendation of the Tyfiant Coed project of the University of Wales, Bangor. The Bergel function produced the best fit out of 15 functions that were trialled using data from 36 full stem samples derived fro 4 sites across Wales.

Volume calculated in this manner agreed well with volume values derived from destructive sampling in section 2.6, using the protocol derived from Geißler and Wenk (1988). When compared against the harvester vehicle log of volume cut a negative relationship was found with increasing diameter, suggesting decreasing cubic recovery percentage (CR%) (Stevens & Barbour, 2000). Stand form height produced a positive relationship of CR% with diameter. A decision was made to use stand form height and not use data calculated using d_q or d_{q-10} such as volume increment. Removed work can be found in Appendix 2.9. Diameter increment data were retained and are used for calculation of tree diameter growth to oversize and the associated volume loss in Section 7.5

2.5.4 Discussion of Analysis & Data Processing

2.5.4.1 Diameter

The statistical analysis of diameter distributions indicated significant differences between plots of a medium to large effect size. The Tukey HSD post-hoc comparison indicates that no significant differences can be found when comparing plots 4 & 6; 1, 5, 7 & 8; 1, 8 & 5; and 2 & 5. Plot 3 however, has a mean diameter significantly lower than al other plots.

The implications of the disparity in diameter distributions are covered further in 2.7.

Diameter distributions within all plots can be seen to be normal as described by distribution curves, normal Q-Q plots and analysis (see 3.4.4.1). The Weibull parameters derived from regressions of the diameter distributions all have values for c, the parameter controlling shape, of between 5.08 and 7.3, however. The values for c all are greater than 3.6, the value which would indicate a perfectly normal distribution. The derived values do then suggest slightly negatively skewed distributions.

2.5.4.2 Height

Comparison of the height curves produced in Figure 2.3 confirms what has been stated before regarding plot site index. The lowest curve, and hence the plot of lowest site index, is that of plot 8. The curves of plots 4 and 5 are very similar and are the next lowest, followed by a grouping of the curves of plots 1, 2, 3 and 6. The plot 7 curve is the uppermost, indicating the plot of highest site index.

The values of H_g also correlate well to the calculated dominant heights / site index values, all plots being ranked in the same order.

2.5.4.3 Estimated Plot Volumes

Plot volumes are a product of site index (top height), diameter distribution and stocking.

Plots 1, 2 and 3 share common site conditions and hence similar top height and yield class, but have different stocking densities. Plot 2 can be viewed as the median plot of the group. Plot 1 contains a slightly lower stocking density of trees with a larger average diameter and so has a slightly larger standing volume than plot 2. Plot 3 contains a significantly higher stocking density of trees of smaller average diameter and hence volume. The standing volume in plot 3 is still the greatest of the three owing to the much greater number of trees present.

Plots 4 and 5 share similar site conditions and have similar standing volumes. Plot 4 has a lower stocking density of trees of greater average diameter whereas plot 5, as plot 3, contains a higher stocking density of trees of smaller diameter and has marginally more volume.

The stocking densities in plots 6, 7 and 8 are similar, but plot 8 shows the effects of its poor site through a small mean tree volume, leading to a smaller standing volume whereas plots 6 and 7 have a higher site index and therefore larger mean tree sizes to provide the highest standing volumes of all the plots.

2.6 DESTRUCTIVE SAMPLING FOR CALCULATION OF INCREMENT

2.6.1 Destructive Sampling Method

Destructive sampling of crop trees was carried out in March 2005 following a protocol adapted from Geißler and Wenk (1988), included in full in Appendix 2.2.

Sampling entailed the felling and measurement of trees and the removal of two sample discs from each felled stem, one at breast height and the other from the point on the stem at which mean cross-sectional area occurred ten years previously (h_{0-10}).

Increment data is essential if modelling is to take into account stand growth. Of particular interest is the potential volume loss due to trees growing oversize and producing butt logs with end diameters greater than 60 cm. At present, most UK sawmills that routinely comminute Sitka spruce do not have the ability to process logs with a butt diameter of greater than 60 cm and reject logs of this size or larger. Until sawmill infrastructure changes in the medium to long-term, oversize logs represent a potential volume and revenue loss to growers.

2.6.1.1 Fieldwork

Felling of sample trees was carried out during the spring following the harvesting within the plots so that the crop had not entered its next season of growth.

A total of 24 trees were felled; 12 each from the plots of highest and lowest site index, plots 6 and 8 respectively. The choice of these plots was to allow interpolation, if required, of data for the other plots.

For each plot, 12 trees were selected across the known dbh range. Trees were picked from the stand adjoining the plots (assumed to be the same population) so that felling of plot trees was minimised. Where no non-plot tree of a required diameter was available, a plot tree from the buffer was felled.

Measurements taken in the field were current height (h), heights for the previous ten years measured from whorls (h_{-1}, h_{-2},....., h_{-10}) and diameters at 1.3 m (dbh) and 1/8, 4/8 & 7/8 of the tree height ($d_{1/8}$, $d_{4/8}$, $d_{7/8}$).

In-field measurements were used to calculate the diameter of the mean cross sectional area (d_q) using the function (after Geißler & Wenk, 1988):

$$d_q = \sqrt{\frac{k}{3} \cdot \left(d_{1/8}^2 + d_{4/8}^2 + d_{7/8}^2\right)}$$

The value used for the correction factor k was 1.040 for Sitka spruce, so giving:

$$d_q = \sqrt{0.3467\left(d_{1/8}^2 + d_{4/8}^2 + d_{7/8}^2\right)}$$

The point along the stem where d_q occurred was found through measurement and its height from the point of cutting recorded as h_0.

The location of mean cross sectional area ten years previously (d_{q-10}) in relation to the point of cutting was then calculated and identified through the function:

$$h_{0-10} = \frac{h_0}{h} \cdot h_{-10}$$

All field measurements and calculations are presented in Appendix 2.3.

Discs were cut from dbh and the point at which d_{q-10} was calculated and then transported to the laboratory for preparation and analysis.

Where there was confusion over leader measurement and hence tree height, the location of d_{q-10} was calculated for both values and a disc cut at each calculated position.

Tree 11 in plot 8 was cut but found to be unsuitable for analysis owing to the crown being heavily forked.

2.6.1.2 Laboratory Based Work

Sample discs were planed, marked with measurement paths and scanned within 24 hours of cutting to prevent distortion through drying. Scanned images were measured in WinDendro and measurements transferred to Excel for data processing. Three measurements were taken along each of four measurement paths. Measurements were centre to t_{-10}, t_{-10} to t and bark thickness. Data are included in Appendix 2.3.

2.6.2 Destructive Sampling Results

2.6.2.1 Defining Under-bark Diameter to Over-bark Diameter Relationship

The relationship between under-bark diameter (d^{UB}) and over-bark diameter (d^{OB}) was derived through a linear regression (see appendix 2.3) in order to calculate over-bark diameter for the under-bark diameters measured through WinDendro.

The relationships were calculated as $d^{OB} = 1.0112d^{UB} + 6.6954$ ($R^2 = 0.9995$) and $d^{OB} = 1.0256d^{UB} + 3.749$ ($R^2 = 0.999$) for plots 6 and 8 respectively.

2.6.2.2 Calculating d_{-10}, dq_{-10}

Under-bark values for d_{-10} and d_{q-10} were derived from the quadratic mean of the radii measured in WinDendro. The $d^{UB} : d^{OB}$ relationships were used to calculate the bark thickness for the diameters.

2.6.2.3 Diameter Growth

Diameter growth for the previous ten years is calculated by:

$z_d = d - d_{-10}$

Ten-year diameter increment is plotted against d_{-10} in Figure 2.4.

In order to statistically test whether the two regression lines in Figure 2.4 were significantly different, a linear model for z_d was fitted using d_{-10} as a continuous variable and *plot* (6 or 8) as a factor. A significant difference for the factor *plot* would indicate a difference in slope and a significant difference for the interaction between d_{-10} and *plot* would indicate a difference in intercept. No significant difference was found between the slopes of the two regression [F(1)=0.001, p=.970] or between the two intercepts [F(1)=0.058), p=.812]. The two data-sets were combined to form an amalgam, also presented in Figure 2.4.

The root-mean-square error (RMSE) was calculated for the linear regressions for plot 6, plot 8 and the combined data-set. RMSE values were found to be 15.58 mm, 11.06 mm and 13.84 mm for the regression functions of plot 6, plot 8 and the combined data-set respectively with mean bias values of -0.0002 mm, 0.0002 mm and -0.0005 mm.

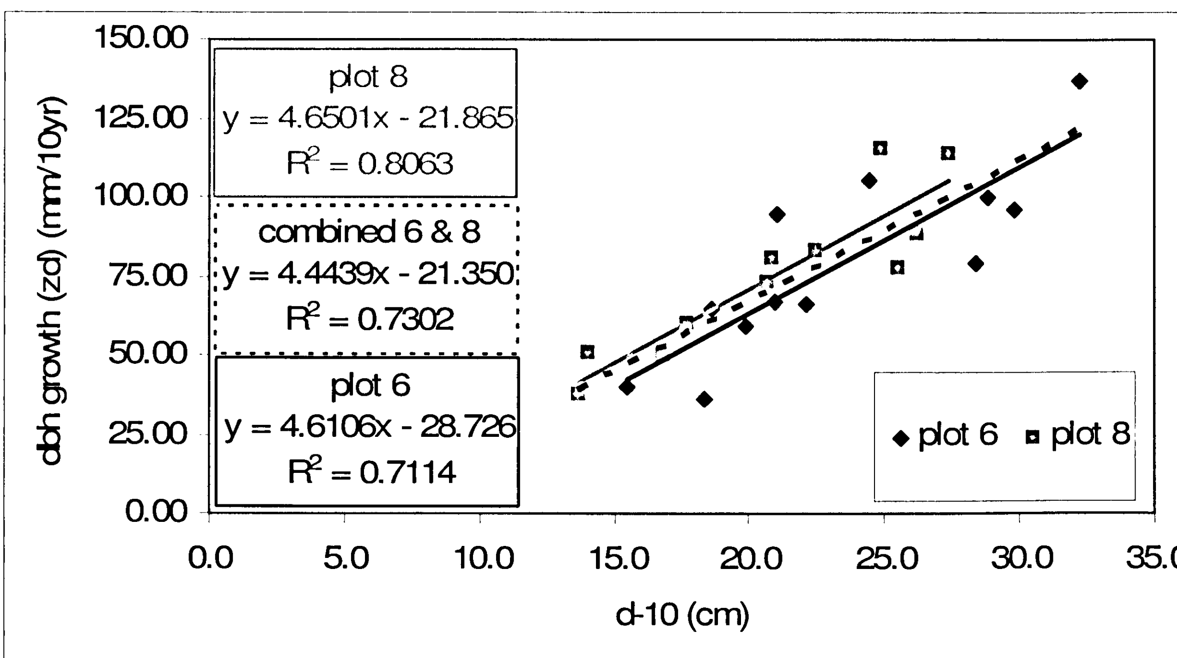


Figure 2.4 Ten year diameter growth in relation to diameter for plots 6 & 8 and combined data

2.6.2.4 Height Growth

Height growth is represented in the measured sequence of h, h_{-1}, h_{-2},....., h_{-10}. Height growth for the previous ten years is calculated by:

$$z_h = h - h_{-10}$$

The annual height growth of the shortest and tallest trees within plots 6 and 8 is shown in Figure 2.5 with mean values for the plot included for overall plot comparison.

The ten-year height increments for plots 6 and 8 were compared using an independent samples t-test and found to be significantly different ($t(21)=4.113$, $p=0.000$), the plots having means of 7.66 m and 5.88 m with standard deviations of 0.77 m and 1.27 m respectively.

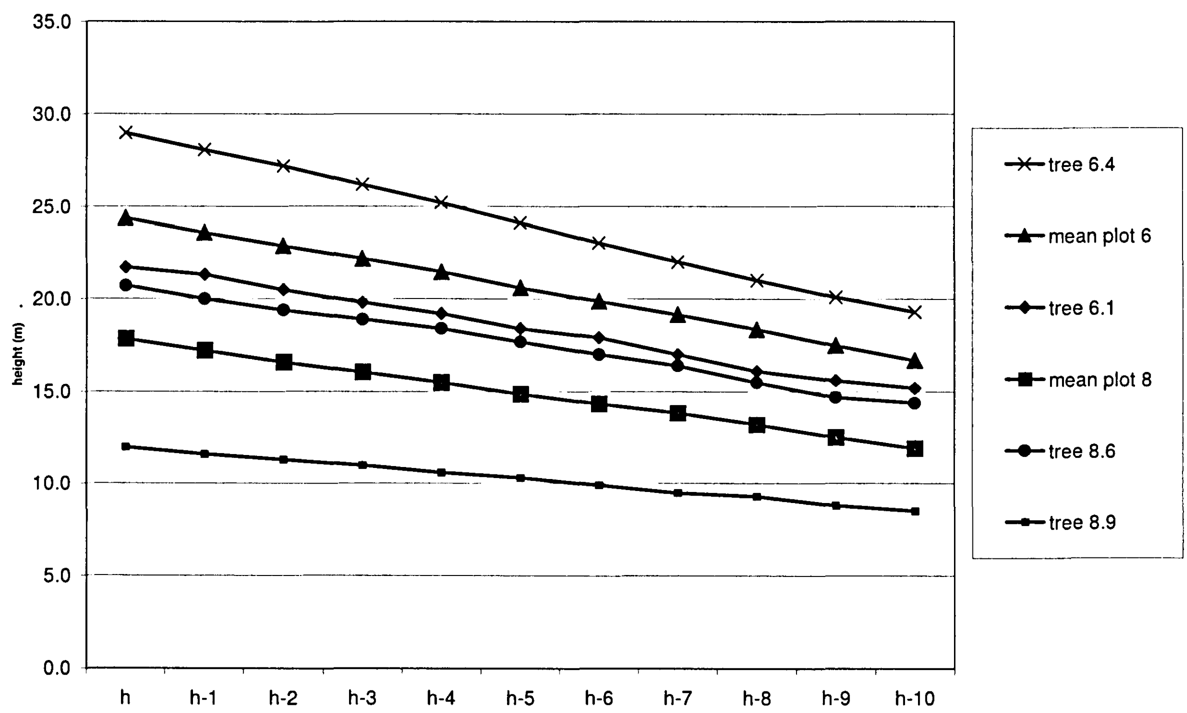


Figure 2.5 Annual height-growth for the tallest, shortest and combined-mean sampled trees from plots 6 & 8

2.6.3 Discussion of Destructive Sampling

When comparing the rate of diameter growth to initial diameter, no significant difference was found between the two sampled plots. The RMSE values for plots 6 and 8 of 15.58 mm and 11.06 mm represent 19.8% and 14.6% of mean ten-year increment. The amalgamated regression provides an intermediate solution with precision equivalent to 17.9% of mean ten-year increment. The bias of all regressions is low indicating almost no tendencies.

The assumption in predicting future diameter growth using the regression in 2.6.2.3 is that increment will be put on at the same rate in the next ten years as that of the past ten years. This assumption may not be entirely justified as the relationship between diameter increment and diameter is not linear and can decrease with increasing diameter (Gadow & Hui, 1999).

The growing space available to the tree is also a major factor in setting the rate of diameter increment (Oliver & Larson, 1996; Philip, 1994). The initial stocking density will, therefore, affect the sampled rate of diameter growth, and the use of different thinning types, albeit at the same intensity, may have some impact on diameter increment as growing space will be reallocated differently spatially and between tree social classes.

It is worth noting that growing space also influences the placement of growth within stems which will then change tree form and height-diameter ratio (Philip, 1994).

The similarity of rates of diameter growth in plots 6 and 8 is likely to be due to the similar thinning regime employed and stocking density held within the plots.

Height growth for the two sampled plots correlates well with their respective site indices. The mean height growth of the sampled trees of 7.66 m and 5.88 m for plots 6 and 8 respectively reflect the different growth rates that would be expected of sites representing YC 24 and YC 16. Height growth for the past ten years in both sampled stands correlates well with published height curves (Edwards & Christie, 1981) and appears to be quite linear with no indication of a fall in rate with age, making it likely that the trees are in their period of highest height growth rate (Oliver & Larson, 1996). The height growth for the next ten years is, however, likely to start to slow (Edwards & Christie, 1981; Kilpatrick & Savill, 1981). Although the rate of slowing cannot be known, if increment continues to match published curves, a reduction of around 50% can be expected in the next ten years.

2.7 DIRECT COMPARISON OF PLOT HARVESTING DATA

Analysis has shown that there were notable differences between plots in their diameter distribution, stocking and site index. As further work investigates the effects of altering diameter distribution and the products derived from different treatments, it is of interest to assess the magnitude of the existing differences.

As illustrated in Figure 2.6, form factor decreases with site index, although the size of the difference is not substantial. Tree height is therefore the parameter that will most control volume for trees of given diameter. The stand height curves presented in Figure 2.3 indicate the differences in height between plots of trees for a range of diameters; approximately 5.5 m between plot 6 and plot 8 for a tree of 50 cm diameter.

As can be seen in Figure 2.6, the slower height growth in plots of lower site index is associated with an increasing difference in volume of trees of equal diameter.

To illustrate the effect size caused by the difference in diameter distributions and site indices between plots, a comparison of volumes is made of the trees of plot quadratic mean diameter (D_g).

The first comparison is made to illustrate the difference in tree volumes for the eight values of D_g whilst maintaining the same site index. Tree height was calculated for each value of D_g using the Plot 1 height curve (figure 2.3) to compare volumes for the same site index.

As a second comparison, height was calculated for each value of D_g using the stand height curve derived for its plot (figure 2.3) and volume calculated. This comparison shows the effects of both differing diameter distributions and site indices. The results are presented in Figure 2.7.

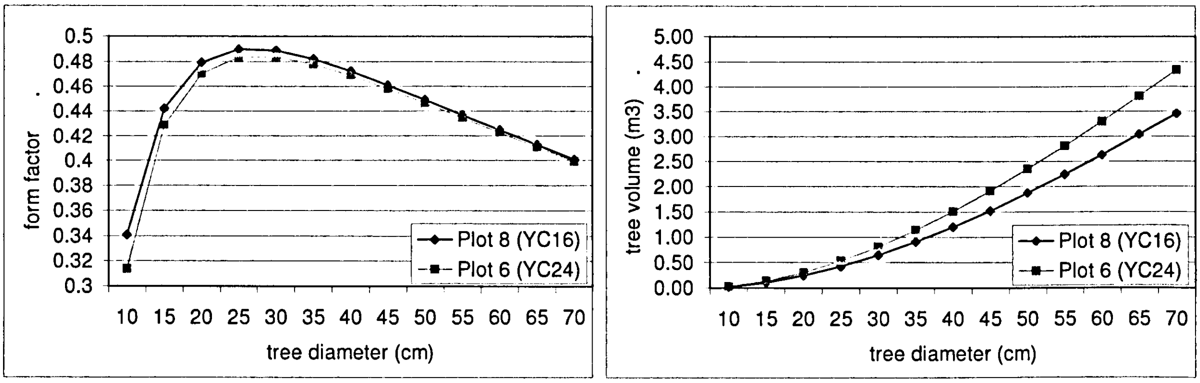


Figure 2.6 Variation of calculated form factor (ff) and volume (v) with tree diameter (d) for different site indices

Form factor calculated after Bergel (1974) for commercial volume using stand height curves derived from plots

As can be seen in Figure 2.7, even if the site index was equal amongst plots, the variation in tree volume for a tree of D_g is substantial; variation ranging from 0.71 m^3 to 1.09 m^3. This variation is due to the effects of plot stocking density and diameter distributions and the inherent differences in form factor.

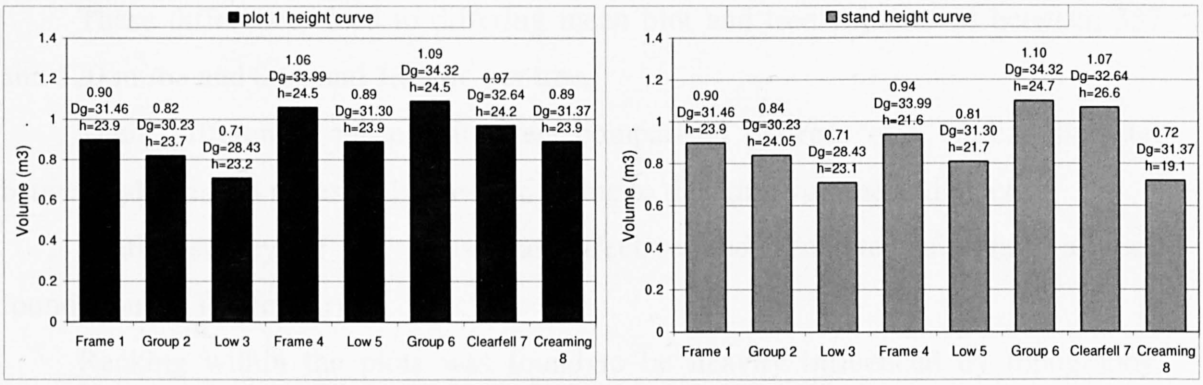


Figure 2.7 Variation of calculated volume (v) for plot values of quadratic mean diameter

Figure on left represents use of a single height curve and figure on right the use of specific height curves. Volume is calculated after Bergel (1974) for commercial volume using stand height curves derived from plot 1

If site index is taken into consideration there is some change in values. The range of values slightly increases to 0.71 m^3 to 1.10 m^3 with the greatest change occurring in plots 7 and 8 due the their site indices varying the most from that of Plot 1.

What is also notable is the difference in height:diameter ratios. This is most easily seen in a comparison of Plots 3 & 8 where volumes are nearly identical but Plot 8 has comparatively fatter-shorter trees to Plot 3' slimmer-taller trees.

The conclusion to be drawn is that between plots there is a very noticeable difference in mean tree volume due to differing diameter distributions and exacerbated by differing site indices. Height:diameter ratio (taper) will also vary for a given diameter between plots. For a tree cut of given diameter, both total volume and the product assortment possible will therefore vary between plots, making direct comparison problematic.

2.8 CONCLUSIONS

The initial survey and setup of the plots has, due to the constraints of the available resource, yielded plots that differ slightly from the ideal.

The plots were not found to be as homogeneous as perhaps is desirable, stocking varying between 465 and 719 trees per hectare and basal area ranging between 39.3 and 45.8 m^2/ha. Top height and hence site index also varied between plots from 20.1 m (YC 16) to 28.8 m (YC26). Diameter distributions between plots were also found to differ significantly, quadratic mean diameter varying between 28.43 and 34.32 cm.

These differences lead to differing mean plot and tree volumes of between 337 and 520 m^3/ha and 0.66 and 1.05 m^3 per tree.

These differences mean that direct comparison of trees of a similar diameter between plots is not necessarily possible owing to differing volume and taper.

Spatial survey of the plots was effective and accurate, providing a good foundation for further survey.

Racking within the plots was found to be heavily influenced by topography, ground conditions and the original ploughing pattern, leading to much higher densities in the more difficult plots.

Destructive sampling was used to analyse diameter and height increment over the previous ten years. A relationship for diameter increment, suitable for use in all plots, was derived from the analysis as was height growth for highest and lowest yield-class sites which can be interpolated to cover the intermediate plots.

CHAPTER 3: SILVICULTURAL APPLICATION

3.1 INTRODUCTION

This chapter covers the process of marking the plots for thinning, and assessment of the thinning decisions made and of how stand parameters changed with thinning.

Using the stand measures covered in Chapter 2, knowledge of the felled portion of the plots and residual stand will be gained, which is essential for analysis of harvesting vehicle activity in later chapters.

This knowledge will also be used to quantify thinning intensity and type and comment on stand structural diversity and stability.

3.1.1 Aims

- Describe and present results of thinning intensity and type
- Assess stand marking decisions
- Confirm that different thinning prescriptions produced different stand effects
- Describe thinning effect on stand structural diversity
- Describe thinning effect on measures of stand stability

3.2 LITERATURE REVIEW

3.2.1 Description and Effects of Thinning

3.2.1.1 Introduction

The development of a managed forest is a product of both tree growth and the type and intensity of thinning and tending operations imposed on it (Gadow & Hui, 1999). The objective of thinning is to manage volume production on a stand basis by reallocating volume increment on a tree basis through the manipulation of growing space by intervening in inter-tree competition (Smith *et al.*, 1997; Oliver & Larson, 1996; Price, 1988, 1987, 1985).

Thinning is the foremost management tool in manipulating stand dynamics to meet silvicultural, ecological and economic objectives by manipulating stem form and quality, tree stability, spatial stand structure, volume increment and regulation and the maintenance of future silvicultural freedom (Rollinson, 1999; Smith *et al.*, 1997; Hart, 1994).

Given the infinite permutations derived from the mix of stand attributes and possible thinning types, the description of interventions can be somewhat difficult, especially when trying to convey meaning across differing cultures and traditions (Schutz, 2002a). An illustration of this is given by Gadow & Hui (1999) indicating how the term *plenterdurchforstung* is used to describe different thinning types. Brandl (1992) uses the term to describe thinning from above, so giving growing potential to previously suppressed trees of often superior quality. Shutz (1989), however, describes the term's use by Swiss foresters to describe a removal of intermediate trees to move the stand toward a single tree selection system (*plenterwald*) structure.

Thinning is normally described within the context of intervention *type*, intervention *intensity* and intervention *cycle.*

3.2.1.2 Crown Classes

In order to define thinning type it is necessary to describe trees in a stand by their relative positions within the canopy. Differentiation of a cohort through inter-tree competition produces a range of crown classes which will be treated differently by different thinning types (Schutz, 2002b). Stand prescriptions can be implemented in a subjective manner through qualitative classification of the trees within it (Gadow & Hui, 1999; Smith *et al.*, 1997).

There are four commonly recognized and defined crown classes which are presented below with their synonyms:

Dominant

Co-dominant

Intermediate; sub-dominant

Overtopped; suppressed

(Smith *et al.*, 1997; Nyland, 1996; Oliver & Larson, 1996; Hart, 1994).

Some extension of this scale can be made through subdivision of classes. Gadow and Hui (1999) present an example by Schober (1991) where five divisions are made: dominant; co-dominant; weakly co-dominant; suppressed; completely suppressed. Hart (1994) also defines more classes, listing seven: dominant; co-dominant; sub-dominant; suppressed; wolf trees; whips; dead and dying.

Finer classification can be further made by dividing stand vertical structure into strata of discrete horizontal layers such as those found in double cohort stands, or by comparing trees of similar age and species in even more complex stands (Smith *et al.*, 1997; Nyland, 1996; Oliver & Larson, 1996). Crown classes can then be used to describe the development of trees within the separately occurring strata. Nyland (1999) notes that terminology may also have to vary with the silvilcultural characteristics of different species encountered. An example is given of an overtopped light-demanding tree with no potential to recover which would be classed as *suppressed* and would be equal in size and crown position to a shade-bearing tree classed as *oppressed* which could be released.

In general however, live crown ratio, leaf volume, tree vigour, diameter and diameter increment all increase in relation to dominance of crown class (Nyland, 2003).

3.2.1.3 Thinning Types

The classification of thinning type is based on how trees are selected for thinning and their canopy positions. Rollinson (1999) and Hart (1994) both used a pre-classification of whether the thinning is *systematic* or *selective* with further sub-classification of selective thinning into *low*, *intermediate* and *crown* thinning.

Systematic thinning, also known as *geometric* or *mechanical* thinning, is the removal of rows, strips, chevrons or a preset pattern of trees (e.g. every third tree) and is comprehensively covered by Hamilton (1980; 1976). This intervention type results in a neutral thinning where no crown class in particular is targeted. The benefits of this thinning type are ease of operation and likely reduction in unit cost due to increased speed of working and reduction of the need for skilled labour input (Rollinson, 1999; Nyland, 1996; Dhubháin *et al.*, 1989). Drawbacks of systematic interventions include reduced cumulative volume production, lower residual stem quality and poorer stand stability and resilience. (Rollinson, 1999; Zachara, 1992; Hamilton, 1980, 1976; Grynkiewicz, 1972). Due to its relative strengths and weaknesses, systematic thinning can be a valid approach to low input first thinnings in suitable areas with the assumption of further thinnings being selective (Smith *et al.*, 1997; Nyland, 1996; Boudru & Rondeux, 1977).

Selective thinning can be seen as a continuum of approaches running between the extremes of *low* thinning and *crown* thinning.

Low thinning, also known as *thinning from below*, *ordinary thinning* and *the German method*, mimics and speeds-up natural competition processes by targeting overtopped trees, and depending on intensity, some or all intermediate and co-dominants (Rollinson, 1999; Smith *et al.*, 1997; Nyland, 1996; Hart, 1994). Low thinning requires a comparatively lower level of skill to select or mark trees and control intensity, making it a more suitable method for less costly feller-select or squad marking as opposed to forester marking, the system of *thinning grade* often being used to facilitate this (Gadow & Hui, 1999; Smith *et al.*, 1997; Nyland, 1996). Low thinning does however produce a higher percentage of small dimension produce making it financially less attractive, especially in younger stands (Smith *et al.*, 1997; Nyland, 1996). Low thinnings have the least effect of all thinning types on the stand canopy for a given intensity. This is due to the targeted trees from the lower canopy leaving little or no canopy gap when removed. Consequently, low thinnings must either be heavy or frequent if the stand is not to become under-thinned (Smith *et al.*, 1997; Nyland, 1996).

Crown thinning, also known as *thinning from above*, *high thinning*, *thinning in the dominant* and *the French method*, removes trees from the upper and middle canopy and so creates more canopy disturbance for a given intensity. Crown thinning is used to favour the development of dominant and co-dominant trees that are usually selected for their potential and vigour as crop trees. Thinning mainly targets competing co-dominants but will also include dominants and intermediates which interfere with the development of selected trees (Rollinson, 1999; Smith *et al.*, 1997; Nyland, 1996; Hart, 1994). In the most extreme theoretical crown thinning, no intermediate or smaller trees are cut as they do not compete with selected crop trees and as such can be ignored. In reality however, smaller trees may or may not be taken depending on management objectives, their merchantability and profitability now and their ability to take on increment and hence volume and value in the future (Smith *et al.*, 1997; Nyland, 1996). Crown thinning aims to concentrate increment on selected trees so increasing their growth through maintaining crown growing space (Rollinson, 1999; Smith *et al.*, 1997; Nyland, 1996; Hart, 1994) in the same principle as *free growth* (Lemaire, 2004; Freise & Spiecker, 1999; Kerr 1996). Space not taken by crop trees is filled with subordinates so maintaining overall stand volume production (Smith *et al.*, 1997; Nyland, 1996).

Crown thinning benefits by producing larger diameter material than low thinning and so tends to produce greater returns, an attribute which can make early thinnings less economically marginal (Rollinson, 1999; Smith *et al.*, 1997; Nyland, 1996). Crown thinning does not lend itself to the use of thinning grades as the decision of which trees should be removed revolves around competition issues rather than canopy position. Regulation of crown thinning must be through a stand index such as G and as such, marking requires greater skill (Smith *et al.*, 1997; Nyland, 1996).

Smith *et al.* (1997) and Nyland (1996) also present other thinning types that do not use the pre-classification of selective / systematic thinning.

Selection thinning, also known as the *Borggreve method* or *removal of dominants* (Smith *et al.*, 1997; Nyland, 1996) is the removal of the most dominant trees within the stand and can take slightly different forms depending on stand objectives, structure and the number of times the intervention type is repeated.

Smith *et al.* (1997) suggest two common scenarios which would dictate the use of selection thinning. The first example is where poor quality dominants are removed to favour higher quality trees of potential in lower (although as high as possible) crown classes. This can be seen as a progression of crown thinning where a poor dominant would be thinned to favour a selected co-dominant. The second example would be to carry out selection thinnings to the point where further felling would produce canopy gaps un-fillable by the lower canopy trees, after which attention would change to low thinning or a method of regeneration. This approach could be used to maximise medium size tree production if that were a priority.

A third approach is also suggested by Smith *et al.* (1997) where selection thinning is combined with low thinning in overstocked unmanaged stands where a crop of co-dominants can be released whilst also removing poorer lower crown-class trees.

The greatest criticism and concern of selection thinning is its similarity to the silviculturally and genetically vilified practice of "creaming", "economic selection cutting" or "high grading". Creaming is a practice associated with exploitation logging where the most valuable trees are removed for the highest financial surplus per unit volume. The trees removed are often the biggest but must also be of high quality to be valuable and maintain a high ratio. As creaming is a tool of exploitative logging, no consideration is given to stand regeneration, future stand quality or sustainability. A common method of creaming is that of diameter-limit cutting where all commercial trees over the diameter-limit threshold are taken irrespective of stand condition after felling (Kenefic *et al.*, 2005; Ward *et al.*, 2005; Bravo & Montero, 2003; O'Hara, 2002; Buongiorno *et al.*, 2000).

Diameter-limit cutting should not be confused with target diameter felling where trees are grown up to an identified production goal diameter and stands are managed with the concept of growing space or the crown "footprint" area required for a tree at target diameter (Nagel, 2004; Abetz & Kladtke, 2002; Sterba & Zingg, 2001). Target diameter harvesting is generally associated with frame tree management with equilibrium stand volume maintained through BDq harvesting.

The species composition and structure of a stand heavily influences its ability to sustain successive selection thinnings. Stands of shade tolerant species with strong epinastic control such as spruce and fir are well suited in this respect and target diameter harvesting has been shown to be silviculturally sustainable in Norway spruce (*Picea abies*) (Sterba & Zingg, 2001). Stands of weakly epinastic and/or positively phototropic species are unsuited to selection thinning as lower crown class trees will have poor form from loss of leader or from growing toward the light of canopy gaps created (Smith *et al.*, 1997; Oliver & Larson, 1996).

The use of selective thinning in stands will decrease overall genetic diversity but may well increase the percentage of heterozygous individuals (Dounavi *et al.*, 2002). The repeated removal of the largest and most vigorous trees within a stand (by whatever thinning type) raises concerns, however, over the degradation of genetic quality due to decrease in population density, so causing inbreeding. The removal of the most economically desirable trees might also directly select against the genes responsible for their desirable phenotypic characteristics. The reduction of this genotypic frequency may lead to a drop in stand growth potential (Finkeldey & Ziehe, 2004; Finkeldey, 2002; Ziehe & Hattemer, 2002).

3.2.1.4 Free Thinning

Free thinning (Smith *et al.*, 1997; Nyland, 1996) is described as a combination of all thinning types used within a stand to favour only selected trees regardless of their crown position and so has a greater application in fully irregular stands rather than uniform ones. The method therefore works well with frame trees management.

3.2.1.5 Frame Trees

Frame trees have a number of synonyms including Z-Baum, target trees (Abetz & Kladtke, 2002), future crop trees (Abetz, 1992), final crop trees (Smith *et al.*, 1997) and elite trees (Gadow & Hui, 1999).

Frame tree management concerns optimizing the growth of large diameter quality stemwood through managing the stand to service and develop only the final crop trees (Kladtke, 1993). Stocking and yield control is based on the growing space (crown footprint area) of the frame trees at target diameter and known growth norms for site and species (Kladtke & Abetz, 2001; Abetz & Kladtke, 2002). Stocking density can be controlled by comparing the number of marked frame trees against the density calculated as optimal for the target diameter. A crop-tree density index (CDI) is produced where 1.0 is perfectly stocked, >1.0 is over stocked and <1.0 is understocked (Abetz & Kladtke, 2002; Abetz & Ohnemus, 1994). Competition and thinning requirements can be calculated by comparing frame tree diameter growth to an expected norm.

3.2.1.6 Indices for Thinning Type

Whilst describing the approach of an intervention in terms of the crown classes targeted can provide some insight, the description is somewhat subjective and as such not easily compared with other interventions. Thinning indices are an objective method of describing thinning type used and are calculated using stand parameters and their changes due to the intervention.

The SG ratio (Gadow & Hui, 1999) provides a ratio of the relative number of stems removed to the relative basal area removed. The ratio provides a value of 1 for a neutral or indifferent thinning whereas a low thinning will remove more stems for a given basal area reduction and so produce values of more >1 and crown thinning will produce values of <1 as relatively fewer stems will be cut for a given basal area reduction.

$$SG = \frac{(N_{thin} / N_{total})}{(G_{thin} / G_{total})}$$

N_{thin}, N_{total} = removed and total number of stems

G_{thin}, G_{total} = removed and total basal area

The S_1 separation parameter (Gadow & Hui, 1999) uses known stand diameter values to express thinning type. The difference between the mean diameters of felled and retained trees is expressed as a fraction of pre-thinning diameter standard deviation.

$$S_1 = \frac{\bar{d}_{post} - \bar{d}_{thin}}{\sigma_{\bar{d}pre}}$$

Where:

S_1 = Separation parameter

$\bar{d}_{post}$ = Mean diameter remaining trees

$\bar{d}_{thin}$ = Mean diameter thinned trees

$\sigma_{\bar{d}pre}$ = Standard deviation of diameters before thinning

The value of S_1 can be classified with an association function. The function indicates the strength of association of the S_1 value with high or low thinning. Figure 3.1 is a graphical representation of this association reproduced from Gadow & Hui (1999) which shows neutral thinning to have an S_1 value of 0.5 and S_1 values being fully associated with crown and low thinning at 0.2 and 0.8 respectively.

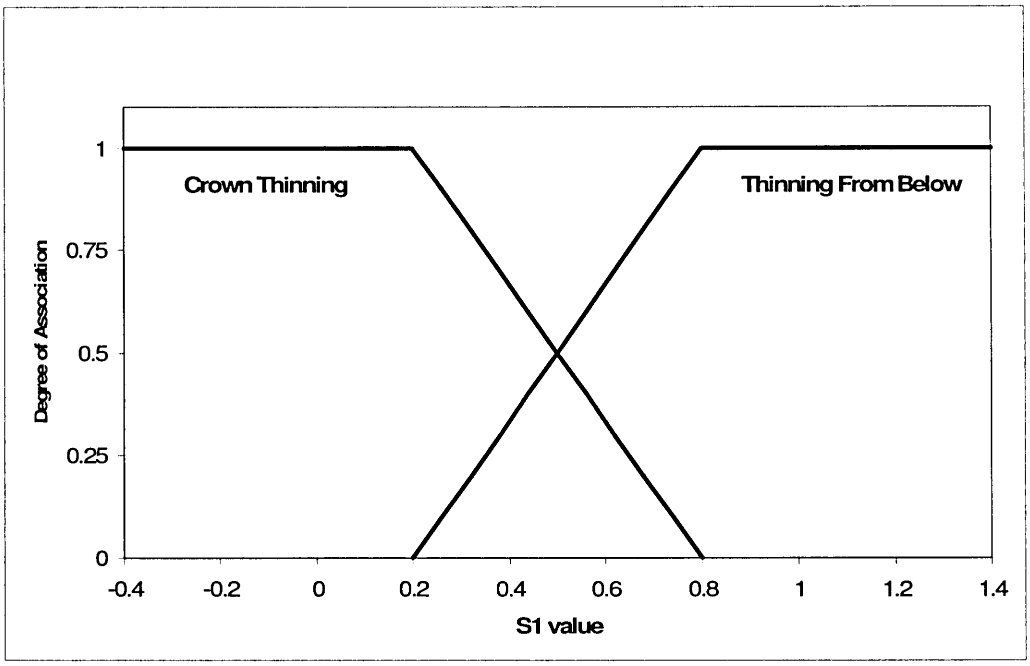


Figure 3.1 Association function for the categories high thinning and low thinning (after, Gadow & Hui, 1999)

3.2.1.7 Thinning Intensity

Where thinning type describes the manner in which a stand is thinned, thinning intensity describes the rate at which volume is removed from the stand.

Stand cumulative (commercial) volume increment remains similar over a wide range of thinning intensities. Where interventions are too weak stands become overstocked and volume production is lost through inter-tree competition, higher rates of mortality and increase in the proportion of un-commercial sizes. Where interventions are too strong the remaining trees are unable to utilise all growing space and so production is lost. The maximum intensity of thinning achievable before this drop in production is known as the marginal thinning intensity (MTI) (Rollinson, 1999; Smith *et al.*, 1997; Nyland, 1996; Hart, 1994).

Hart (1994) noted that the thinning intensity of maximum profit is generally higher than that of MTI although the difference between them is generally small enough for them to be used synonymously. Price (1989, 1988, 1987, 1985) noted however that discount rate will dictate the calculation of profit and so the difference between maximum profit intensity and that of MTI.

In an even-aged crop MTI is generally around 70% of mean annual increment (MAI) (Rollinson, 1999; Hart, 1994).

Thinning intensity can be regulated through several stand parameters.

Stocking density can be used and although it takes no account of tree sizes or growing space it can provide a useful measure particularly in regular stands which have been managed to a schedule (Smith *et al.*, 1997). A derivative of simple stocking density is given by Gadow & Hui (1999) in the form of relative stocking (RS). RS is useful for producing stand prescriptions for areas of differing site indices and can be used both to determine the need for thinning, such as when a given dominant height is reached for a given stocking density, and as a regulator of thinning intensity where a reduction in RS for a given dominant height will dictate residual stems per hectare. Relative Stocking Index (RSI) (Gadow & Hui, 1999) presents RS as a proportion of dominant stand height.

$$RSI = \frac{\sqrt{10000/N}}{H}$$

Where:

RSI = relative spacing index

N = stems per ha

H = dominant stand height (m)

Stand *basal area* (G) is the most commonly used parameter in regulating intensity. G benefits from being composed of both stand density and diameter distribution and is easily associated with tree volume (Smith *et al.*, 1997).

3.2.1.8 Thinning Grade

Thinning grade is a method of intensity regulation usually associated with low thinning regimes (Smith *et al.*, 1997; Nyland, 1996) but also applicable to other thinning types (Gadow & Hui, 1999). Grades use crown classes to prescribe cutting limits, dictating no cutting, partial or full cutting within a crown class. Grade severity is intensified by sequentially increasing the number and proportion of crown classes cut. Smith *et al.* (1997) and Nyland (1996) classify 4 grades for low thinning; A, B, C & D, with A being the lightest. Gadow & Hui (1999) present thinning grades A to E, after Schober (1991), which cover a variety of thinning types and intensities.

3.2.1.9 Intervention Cycle

The intervention cycle (thinning cycle) is the return period or frequency of thinning. The intervention cycle is a balance between the net profitability of a given intervention and maintaining the desired stand parameters and development (Price, 1989). The net profitability of harvesting generally increases with the volume cut per area, leading to the temptation to increase the return period and the intensity of each intervention, particularly if markets are poor. The downside of this approach is to open the stand to wind excessively and potentially to reduce cumulative volume (Rollinson, 1999; Smith *et al.*, 1997; Nyland, 1996; Hart, 1994).

3.2.2 Diversity Indices

Diversity indices have been extensively used and commented upon for assessing biodiversity through the structure of communities (Magurran, 2004).

Measures of diversity can be classified as either parametric or non-parametric. Parametric measures include the log series α, log normal λ and Q statistic. Non-parametric measures include the Shannon index, Heip's index of evenness, SHE analysis, the Brillouin index, Simpson's index, McIntosh's measure of diversity, the Berger-Parker index, Nee, Harvey and Cotgreaves's evenness measure, Carmargo's evenness index and Smith and Wilson's evenness index.

Diversity can be considered to consist of two parts; *richness* and *evenness*. Richness describes the number of classes observed (e.g. species, diameter classes) and evenness is the comparison of numbers within each class. Indices describing diversity vary in how each component is used and emphasized (Magurran, 2004, Franc & Mai, 1998) and hence why distributions and changes within them are ranked and presented inconsistently between indices (Standovár, 1996).

Whilst diversity indices were developed to describe species diversity, their form can also be used to describe stand structure through a measure of parameter range and distribution e.g. McCarthy & Weetman (2006) and Standovár (1996).

In the context of forest management, measurement of diversity can be seen as another tool for monitoring stand changes. Pommerening (2002) states that species diversity and ecological stability are positively linked to increased heterogeneity of stand spatial structure. The description of stand species diversity as well as structural complexity can be seen as a means to monitor and make inferences about management decisions.

One of the most widely used diversity indices is the Shannon index (H') which can be expressed as:

$$H' = -\sum_{i=1}^{s} p_i \ln p_i$$

Where:
S = number of classes (e.g. dbh class)
p_i = proportion of individuals within the class
(Magurran, 2004; Standovár, 1996).

Though not without its significant critics, the index has a high popularity due to its simplicity of use and the fact that it features heavily in past and present monitoring, so enabling some direct comparisons to be made (Magurran, 2004).

The application of the index assumes the random sampling of individuals from an infinitely large community and that all species are represented by the sample (Magurran, 2004). When calculated from empirical data, the index value is generally in the range of 1.5 to 3.5, with values of 4 and above, indicating high diversity levels, occurring occasionally (Magurran, 2004).

The Shannon index gives a higher value with increasing range (increase of numbers of species or classes) and the highest values when the classes are proportionally equal and hence when the variance of the distribution function is zero (Pommerening, 2002; Franc & Mai, 1998). The index has a poor sensitivity to rare species due to the expression not differentiating well between classes with very low frequencies and absent classes (Neumann & Starlinger, 2001; Franc & Mai, 1998; Standovár, 1996). Another of the Shannon index's best known failings is that it produces very constrained values, so making it difficult to interpret (Magurran, 2004).

Neumann & Starlinger (2001) stated however that the Shannon is preferable to the Simpson index as it is more sensitive in detecting changes in richness. Simpson's index (D) can be expressed as:

$$D = \frac{\sum_{i-1}^{s} n_i(n_i - 1)}{N(N-1)}$$

Where:

S = number of classes

n_i = number of individuals in the *i*th class

N = total number of individuals in the community

(Magurran, 2004; Standovár, 1996).

Values of D decrease with increasing diversity and therefore the index is generally expressed as 1-D or 1/D. Magurran (2004) also lists the transformation of –ln(D) as a solution to variance problems of 1/D.

The index is heavily weighted towards evenness and less sensitive with regard to richness (Magurran, 2004).

Neumann & Starlinger (2001) found high correlation between the Simpson and Shannon indices when describing forest structure.

3.2.3 Stability

Catastrophic wind damage to trees can occur as *windthrow* (tree overturning) or *windsnap* (stem breakage). Snow and ice damage tends to cause crown damage and stem breakage.

Wind loading of a tree will cause the tree to sway. Wind acting as a force at the centre of pressure will create the primary turning moment equal to the force multiplied by the height of the centre of pressure above the ground. A secondary turning moment is produced by the weight of the tree crown and stem being displaced. The force is equal to the weight of the crown multiplied by the horizontal distance between the fulcrum and the centre of gravity. Windthrow and windsnap are the effect of the turning moment exceeding the mechanical strength properties of the tree roots and stem respectively (Quine *et al.*, 1995). Tree sway will vary between trees as the oscillation in response to wind gusting is a function of tree height, canopy mass, dbh and taper. Increasing tree mass, effective drag area (crown size) and height of the centre of pressure (increasing with maturity) increase the turning moment of a tree, however, increased taper will also increase stiffness and damping which counteract the turning moment. Trees within stands are supported to some extent by the trees around them, their oscillations being buffered by others (Cameron, 2002; Quine *et al.*, 1995). Thinning will therefore initially destabilise a stand as inter-tree support is lessened and individual tree stability has not had time to respond through adaptive growth. The increase in sway experienced by the trees will trigger adaptive growth, stabilising the tree. Adaptive growth occurs in the roots, tree form and wood structure and includes a decrease in height increment in favour of diameter increment and root growth (MacDonald & Hubert, 2002; Cameron, 2002; Mason, 2002).

The height : diameter ratio (h/d) or stem taper is a widespread indicator of adaptive growth and hence stability. The ratio is indicative of the degree of competition in a stand and of tree vitality due to height increment being preferentially gained over diameter increment and so h/d will decrease with growing space. The ratio also indicates the degree of mechanical resistance of the stem form to bending and hence implies the resilience of the trees and stand to wind. (Abetz & Chroust, 2004; Abetz & Kladtke, 2002; Cameron, 2002; Mason, 2002; Bergqvist, 1999; Abetz, 1982).

Many studies have shown a decrease in h/d in response to a reduction in stocking, for example Rollinson (1988) in respacing trials of young Sitka spruce, Slodicak & Novak (2006) in heavy early thinnings of Norway spruce (*Picea abies* (L.) Karst.) and Bachofen & Zingg (2001), Bruchert *et al.* (2000) and Bergqvist (1999) in thinnings of Norway spruce.

Values of h/d that constitute stability for commonly grown European conifers have been variously proposed and appear to be in the region of 80 (height and diameter in same units). Mason (2002) provides several references for the use of 80 as do Bachofen & Zingg (2001) who noted that trees of around or above 35 cm diameter displayed a h/d ratio of 80 or below. A diameter of 35cm was also found to correspond to the diameter above which no snow damage occurred, corresponding well with the findings of Petty and Worrell (1981) that trees with a h/d ratio of 75 or below were at very little risk from snow damage. Slodicak & Novak (2006) reviewed a wide range of sources and subdivided the scale of h/d values to describe stability as: excellent <82, good 83–92, satisfactory 93–101 and unsatisfactory >102.

The crown : height ratio (c/h) is also seen as another indicator of stability as it is positively linked with tree dominance and so reduced h/d. An increase in live crown will allow greater photosynthate production and hence greater growth. As height increment is gained preferentially over diameter increment, greater resources will allow higher diameter growth relative to height growth, so helping to lower h/d and increase resistance to turning through stiffness and oscillation damping. Increased root growth will also be possible which will also resist overturning (Cameron, 2002; Quine *et al.*, 1995). The c/h ratio decreases with increasing stocking density due to increased inter-tree competition (Cameron, 2002; Bachofen & Zingg, 2001; Rollinson, 1988). Increasing the c/h ratio also lowers the centre of gravity of a tree and hence the secondary turning moment produced by the tree's own weight when it is bent over and its centre of gravity moves away from its base; up to 30% of total turning moment (Cameron, 2002; Quine *et al.*, 1995).

3.3 PLOT MARKING

3.3.1 Marking Methods

Part of the experimental design for Trallwm (see 1.1.2 & 2.3.1.1) was a reduction in thinning plot basal area by 20% as opposed to a reduction of basal area to a target level such as below 30m^2/ha in order to provide sufficient light for natural regeneration (Hale, 2004; Mason *et al.*, 2004; Page *et al.*, 2001). This approach fulfilled two main purposes. Firstly, the exposed, upland nature of the study plots made stand stability a concern. Thinning at a relatively low intensity but with the intention of a short thinning cycle was seen as a lower risk method of reducing basal area to sub-30 m^2/ha levels than a single high intensity intervention. Secondly, a reduction of 20% of basal area in all treatments allows comparison of how productivity and outputs vary at an equal intervention intensity rather than altering both thinning intensity and type in the comparison.

3.3.1.1 Low Thinning, Plots 3 & 5

Plots three and five were marked to undergo a thinning from below, representing conventional British thinning practice. The intervention was to be the last thinning before clearfelling at rotation end.

Thinning type and intensity were typical of those used in previous stand interventions.

The marking of both plots was carried out by the forest owner, George Johnson, after the plots had been demarcated and trees numbered; an even marking of 20% of basal area. Suppressed, sub-dominant, dead and dying trees as well as trees of poor form or suffering from damage were marked.

Trees to be removed were marked with an orange painted band at around dbh.

3.3.1.2 Frame Tree, Plots 1 & 4

Plots one and four were marked to be a compromise between the classical frame tree system and the use of shelter building trees purely as structural retentions within the stand.

In the classical use of frame trees a number of trees of superior form and growth are identified at a relatively early stage in stand development and thinning is used to tend them to create a final crop of high quality value bearers. The number of frame trees selected per hectare will vary with the species present and the target diameter desired.

As transformation was starting at a late stage in stand development at Trallwm, frame trees in the classical sense could not be selected, although a quality component was still desired. Shelter building trees were therefore selected with thought not just to the stability of the tree, although this was paramount, but also to selecting quality stems if possible.

A target of between 60 and 80 shelter building trees per hectare was planned, corresponding to spacing of 11 m to 13 m between trees. Shelter building trees were distributed as evenly as possible through the plot.

When marking within the stand, thinning cells were used to identify trees for removal. Cells were identified as "areas which are sufficiently small for judging the effect of a particular removal on the remaining survivors and large enough so that at least one tree is a potential candidate for removal" (Gadow & Hui, 1999) and generally defined by the approximate mid-points between frame trees. The thinning type used was a crown thinning, only removing direct competitors to shelter building trees so as to increase growing space and increase crown development and tree stability.

Shelter building trees were marked with a yellow tape at around dbh. Trees to be removed were marked with a painted orange band at around dbh.

Marking was carried out as a group including the author, Dr Arne Pommerening (Bangor University) and Carl Foster (Forest Research).

3.3.1.3 Group, Plots 2 & 6

The aim of the interventions in plots 2 and 6 was to establish groups within the stand as regeneration loci and prepare the matrix for group expansion in subsequent interventions.

A target basal area reduction of 20% through felling of groups and matrix was set during marking. Marking in both plots was carried out by the author with assistance from Carl Foster (Forest Research).

Group sizes of 0.1ha or smaller were considered for use. Owing to the high risk of windthrow in the stands, both plots having a DAMS score of 20 (Gardiner *et al.*, 2004), the size of groups and their subsequent effect on stand stability was of great concern.

The forces exerted by wind on the trees bordering the leeward side of gaps decreases rapidly as the gap diameter is reduced from around two tree lengths (Stacey *et* *al.*, 1994). Smaller groups will therefore have less force exerted on their leeward side with a reduced chance of wind-damage.

The size of circular felling used, 0.05 ha or 12.6 m radius, was felt by the author and consulting members of Forest Research to offer the best compromise between loss of stand windfirmness and maintenance of group function. The size of group also matched the scale of the plot well, allowing desired spatial placement within the confines of the plot area.

Mean tree height was 23.8 m in plot 2 and 24.5 m in plot 6 so gap diameter was approximately equal to a tree length in both plots.

Three groups were marked in each plot, one group entirely within the inner 0.5 ha and the other two centred on inner plot corner posts. This distribution meant that one and a half groups (1 group + 0.25 group + 0.25 group) were in the inner plot and will be subject to long-term monitoring and one and a half groups (0.75 group + 0.75 group) in the outer plot. Group layout is depicted in Figures 3.2a and 3.3a.

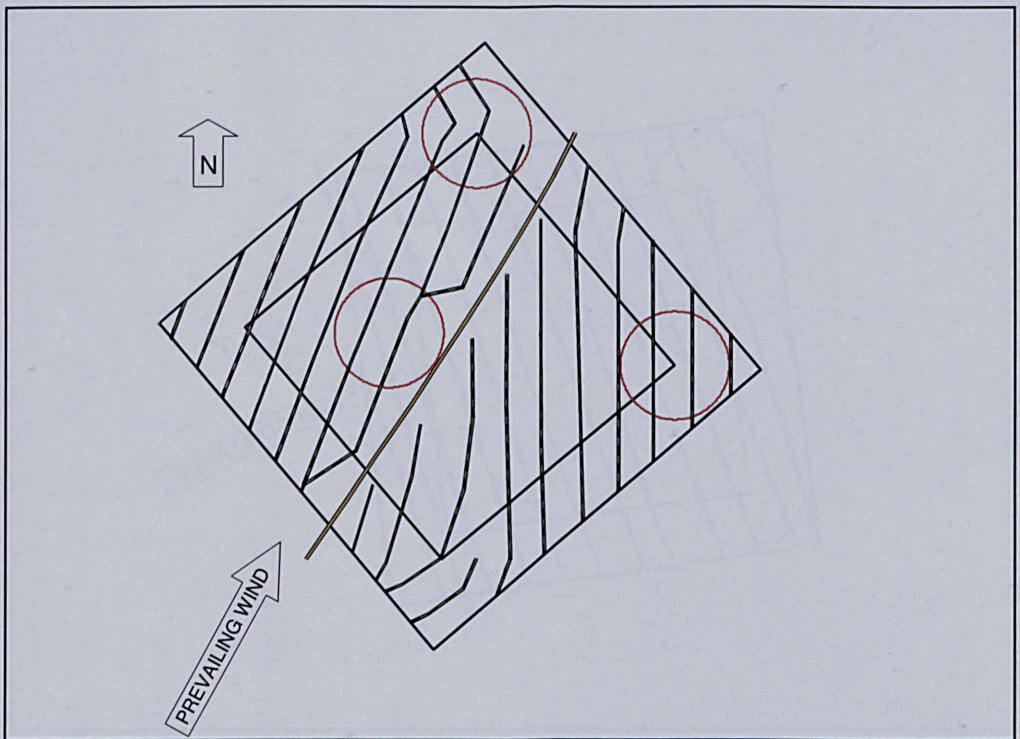
The groups centred on corner posts were positioned in the northern and eastern half of the plots so that the groups would expand in a south-westerly direction through the plot into the prevailing wind.

The third group was positioned as equidistantly as possible from the other two groups at a distance from the inner plot boundary that would allow at least two further interventions to enlarge the group whilst remaining within the inner plot.

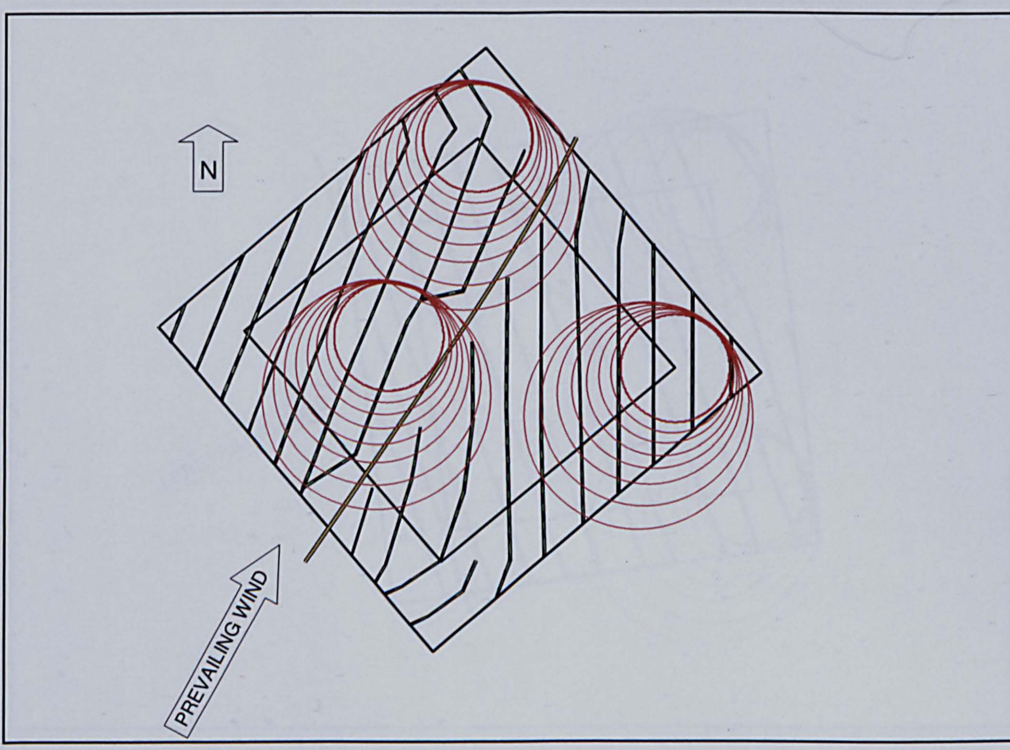
Whilst centring two of the groups on fixed points within the plot precluded any choice in group position, a greater choice could be exercised with the positioning of the third group.

As there was no advanced regeneration within the plots, positioning of the groups was not influenced by the need to locate over regeneration cones. The presence and layout of the extraction rack network and occurrence of internal unstable edges are the only two factors of those indicated by Yorke (2001) which would influence group positioning.

The plots have a well developed extraction rack network consisting of every fifth row of trees removed for access, so producing racks at approximately 9 m spacing. A group cannot therefore avoid having at least two racks passing through it. Rack width was approximately 3.3 m which allowed free passage to the harvester's width of 2.62 m, although pinch-points would occasionally occur.



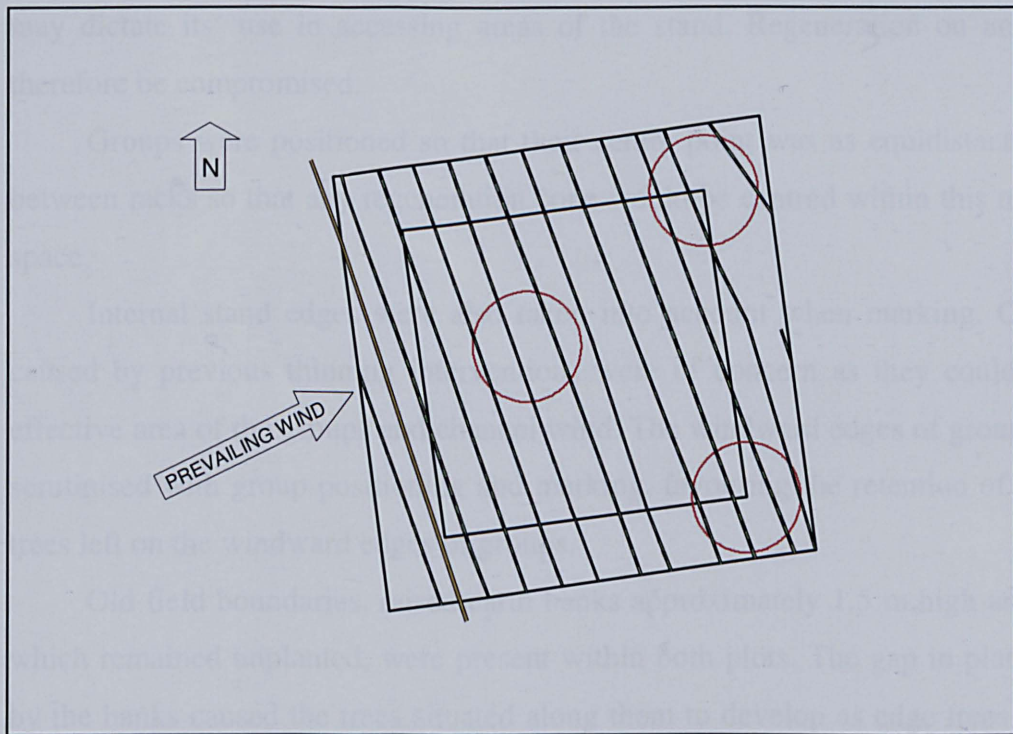
a)



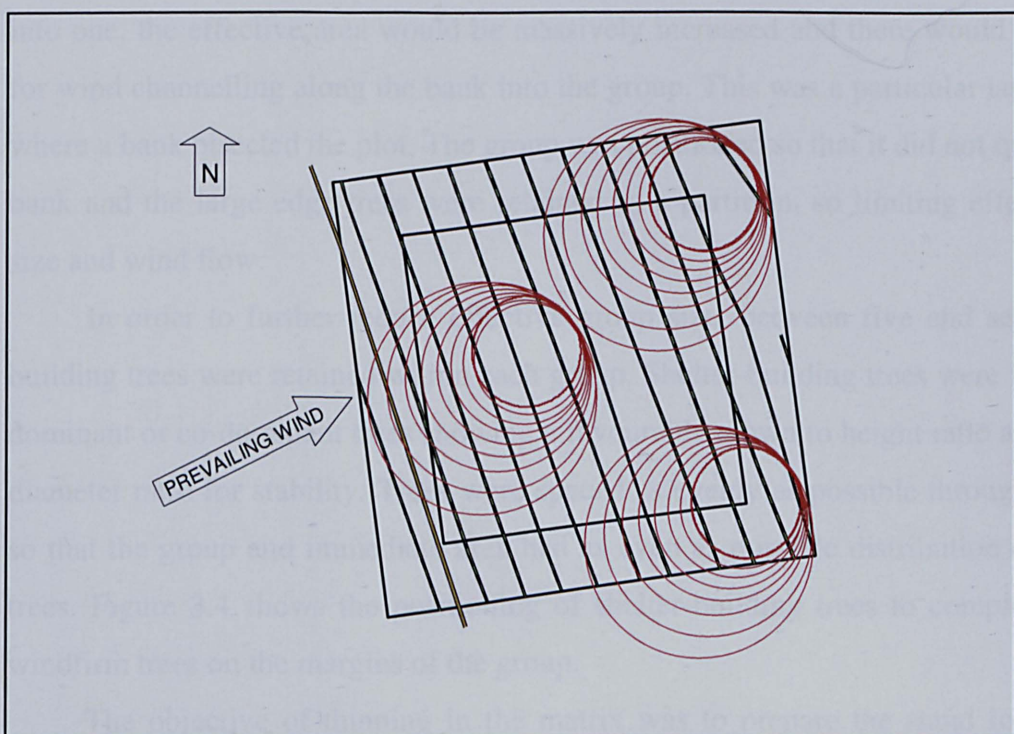
b)

Figure 3.2 Diagramatic representation of groups within plot 2

(a) initial group layout within plot 2 (b) envisaged future group expansion. Dashed lines represent racks, solid brown lines running outside plot boundaries represent derelict field boundary earth banks. Not to scale.



a)



b)

Figure 3.3 Diagramatic representation of groups within plot 6

(a) initial group layout within plot 6 (b) envisaged future group expansion. Dashed lines represent racks, solid brown lines running outside plot boundaries represent derelict field boundary earth banks. Not to scale.

Whilst double-drifting, vehicular use of every-other rack, is preferred, there can be no guarantee that a rack will not be used by a vehicle as spacing and position of racks may dictate its' use in accessing areas of the stand. Regeneration on any rack may therefore be compromised.

Groups were positioned so that their centre point was as equidistant as possible between racks so that any regeneration cone would be centred within this non-travelled space.

Internal stand edges were also taken into account when marking. Canopy gaps caused by previous thinning interventions were of concern as they could extend the effective area of the groups and channel wind. The windward edges of groups were also scrutinised with group positioning and marking, favouring the retention of more stable trees left on the windward edges of groups.

Old field boundaries, raised earth banks approximately 1.5 m high and 3 m wide which remained unplanted, were present within both plots. The gap in planting caused by the banks caused the trees situated along them to develop as edge trees bordering a long thin open internal space. These linear features were stable but if a group opened into one, the effective area would be massively increased and there would be potential for wind channelling along the bank into the group. This was a particular issue in plot 2 where a bank bisected the plot. The group was positioned so that it did not quite abut the bank and the large edge trees were retained as a partition, so limiting effective group size and wind flow.

In order to further reduce effective group size, between five and seven shelter-building trees were retained within each group. Shelter-building trees were identified as dominant or co-dominant trees showing a favourable crown to height ratio and height to diameter ratio for stability. Trees were spaced as evenly as possible throughout groups so that the group and immediate area had as even as possible distribution of windfirm trees. Figure 3.4 shows the positioning of shelter-building trees to complement other windfirm trees on the margins of the group.

The objective of thinning in the matrix was to prepare the stand for the future enlargement of the groups. The target reduction of 20% of standing basal area within the plots was approximately half met by the cutting of the groups i.e. the basal area removed from the groups was equal to 10% of the plot total. The remaining 10% was marked in the matrix.

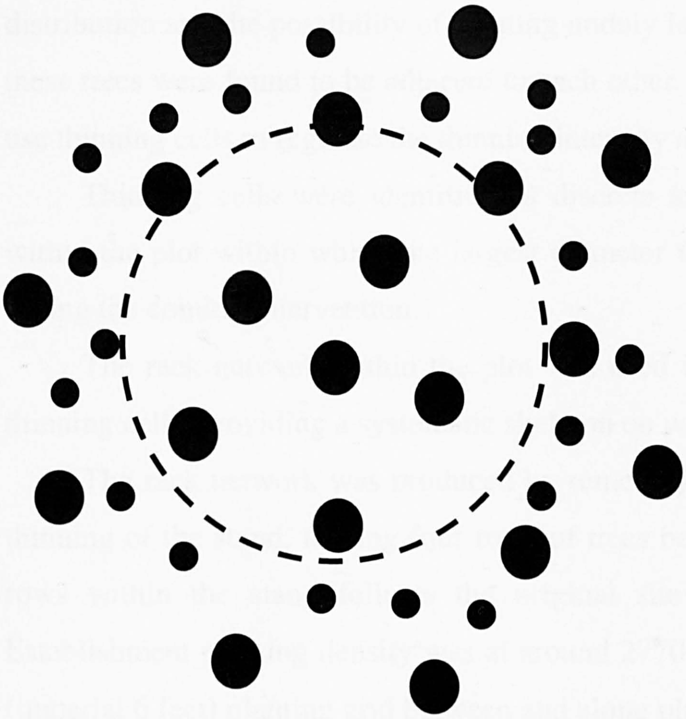


Figure 3.4 Diagramatic representation of the positioning of shelter-building trees within groups

Large filled circles represent stable dominant trees, smaller filled circles represent less stable trees. Stable trees within the group boundary (dotted line) are shelter-building trees. Stable trees outside the group boundary are likely to become shelter-building trees as the group expands with further interventions. Diagram not to scale and not a record of positions in an actual group.

Marking was carried out in arcs leading from the groups into the direction of the prevailing wind and thinning was thus concentrated in these areas with other parts of the matrix receiving very little or no basal areas reduction. Figures 3.2b and 3.3b show the envisaged future expansion of the groups, the areas of matrix targeted by the thinning.

Trees possessing greater stability and hence likely to be retained as shelter building trees were identified and thinned around to develop further stability and crown growth for cone production.

Trees showing unstable growth were marked for removal so as to increase the overall stability of the stand.

3.3.1.4 Creaming, Plot 8

The aim of the thinning prescription in Plot 8 was to harvest as many of the largest diameter trees as possible in a 'creaming' type intervention. If only the very largest trees were to be removed however, there was concern over the spatial distribution and the possibility of creating unduly large gaps within the stand if some of these trees were found to be adjacent to each other. The approach taken in plot 8 was to use thinning cells to regulate the thinning intensity and distribution within the plot.

Thinning cells were identified as discrete and approximately equal-sized areas within the plot within which the largest diameter tree would be identified for removal during the coming intervention.

The rack network within the plot was used as the basis for the identification of thinning cells, providing a systematic skeleton on which to build cell structure.

The rack network was produced by removing every fifth row of trees in the first thinning of the stand, leaving four rows of trees between racks. The layout of planting rows within the stand follows the original site cultivation of shallow ploughing. Establishment planting density was at around 2770 trees per hectare caused by a 1.8 m (imperial 6 feet) planting grid between and along plough furrows.

The assumption was made that the distance between rack centres was equal and the equivalent to five times the planting spacing i.e. 9.0 m. Therefore if the inter-rack area was broken into segments of equal length as measured parallel with the rack direction, a number of cells of equal area would be created. Figure 3.5 shows an estimation of the thinning cell layout in plot 8.

The use of thinning cells in this manner was seen as easy to replicate in other situations and particularly easy to apply under a 'feller-select' system where no trees are marked and instead selection of stems for thinning is assessed by the operator.

The intervention was planned to reduce the plot basal area by 20% through the removal of the largest diameter trees possible. In order to control the marking intensity through the number of thinning cells a diameter (d_{tc}) was identified.

The diameter used in plot 8 (d_{tc}) is not a threshold value as the target diameter seen in classical frame tree production but a form of estimate of the mean tree diameter to be removed in the coming intervention in each cell. The value of d_{tc} was used to provide the number of cells required (n_{cells}) within the plot by its conversion into a basal area (g_{tc}) and division into the target plot basal area reduction (G_{tr}) as described by the equation:

$$n_{cells} = \frac{G_{tr}}{g_{tc}}$$

The full enumeration of the stand showed that if the largest 64 trees were removed, the smallest of which had a dbh of 37.0 cm, the target basal area reduction would be met exactly. This would not be possible if a thinning cell approach was to be used as tree distribution was unlikely to be so even that each of the 64 largest trees fell neatly into individual cells.

The diameter d_{tc} could be placed between a known minimum and maximum value. The stand mean diameter, 30.9 cm, was used as the minimum value and the maximum could not be more than 37.0 cm.

A value of 33.95 cm, half-way between the minimum and maximum diameters was chosen as the trial value of d_{tc}. The positioning of the mean diameter between the maximum and minimum values acted as a spatial distribution factor allowing for the clumpiness in large diameter tree distribution.

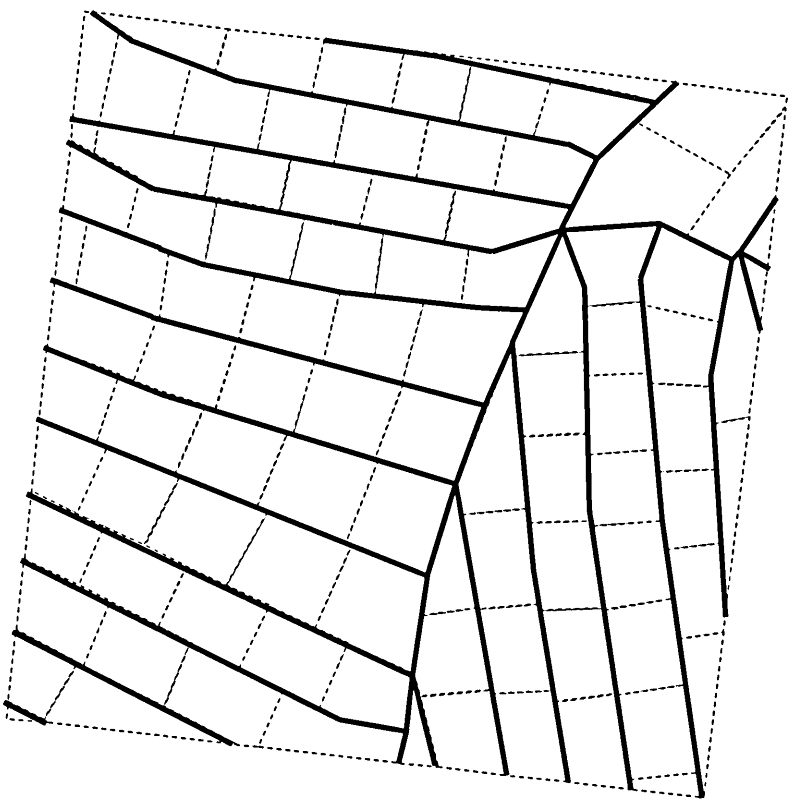


Figure 3.5 Diagramatic representation of thinning cells within plot 8

Racks are represented by heavy black lines. Thinning cells are delineated by dashed lines. Not to scale. Diagram is intended to convey principle of cell selection and is not presented as an accurate record of cell position.

Worked Example:

Plot area (A) = 1 ha

Stocking per hectare (N_{pre}) = 508

Basal area of plot before intervention (G_{pre}) = 39.26 m^2

Target basal area removal (G_{tr}) = 7.85 m^2

Arithmetic mean diameter ($\overline{D}$) = 30.89 cm

Plot d range = 9.5 cm – 48.1 cm

d_{tc} was 33.95 cm

g_{tc} of d_{tc} is 0.0905 m^2.

The number of trees of target diameter required to complete target basal area was 86.7 and therefore 87 thinning cells are required.

Thinning cell length was calculated by dividing plot area by rack spacing (s_{rack}) to find the length of plot inter-rack matrix, the length parallel to the rack network of the areas between racks. Length of thinning cell is calculated by dividing matrix length by the number of cells (n_{cells}). The expression is presented below.

$$l_{cell} = \frac{10000}{s_{rack}} \bigg/ n_{cells}$$

A length of 12.8 m was calculated for l_{cell}.

The cells were measured by pacing the 12.8 m length parallel with the rack. Where cells crossed the plot boundaries the largest tree within the cell was still identified and, if not within the plot was discounted. Where irregularly shaped cells were encountered, often at the junction of racks, they were counted 'in' or 'out' alternately and a tree chosen if it was defined as 'in'. Where the marking of the largest diameter tree in a cell would create an unduly large gap the markers could select the tree of second largest diameter, at their discretion.

The intention was to mark temporarily and re-mark subsequently when the marking intensity for the plot had been assessed and the spatial distribution factor adjusted (similar to checking conventional thinning marking to adjust and monitor).

The marking was found to remove 82 trees and 21.8% of the basal area. This was deemed close enough to the target of 20% and the initial marking was marked permanently to indicate trees for removal during the thinning.

3.3.1.5 Premature Clearfell, Plot 7

The plot would have reached maximum mean annual increment at 44 years old and so the clearfell was premature by 7 years.

As all trees within the plot were to be felled, no trees were marked with a band, only the identification number.

3.3.2 Results of Plot Marking: Intervention Intensity

This section characterises the interventions carried out by presenting the changes in the stand parameters covered in Chapter 2. In addition, it provides plot parameter means for pre and post thinned stands and felled trees which can be used as variables for analysis of machine working in later chapters.

Appendix 2.1 contains details on the marking status of each tree of the eight plots in the "Fell Code" column. Codes represent marking options as follows:

0 = not marked

1 = fell tree in matrix

2 = fell tree in group

3 = tree retained for structure (frame or shelter building tree)

4 = dead or dying tree

3.3.2.1 Stocking Density

Changes in absolute plot stocking density are presented in Appendix 4. Numbers of residual trees within thinned plots vary from 374 in plot 4 to 516 in plot 3. The mean stocking density of the plots was reduced from 548 before felling to 429 with standard deviation changing from 79.7 to 48.4.

The percentage of trees thinned within a plot varied from 16.1% in plot 8 to 28.2% in plot 3, the mean being 22.3% with a standard deviation of 4.3%.

3.3.2.2 Basal Area

Basal area reductions achieved within the plots by the intervention are presented in Table 3.1. Basal area reductions by thinning varied from the target of 20% to a minimum of 18.77% in plot 6 to a maximum of 21.81% in plot 8. Plot 7 achieved a 100% reduction of basal area through clearfelling.

Residual basal area in thinned plots varied from 30.7 m^2/ha in plot 8 to 36.9 m^2/ha in plot 6, the mean being 34.3 m^2/ha with a standard deviation of 2.1 m^2/ha.

Table 3.1 Summary of changes in plot basal area (G)

	Frame tree plot 1	Group plot 2	Low thinning plot 3	Frame tree plot 4	Low thinning plot 5	Group plot 6	Clearfell plot 7	Creaming plot 8
G pre-felling (m^2/ha)	43.2	41.4	45.7	42.2	43.7	45.8	44.0	39.3
G post-felling (m^2/ha)	34.7	33.1	36.3	33.9	34.8	36.9	0.0	30.7
% reduction	19.73	20.07	20.49	19.55	20.30	18.77	100.00	21.81

3.3.2.3 Diameter

Plot diameter ranges for pre and post intervention stands and felled trees are compared in Figure 3.6. The pre and post felling and felled tree values for d_g, the diameter of the tree of quadratic mean cross-sectional area (Husch *et al.*, 2003; Hamilton, 1975), were calculated for all plots and are presented in Table 3.2.

Weibull parameters b and c for post felling 4 cm diameter classes are presented in Table 3.3 with pre-felling values as a comparison. Weibull curves describing diameter distributions for all plots, post-felling, are presented in Figure 3.7 and are overlaid on 4 cm diameter class distributions in Appendix 6. Appendix 7 compares Weibull curves for pre and post felling diameter distributions for each plot and Appendix 8 shows change in 4 cm diameter classes with felling.

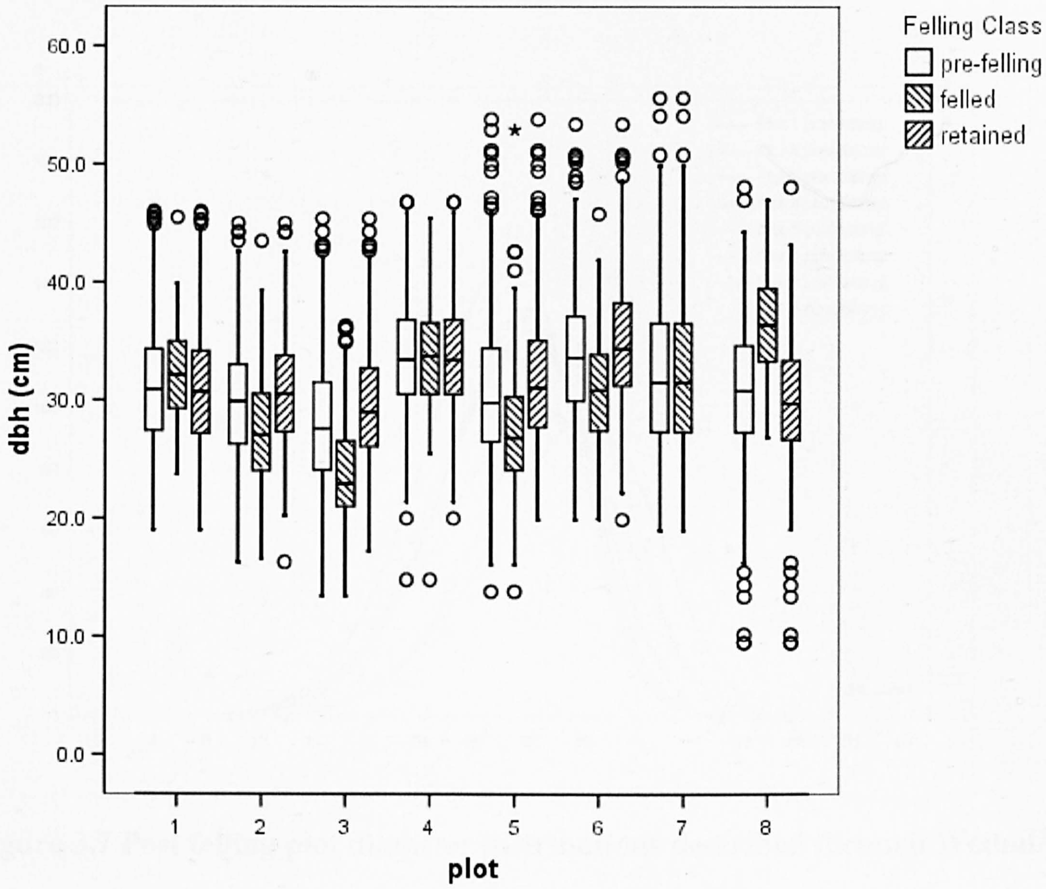


Figure 3.6 Comparison of plot diameter ranges for pre and post intervention and felled trees

Heavy black lines represent plot medians, box represents 50% of population. Outliers are classified as points lying greater than 1.5 box-lengths from the edge of the box. Circles represent outliers lying 1.5 to 3.0 box lengths from the edge of the box, asterisks represent outliers lying more than 3.0 boxes away. Whiskers define maximum and minimum values not including outliers.

Table 3.2 Comparison of plot pre and post felling and felled tree quadratic mean diameters (d_g)

	Frame 1	Group 2	Low 3	Frame 4	Low 5	Group 6	Clearfell 7	Creaming 8
D_g pre-felling (cm)	31.46	30.23	28.43	33.99	31.30	34.32	32.64	31.37
D_g felled (cm)	32.30	27.60	24.25	33.97	27.96	30.93	32.64	36.46
D_g post-felling (cm)	31.26	31.02	29.91	33.99	32.36	35.33		30.29

Table 3.3 Calculated pre and post felling Weibull parameters for all plots

	Frame 1	Group 2	Low 3	Frame 4	Low 5	Group 6	Clearfell 7	Creaming 8
b pre felling	33.2161	31.9492	30.1484	35.7708	33.2282	36.2908	34.6620	33.1451
c pre felling	6.4235	6.2615	5.4707	7.2623	5.0849	6.1110	5.1039	6.2140
b post felling	33.0534	32.7274	31.6055	35.7922	34.3021	37.3044	0.0000	31.9509
c post felling	6.1325	6.6612	6.2301	7.1934	5.4567	6.4076	0.0000	6.5153
b change	-0.1627	0.7782	1.4571	0.0214	1.0740	1.0136	-34.6620	-1.1942
c change	-0.2910	0.3997	0.7594	-0.0689	0.3718	0.2965	-5.1039	0.3013

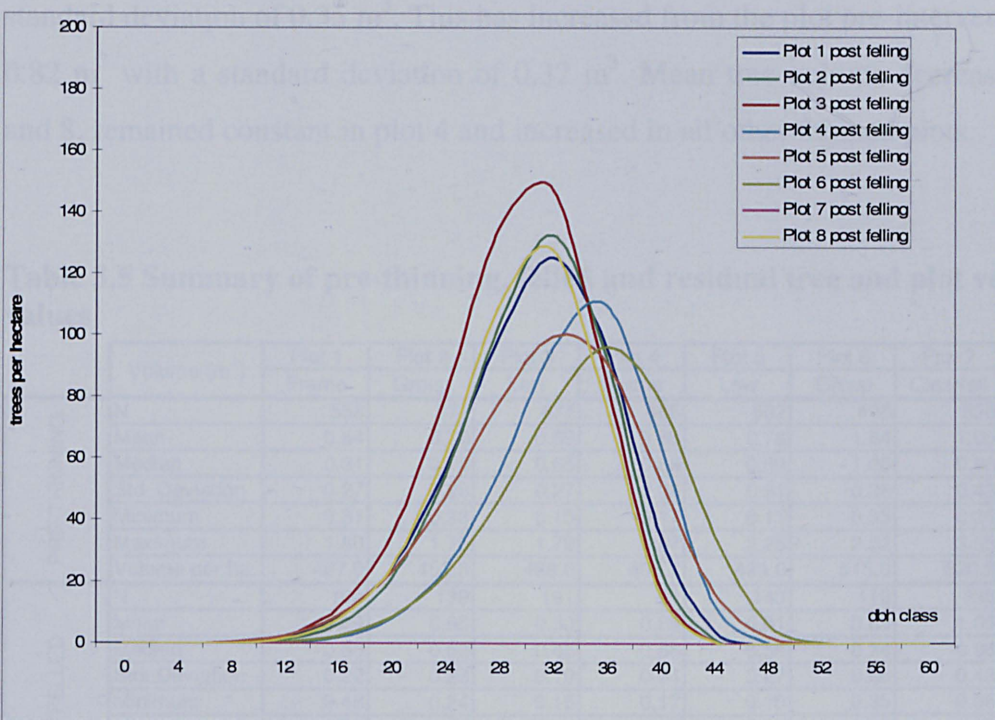


Figure 3.7 Post felling plot diameter distributions described through Weibull curves

3.3.2.4 Height

The plot values for the height of the tree of quadratic mean diameter (H_g) were calculated using pre and post-felling values of D_g (section 2.5.1.2 & 3.3.2.3) and the stand height curves (Loetsch *et al.*, 1973). Values for H_g are provided in Table 3.4.

Table 3.4 Calculated pre and post felling values of h_g; the height of the tree of quadratic mean diameter

	Frame 1	Group 2	Low 3	Frame 4	Low 5	Group 6	Clearfell 7	Creaming 8
H_g pre-felling (m)	23.94	24.05	23.07	21.58	21.68	24.73	26.60	19.07
H_g post-felling (m)	23.89	24.21	23.47	21.58	21.88	24.91	0.00	18.88

3.3.2.5 Volume

Plot and tree pre-intervention, felled and residual volumes are summarised in Table 3.5 and Figure 3.8 for all plots.

Standing volume in the thinned plots was reduced to a mean value of 322.8 m^3 from the previous mean of 450.8 m^3. Plot 8 has the lowest residual volume of 263.3 m^3 and plot 6 the highest with 414.7 m^3.

The mean tree volume of trees retained within the thinned plots was 0.83m^3 with a standard deviation of 0.35 m^3. This has increased from the plot pre-intervention mean of 0.82 m^3 with a standard deviation of 0.32 m^3. Mean tree volume decreased in plots 1 and 8, remained constant in plot 4 and increased in all other thinned plots.

Table 3.5 Summary of pre-thinning, felled and residual tree and plot volume values

	Volume (m^3)	Plot 1	Plot 2	Plot 3	Plot 4	Plot 5	Plot 6	Plot 7	Plot 8	All Plots
		Frame	Group	Low	Frame	Low	Group	Clearfell	Creaming	
PRE-THINNING	N	556	577	677	465	562	495	338	508	4178
	Mean	0.84	0.78	0.69	0.88	0.76	1.04	1.05	0.66	0.82
	Median	0.81	0.76	0.65	0.85	0.69	1.00	0.98	0.64	0.77
	Std. Deviation	0.27	0.26	0.27	0.26	0.31	0.36	0.43	0.23	0.32
	Minimum	0.31	0.23	0.15	0.17	0.15	0.35	0.36	0.06	0.06
	Maximum	1.80	1.75	1.79	1.67	2.25	2.52	3.05	1.56	3.05
	Volume per ha.	467.0	452.3	498.0	408.7	433.0	515.3	520.3	336.8	450.8
FELLED	N	104	139	191	91	143	119	338	82	1207
	Mean	0.89	0.65	0.50	0.88	0.61	0.85	1.05	0.90	0.81
	Median	0.88	0.62	0.45	0.86	0.56	0.84	0.98	0.90	0.76
	Std. Deviation	0.22	0.23	0.19	0.24	0.27	0.26	0.43	0.21	0.36
	Minimum	0.48	0.24	0.15	0.17	0.15	0.35	0.36	0.49	0.15
	Maximum	1.76	1.64	1.14	1.58	2.18	1.85	3.05	1.49	3.05
	Volume per ha.	92.1	90.7	102.2	79.9	88.0	100.6	520.3	73.5	128.0
RESIDUAL	N	452	438	486	374	419	376		426	2971
	Mean	0.83	0.83	0.77	0.88	0.82	1.10		0.62	0.83
	Median	0.80	0.80	0.71	0.85	0.75	1.04		0.60	0.78
	Std. Deviation	0.28	0.26	0.26	0.26	0.31	0.36		0.20	0.31
	Minimum	0.31	0.23	0.25	0.30	0.31	0.35		0.06	0.06
	Maximum	1.80	1.75	1.79	1.67	2.25	2.52		1.56	2.52
	Volume per ha.	374.8	361.6	395.8	328.8	345.1	414.7		263.3	322.8

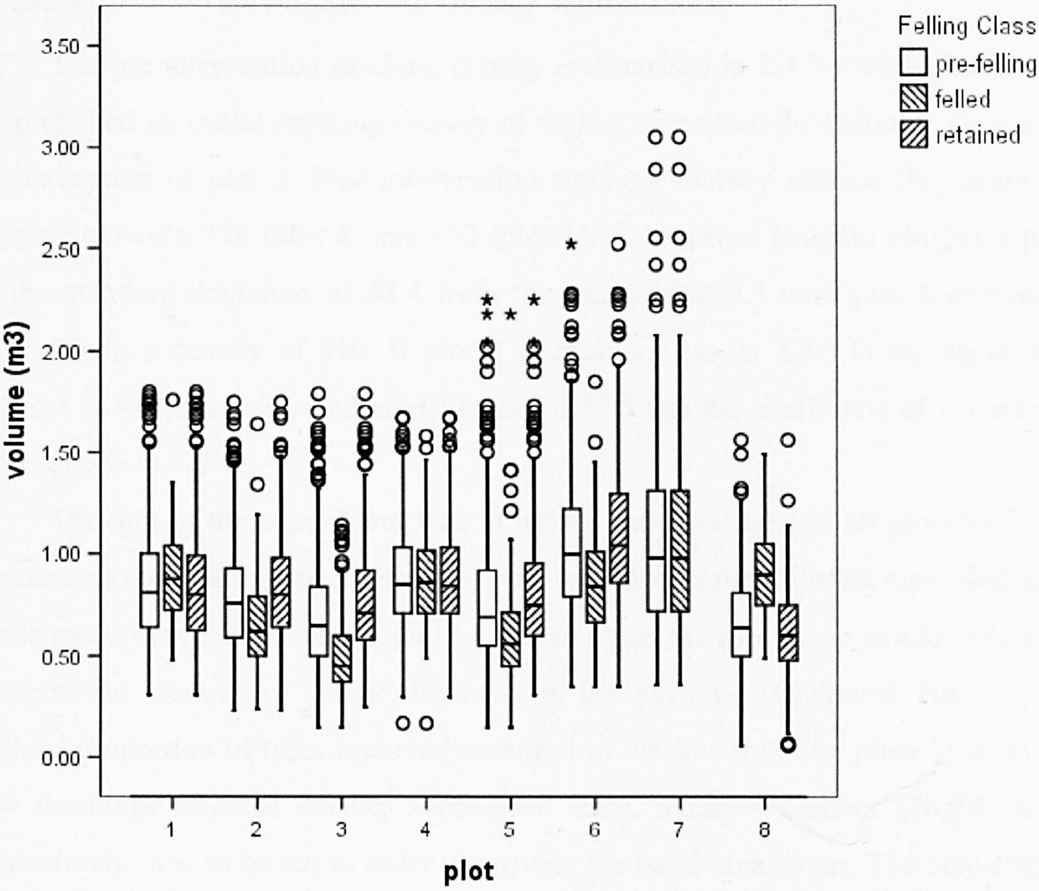


Figure 3.8 Comparison of plot pre and post felling and felled tree volumes

Heavy black lines represent plot medians, box represents 50% of population. Outliers are classified as points lying greater than 1.5 box-lengths from the edge of the box. Circles represent outliers lying 1.5 to 3.0 box lengths from the edge of the box, asterisks represent outliers lying more than 3.0 boxes away. Whiskers define maximum and minimum values not including outliers.

3.3.3 Discussion of Thinning Intensity

3.3.3.1 Intervention Intensity & Thinning Effects on Stand Parameters

Whilst intervention intensity can be described alone it is closely related with stand parameter value changes; the two are therefore presented together. Thinning type cannot always be fully separated from these aspects and, indeed, its inclusion in the discussion is often beneficial. Thinning type is fully covered in 3.4.2 but is also referenced within this section.

3.3.3.2 Post-intervention Stocking Density Within Plots

The pre-intervention stocking density is discussed in 2.4.3.1 which concludes that all plots had an initial stocking density of within a standard deviation of the mean with the exception of plot 3. Post-intervention stocking density reflects this again, values ranging between 374 (plot 4) and 452 (plot 1). This spread is again roughly equivalent to the standard deviation of 48.4 from the mean of 429.3 with plot 3 existing as an outlier with a density of 516. If plot 3 is excluded (as in 2.4.3.1) the mean stocking reduces to 414.8 with a standard deviation of 33.5 and the coefficient of variation drops from 11.3% to 7.8%.

The aim of the experiment was to reduce the basal area of all plots by 20%. The percentage reduction of stems per plot will vary due to the thinning type used and only if the mean diameter of trees removed was to equal the plot mean would 20% of stems be removed. This is, of course, the basis of the SG ratio (Gadow & Hui, 1999). The highest proportion of trees removed occurred in the low thinning plots (3 & 5). As the low thinnings targeted smaller suppressed trees, a larger number (28.2% & 25.4% respectively) had to be cut in order to provide the basal area target. The converse of this occurred in the creaming plot (8) where in order to achieve the target basal area removal only 16.1% of stems were cut – comprising solely dominants. The four other thinning plots also received a density reduction that agreed well with the thinning type applied to them and sat between the extremes of low thinning and creaming. The crown thinning frame tree plots (1 & 4) both had a density reduction of less than 20% and the group plots (2 & 6) had a reduction of more than 20%.

3.3.3.3 Basal Area

A mean basal area reduction of 20.1% was achieved in the thinned plots. Variation between plots of a standard deviation of 0.94% gave a coefficient of variation of 4.7%. Thinning therefore achieved a reasonably similar intensity throughout the plots.

Due to the fairly uniform intervention intensity throughout the plots, residual basal area possesses a similar pattern to initial values; all plots lying within 1.2 standard deviations of the mean (34.3 $m^2.ha^{-1}$) with the exception of plot 8 which is 1.76 standard deviations lower. The coefficient of variation of the plots is 6.01%.

Residual basal areas within plots are all above the 30 m^2/ha which is the critical level suggested for uniform British stands below which natural regeneration is viable

(Hale, 2004; Mason *et al.*, 2004; Page *et al.*, 2001). This suggests that another intervention is likely to be necessary to reduce the basal area to a level likely to encourage natural regeneration.

3.3.3.4 Diameter

As the SG-Ratio (Gadow & Hui, 1999) describes, thinning type can be inferred from the relationship between stand mean diameter and mean removed diameter. Where the mean diameter removed is larger than the stand mean, a crown thinning has occurred and the residual stand will have a smaller mean diameter than before the intervention. The converse would occur in a low thinning, and no or little difference in the means would signify a neutral intervention. Changes of mean diameters indicate that low thinning occurred in plots 2, 3, 5 and 6, plot 4 was close to neutrally thinned, plot 1 was crown thinned and plot 8 was strongly crown thinned.

The change in the two Weibull parameters can be used to describe changes in the diameter distribution. The ‘b’ parameter will describe the change in diameter range and the ‘c’ parameter describes change in distribution form.

All plots have ‘c’ values of between 5.46 and 7.19 suggesting negative skewness. Both frame tree plot values decreased slightly, indicating that the distribution was becoming more symmetrical. This can be explained by the thinning type removing a slightly greater proportion of larger diameter trees but felling trees on both sides of the curve peak. Both group plot and both low thinning plot values have increased slightly suggesting an increase of negative skew through a reduction in smaller diameter class frequency which causes the left-hand side of the curve to become shallower. The value for the creaming plot also increased. The increase is due to the left-hand side of the curve being unchanged by the thinning but the right-hand being reduced significantly. The left-hand side of the curve was therefore made proportionately larger and hence more negatively skewed.

3.3.3.5 Height

The calculation of H_g (3.3.2.4) will reflect thinning type in a similar way to diameter values as it is calculated using D_g. The values of height will increase with a rise of D_g and reflect the occurrence of low thinning, the converse being true for crown thinning. The comments made on thinning type in 3.3.3.4 are therefore transferable to here.

3.3.3.6 Volume

A mean volume reduction of 20.22% was achieved in the thinned plots. Variation between plots of a standard deviation of 0.81% gave a coefficient of variation of 3.99%. Thinning therefore achieved a reasonably similar intensity throughout the plots.

Due to the fairly uniform intervention intensity throughout the plots, residual volume possesses a similar pattern to initial values; all plots lying within 1.2 standard deviations of the mean (322.8 m^3/ha) with the exception of plot 8 which is 1.41 standard deviations lower.

It should be noted that the thinning type combines with the basal area reduction to dictate the percentage volume reduction. This can be seen the best if plots 1, 2 and 3 are compared. All plots are of similar site index and hence dominant height. Plot 1 has the smallest reduction in basal area, plot 3 the largest and plot 2 is intermediate. The mean tree diameter removed is the largest in plot 1, smallest in plot 3 and intermediate in plot 2. An increase in tree diameter will also bring an increase in tree height, therefore where a basal area value is composed of fewer, larger diameter stems, the stems will also be longer and so provide greater volume. Thinning of dominants (plot 1) will yield a greater volume per basal area reduction, thinning of suppressed (plot 3) will yield less.

The change due to thinning type can be seen in mean tree volume as with mean tree diameter. Again, crown thinning will cause a reduction in mean tree volume and low thinning will cause an increase.

3.4 FURTHER ANALYSIS OF PLOT MARKING

3.4.1 Analysis of Thinning Type

Two thinning indices are used to further characterise the interventions by describing thinning type rather than the thinning intensity and effects on stand parameters covered in 3.3. Thinning index can also be used as a variable in analysis of vehicle working.

3.4.1.1 SG-Ratio

The SG-Ratios (Gadow & Hui, 1999) calculated for the plot interventions are presented in Table 3.6. Plot 8 is described as strongly crown-thinned, whilst plot 1 is very mildly crown thinned and plot 4 is neutral. Plots 2, 6, 3 & 5 are all described as being low thinned. Plot 7 is described as being neutral.

3.4.1.2 S_1 Separation Parameter

The values for S_1 calculated for the plot interventions are presented in Table 3.6. Association of thinning type and plot S_1 values is presented in Figure 3.9.

Plot 8 is described as very strongly associated with crown-thinning, whilst plots 1 and 4 are described as strongly associated with crown thinning. Plot 3 is described as strongly associated with low thinning. Plots 2, 5 and 6 are moderately associated with low thinning.

Plot 7 is not described as it was clearfelled.

Table 3.6 Comparison of thinning type by SG-Ratio

SG-Ratio after Gadow & Hui (1999).

	Frame Tree plot 1	Group plot 2	Low Thinning plot 3	Frame Tree plot 4	Low Thinning plot 5	Group plot 6	Clearfell plot 7	Creaming plot 8
SG-Ratio	0.95	1.20	1.38	1.00	1.25	1.23	1.00	0.74
S1	-0.25	0.69	1.06	0.00	0.74	0.75		-1.15

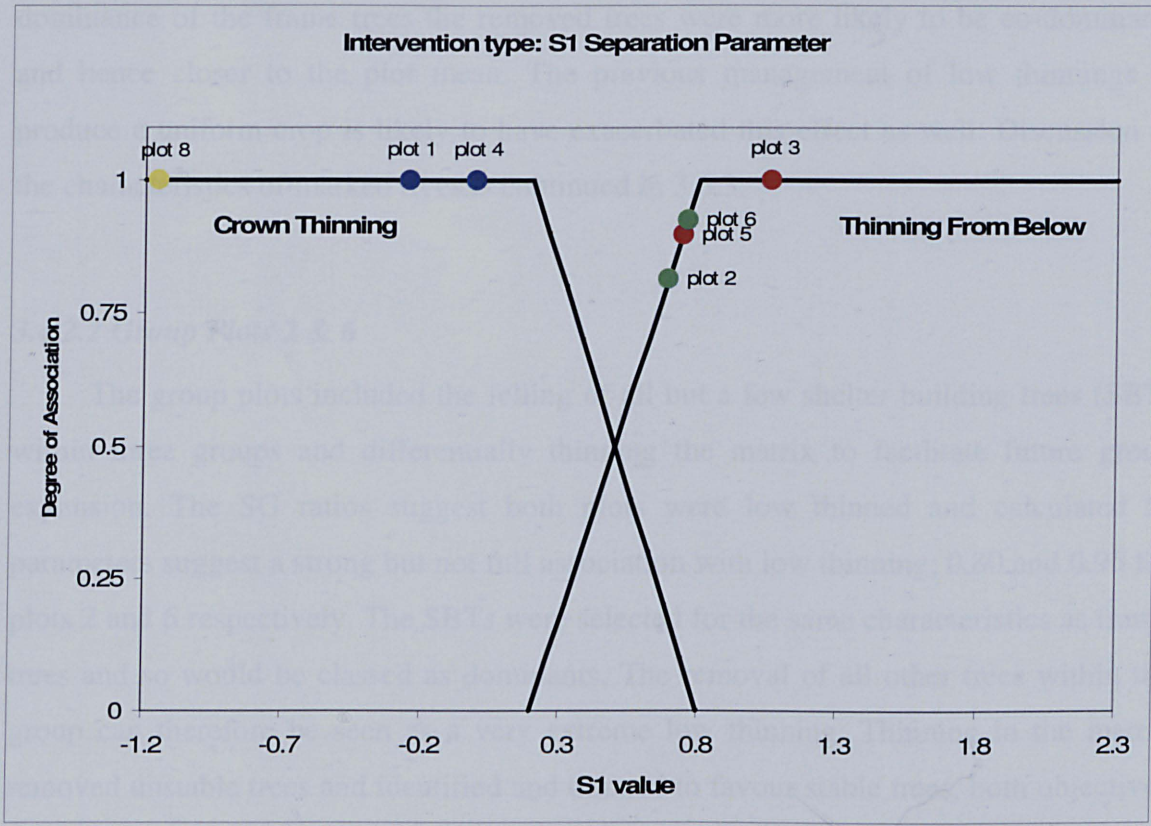


Figure 3.9 Association of plot intervention S1 value and thinning type

After Gadow & Hui (1999). Colours represent treatment types as in Figure 2.1.

3.4.2 Discussion of Intervention Type

3.4.2.1 Frame Tree Plots 1 & 4

Plots 1 and 4 were envisaged as being a crown thinning to favour the development of frame trees. The SG ratio values suggest that in plot 1 a mild crown thinning was achieved and that in plot 4 a neutral thinning. The S_1 parameters calculated for both plots are close to zero and, whilst this shows that the mean diameter of felled trees is close to that of residual trees, suggesting a more neutral thinning, the S_1 values are fully associated with crown thinning (after degree of association values presented by Gadow & Hui, 1999).

The explanation for the neutrality of the crown thinning is that the selection of frame trees in the plots was a compromise between quality and stability. Due to the relatively high windthrow risk in the plots and stand developmental stage, stability was of a higher consideration if the frame trees were to be windfirm into the future. Frame trees were therefore chosen if they had attributes positively linked with stability; attributes corresponding with traits of dominance e.g. h/d, c/h. Thinning removed the greatest competitors to the frame tree within its thinning cell but due to the high dominance of the frame trees the removed trees were more likely to be co-dominants and hence closer to the plot mean. The previous management of low thinnings to produce a uniform crop is likely to have exacerbated this effect as well. Discussion of the characteristics of marked trees is continued in 3.6.3.

3.4.2.2 Group Plots 2 & 6

The group plots included the felling of all but a few shelter building trees (SBT) within three groups and differentially thinning the matrix to facilitate future group expansion. The SG ratios suggest both plots were low thinned and calculated S_l parameters suggest a strong but not full association with low thinning; 0.80 and 0.95 for plots 2 and 6 respectively. The SBTs were selected for the same characteristics as frame trees and so would be classed as dominants. The removal of all other trees within the group can therefore be seen as a very extreme low thinning. Thinning in the matrix removed unstable trees and identified and thinned to favour stable trees, both objectives tending towards selection against lower crown class trees and hence low thinning. It is therefore of little surprise that that the thinning in the plot is described overall as a low thinning.

3.4.2.3 Low Thinning

The calculated SG ratios for the low thinning plots both indicate low thinning. The S_l parameter for plot 3 is fully associated (100%) with low thinning whereas plot 5 is 88% associated. Both thinnings were marked by George Johnson the forest owner to his usual prescription. The difference is likely to be due to local stand conditions and parameters.

3.4.2.4 Creaming

Both the SG ratio and S_l parameter show that there is a strong association with crown thinning as would be expected from the removal of solely the trees of largest diameter.

3.4.3 Effects of Thinning on Diversity

One of the commonly cited advantages of CCF management is an increase in stand structural and species diversity (Pommerening & Murphy, 2004; Mason *et al.*, 1999). Two commonly used indices are used to assess changes in structural diversity due to thinning. As the stands were monocultures and this was the initial transformation intervention, species diversity was not likely to be altered, instead diameter distribution is investigated.

3.4.3.1 Shannon

The Shannon index of diversity (H') was calculated for the plot diameter distributions for before and after felling. Values of H' are presented in Figure 3.10. Values of diversity decrease with felling in all plots except 1 and 4 which increase by 1.96% and 1.05% respectively. The greatest decrease in diversity, with the exception of the clearfelled plot, is found in the low thinned plot 3, falling by 7.15%. The value of the low thinned plot 5 reduced by 3.5% and that of the creaming plot by 4.7%. Value reductions for the group shelterwood plots 2 and 6 were 2.5% and 0.67% respectively.

3.4.3.2 Simpson

The Simpson index of diversity (D) was calculated for the plot diameter distributions for before and after felling. Values of 1-D are presented in Figure 3.10. Values of diversity also decrease after felling in all plots except 1 and 4 which increase by 1.23% and 0.79% respectively. The greatest decrease in diversity, with the exception of the clearfelled plot, is 3.57% in the low thinned plot 3. The value of the second low tinned plot 5 was reduced by 3.57% and that of the creaming plot by 2.23%. Value reductions for the group shelterwood plots 2 and 6 were 1.03% and 0.44% respectively.

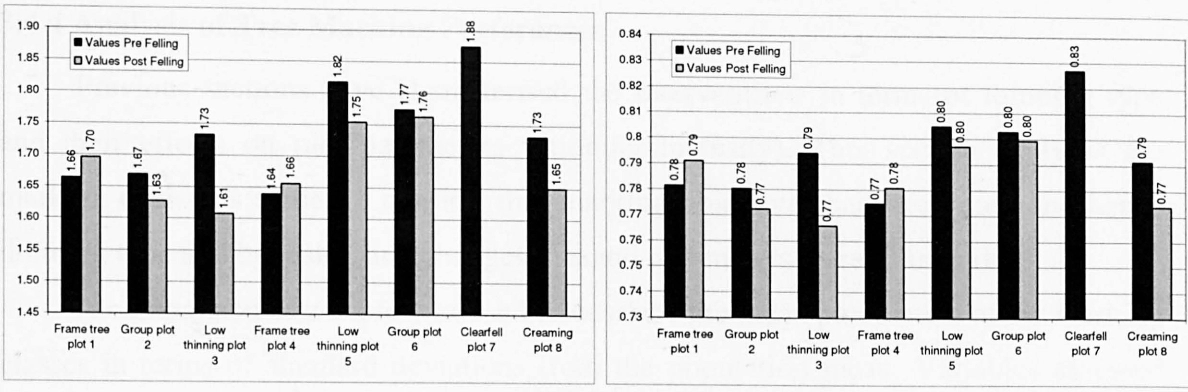


Figure 3.10 Shannon (H´) and Simpson (1-D) diversity indices values for plots before and after felling

Shannon on left and Simpson on right.

3.4.3.3 Discussion of the Effects of Thinning on Diversity

Both Simpson and Shannon indices indicated a reduction of structural diversity in all plots with the exception of the frame tree plots 1 & 4. That the two indices correlate confirms the findings of Neumann & Starlinger (2001). This reduction is due to the thinning of the plots reducing the diameter range. Within the frame tree plots the diameter range stayed the same but the thinning type reduced the kurtosis of the distribution, making the diameter classes, and so their relative abundance, more equal and therefore increasing and the index values.

The proposition that CCF management automatically improves both biodiversity and structural diversity can be seen to be flawed. The expression of structural diversity through changes in values of D and H' also appears poor as they do not take into account any spatial differences in stands; the values for the group plots in particular reduced with the intervention. As the intervention at Trallwm was the first towards transformation of the stands, the effect of CCF management on the stands had been minimal; the stands were still monocultures and no understorey was yet present. Diversity may increase with CCF, but the type (species or structural), the degree of change and the time and duration of the change all appear to be variable and very dependent on species, site and systems. A pine seed tree system, for example, qualifies as CCF but is barely more diverse than conventional clearfelling and very different from a single-tree selection sysytem.

3.4.4 Analysis of Tree Marking Preferences

Previous sections have characterised the interventions in terms of thinning type and their effects on plot parameters (thinning intensity). This section analyses the marking decisions made, to confirm that marking objectives had been met, and hence thinning type and intensity, and changes in stand parameters were as intended.

A comparison of z-score was used to describe the mean parameters of the marking classes in terms of standard deviations from the population mean. Variables assessed were tree dbh, height, crown length, h/d ratio and c/h ratio. For example, frame trees would be expected to have larger diameter, height, longer crown, lower h/d and higher c/h than the mean tree. Low thinned felled trees would be expected to have a smaller diameter, be shorter of height and crown, a lower c/h and higher h/d than the mean tree.

3.4.4.1 Analysis of Normal Distribution

If z-scores are to be used the data being analysed should be as close to normally distributed as possible (Fowler *et al.*, 1998). To assess data distribution type, each list of variable measurements from each plot was sorted in ascending order and ranked in Excel (1,2,3…..n). Each entry was given a percentile rank score of (x-0.5)/n. Percentile score was then passed through the function NORMSIV which returns the inverse of the standard normal cumulative distribution. Function output was then plotted (x value) against original value (y value) in a normal probability plot (normal Q-Q) (Pallant, 2005). A perfectly normal distribution would produce a straight-line graph with an R^2 value of 1.0.

Normal Q-Q plots are presented in full in Appendix 2.8 and R^2 values denoting normalness in Table 3.7.

The high R^2 values (>0.98) indicate near-normal distribution of the data. Plot 8 does have lower R^2 values however which can be traced to a group of outliers consisting predominantly of three persistent side branches / secondary stems which were recorded in their own right. The stems are of small diameter and when excluded from this analysis of normality greatly improve the values of R^2 as can be seen in Table 3.8.

3.4.4.2 Z-scores

Z-scores were calculated for each tree for each of its five variables (d, h, crown length, h/d & c/h) using the formula $(x-\mu)/\sigma$, so describing in terms of standard deviations its divergence from the population mean. Mean z-scores were then calculated for different marking categories. For group plots, z-scores were calculated for the plot as a whole and separately for the groups and matrix as stand-alone populations. Mean z-scores are presented in Table 3.9.

Table 3.7 Normalness of plot variable distributions represented by R^2 values

Frame Tree plot 1	dbh	0.9945	Frame Tree plot 4	dbh	0.9914
	height	0.9620		height	0.9949
	crown length	0.9918		crown length	0.9919
	h / d ratio	0.9946		h / d ratio	0.9915
	c / h ratio	0.9872		c / h ratio	0.9963
Group plot 2	dbh	0.9927	Group plot 6	dbh	0.9835
	height	0.9722		height	0.9837
	crown length	0.9895		crown length	0.9965
	h / d ratio	0.9961		h / d ratio	0.9843
	c / h ratio	0.9887		c / h ratio	0.9888
Low Thinning plot 3	dbh	0.9955	Low Thinning plot 5	dbh	0.9779
	height	0.9841		height	0.9939
	crown length	0.9959		crown length	0.9932
	h / d ratio	0.9891		h / d ratio	0.9937
	c / h ratio	0.9942		c / h ratio	0.9932
Clearfell plot 7	dbh	0.9801	Creaming plot 8	dbh	0.9681
	height	0.9895		height	0.9079
	crown length	0.9864		crown length	0.9520
	h / d ratio	0.9815		h / d ratio	0.8854
	c / h ratio	0.9793		c / h ratio	0.9459

Table 3.8 Plot 8 R^2 values after removal of outliers

Creaming plot 8 entire plot	dbh	0.9681	Creaming plot 8 excluding trees 247, 248, 249	dbh	0.9937
	height	0.9079		height	0.9889
	crown length	0.9520		crown length	0.9901
	h / d ratio	0.8854		h / d ratio	0.9626
	c / h ratio	0.9459		c / h ratio	0.9750

3.4.4.3 Analysis of Variance Between Felling Classes

One-way between-groups analyses of variance were conducted for each plot to investigate differences in dbh, height, crown length, h/d and c/h between felling classes. Significant differences between felling classes (retained, frame/SBT, thinned matrix, thinned group) were found in all plots at the p=0.000 level with the exception of plot 4. Felling class crown lengths in plot 4 were found to be significantly different at the p=0.040 level, h/d ratios at the p=0.001 level and c/h ratios were found not to be significantly different [F(2,325)=0.714, p=0.490]. When Bonferroni adjustment (alpha value/number of tests) is used to compensate for the large number of tests, all plots remain significant at p=0.005 with the exception of plot 4 where dbh, height and h/d remain significant. Results of the ANOVA for plots are presented in table 3.10.

Post-hoc comparison using Tukey HSD and is presented and summarised in Appendix 2.8.

Table 3.9 Mean z-scores for marking categories within the plots

PLOT	POPULATION		DBH Z score	Tree Height Z score	Crown Length Z score	h / d Ratio Z score	c / h Ratio Z score
Frame Tree plot 1	Plot	mean Z felled	0.16	0.18	0.11	-0.13	0.06
Frame Tree plot 1	Plot	mean Z frame	1.03	0.68	0.69	-0.71	0.45
Frame Tree plot 4	Plot	mean Z felled	-0.20	-0.03	0.05	0.23	0.09
Frame Tree plot 4	Plot	mean Z frame	0.56	0.43	0.14	-0.48	-0.06
Low Thinning plot 3	Plot	mean Z felled	-0.75	-0.86	-0.76	0.43	-0.49
Low Thinning plot 5	Plot	mean Z felled	-0.58	-0.44	-0.61	0.54	-0.57
Economic Thinning plot 8	Plot	mean Z felled	1.05	0.44	0.49	-0.82	0.35
Group System plot 2	Plot	mean Z felled matrix	-0.89	-0.62	-0.49	0.81	-0.32
Group System plot 2	Plot	mean Z SBT	0.51	0.21	0.62	-0.52	0.66
Group System plot 2	Plot	mean Z felled group	-0.29	-0.22	-0.34	0.17	-0.27
Group System plot 2	Groups	mean Z SBT	0.72	0.37	0.77	-0.58	0.62
Group System plot 2	Groups	mean Z felled group	-0.25	-0.13	-0.26	0.20	-0.21
Group System plot 2	Matrix	mean Z felled matrix	-0.88	-0.62	-0.50	0.79	-0.33
Group System plot 6	Plot	mean Z felled matrix	-0.85	-0.79	-0.80	0.72	-0.62
Group System plot 6	Plot	mean Z SBT	1.35	1.06	0.63	-1.00	0.26
Group System plot 6	Plot	mean Z felled group	-0.26	-0.20	-0.38	0.20	-0.37
Group System plot 6	Groups	mean Z SBT	1.24	1.02	0.91	-1.00	0.59
Group System plot 6	Groups	mean Z felled group	-0.27	-0.22	-0.19	0.22	-0.13
Group System plot 6	Matrix	mean Z felled matrix	-0.85	-0.79	-0.82	0.72	-0.65

Table 3.10 Summary of one-way between-groups ANOVA investigating differences of dbh, height, crown length, h/d and c/h between trees of different felling codes

plot	ANOVA dbh	plot	ANOVA height	plot	ANOVA crown length
1	[F(2,553)=48.24, p=0.000]	1	[F(2,553)=34.66, p=0.000]	1	[F(2,553)=97.32, p=0.000]
2	[F(3,573)=19.82, p=0.000]	2	[F(3,573)=14.16, p=0.000]	2	[F(3,573)=22.31, p=0.000]
3	[F(1,675)=198.09, p=0.000]	3	[F(1,675)=242.99, p=0.000]	3	[F(1,675)=20.07, p=0.000]
4	[F(2,462)=14.43, p=0.000]	4	[F(2,462)=11.47, p=0.000]	4	[F(2,462)=69.36, p=0.040]
5	[F(1,560)=64.77, p=0.000]	5	[F(1,560)=46.07, p=0.000]	5	[F(1,560)=49.08, p=0.000]
6	[F(3,491)=34.17, p=0.000]	6	[F(3,491)=38.76, p=0.000]	6	[F(3,491)=24.16, p=0.000]
8	[F(1,506)=110.64, p=0.000]	8	[F(1,506)=26.02, p=0.000]	8	[F(1,506)=90.67, p=0.000]

plot	ANOVA c/h ratio	plot	ANOVA h/d ratio
1	[F(2,381)=10.62, p=0.000]	1	[F(2,381)=16.03, p=0.000]
2	[F(3,398)=9.9, p=0.000]	2	[F(3,398)=14.5, p=0.000]
3	[F(1,483)=77.08, p=0.000]	3	[F(1,483)=51.65, p=0.000]
4	[F(2,325)=0.71, p=0.490]	4	[F(2,325)=7.63, p=0.001]
5	[F(1,372)=40.4, p=0.000]	5	[F(1,372)=42.71, p=0.000]
6	[F(3,339)=9.82, p=0.000]	6	[F(3,339)=20.12, p=0.000]
8	[F(1,325)=19.67, p=0.000]	8	[F(1,325)=51.64, p=0.000]

3.4.4.4 Graphical Representation of Marking Preferences

Appendices 11 and 13 present tree height and dbh respectively against h/d ratio for all plots.

Appendices 12 and 14 present tree height and dbh respectively against c/h ratio for all plots.

3.4.4.5 Plots 2 and 6: Group and Matrix

As noted in 3.4.4.2, data for the interventions in group plots can be split into the groups and the surrounding matrix and presented separately. Appendix 2.10 repeats the analyses of this chapter but compares results for the whole group plots and for their matrix and group components.

3.4.5 Discussion of Marking Analysis

3.4.5.1 Suitability of Using Z-score Approach

The R^2 values produced by the analysis of normality in 3.4.4.1 are all above 97% with the exception of those of plot 8. The lower values produced by plot 8 are due to three outliers, trees 247, 248 and 249. The three trees are actually low persistent branches of a diameter large enough to be considered as a secondary stem. If the analysis is redone with the exclusion of these trees the R^2 values for plot 8 increases to 96% and above as can be seen in table 3.8.

The high R^2 values produced by this analysis suggest a high degree of normality in the distribution of plot variables and so validates the analysis by z-score or other parametric approaches.

3.4.5.2 Plot Marking

The object of tree marking analysis was to identify the characteristics of the plot felling classes and compare these with the characteristics prescribed.

Whilst analysis looks at each tree parameter separately, it should be borne in mind that the parameters are not independent and a change in one will be caused by or cause change in another. An increase in diameter will correspond with an increase in height, on average taking the relationship of the calculated height-diameter curve. The shape of the height–diameter curve shows that tree h/d ratio will decrease with increasing diameter. For any given diameter there will be a range of heights caused by individual differences in tree social class and growing space. More dominant and open-grown trees should have a better developed crown (higher c/h ratio) and will be able to put on more diameter increment and so further reduce their h/d ratio (Cameron, 2002; Bachofen & Zingg, 2001; Rollinson, 1988).

3.4.5.2.1 Frame Tree Plots 1 & 4

The frame trees picked within the two plots share the characteristics of social dominants. The frame trees are, on average, larger diameter, taller, have a longer length of crown, a smaller h/d ratio and higher c/h ratio than the plot average. The resistance of frame trees to wind damage (stability) was a major priority and analysis suggests that marking did select more stable trees for this purpose. This analysis is confirmed by Appendices 11-14. Frame trees can be seen to be in a cluster of greater height and lower h/d (Appendix 11), although the higher c/h is not so evident (Appendix 12). The larger average dbh of frame trees can also be seen (Appendices 13 & 14).

The results of the analysis reflect the neutrality of the plot 1 and 4 thinnings, particularly that of plot 4, as it shows less significant differences between marking classes. Both z-scores and the analysis by ANOVA suggest that the thinned trees were more dominant than unthinned trees, all but c/h being significantly different, but the size of difference was not as marked as those found in other plots.

The marking analysis confirms the findings of the thinning indices. The most dominant trees were chosen as stable frame trees and their nearest and largest competitors were removed. The competitors were by default less dominant and so the intervention was a weak crown thinning.

3.4.5.2.2 Low Thinning Plots 3 & 5

When compared to the plot mean, removed trees were on average, of smaller dbh, shorter, had shorter total crown length and smaller c/h ratio and had higher h/d ratios.

Low thinning aims to remove trees from the lower social classes and the analyses of marking suggest that the trees marked were less dominant.

Appendices 11-14 confirm the attributes suggested. The greater association to low thinning of the intervention in plot 3 when compared to plot 5 is also visible in both z-scores and the appendices as the tendency to select less dominant trees is more marked in plot 3.

3.4.5.2.3 Creaming Plot 8

The trees to be felled within plot 8 were selected entirely by diameter. It is therefore of no surprise that felled trees had a mean dbh over a standard deviation higher than average (1.05σ). As would be expected, the felled trees were also taller

(0.44 σ) and were more tapered (-0.82 σ). The trees also had deeper live crowns (0.49σ) and higher c/h ratios (0.35σ).

Analysis by ANOVA confirms that the thinned trees were significantly more dominant than retained trees.

The selection of trees of larger dbh is shown very markedly in Appendices 11-14, as is the associated smaller h/d ratio of these trees. The difference in tree height, live crown length and c/h is less extreme and is less obvious in the appendices.

3.4.5.2.4 Group System Plots 2 & 6

Shelter building trees (SBT) were chosen for their stability and so in their characteristics should be similar to frame trees.

When plot data were analysed together the SBT were found to have larger dbhs, be taller, have longer live crown and higher c/h ratio and a have lower h/d ratios than retained or felled trees. The difference is less marked in plot 2 however and this is confirmed by the appendices with points being far less clustered in plot 2 scatter-graphs (Appendices 12-14). The SBTs are also not always significantly different from the retained matrix trees. The characteristics of the SBTs suggests that they are more dominant and hence possess higher stability than average as was the intention of the marking. The retained matrix trees also exhibit more dominant traits. This again agrees with the marking objective of retaining more stable trees to facilitate group expansion.

Trees felled within the matrix show the least dominant characteristics of the felling classes as they are composed solely of the trees identified as being the least stable. Trees felled within the groups also had below plot average dbh, height, crown and stability indices. This can be explained by the pattern of felling where all but the largest trees (SBTs) were felled in the groups so creating a form of low thining.

3.4.6 Effects of Interventions on Stability Indices

Stand and individual tree stability are commonly mentioned in discussion of CCF and transformation (e.g. Pommerening & Murphy, 2004; Mason *et al.*, 1999). As mentioned in 3.2.2, height : diameter and crown : height ratios are commonly used as indicators of stability. This section comments on changes in these stability indices and also produces tree and plot values which help describe crop morphology and are used as variables in the analysis of machine working.

3.4.6.1 Height : Diameter Ratio – h/d

The h/d class (10 cm classes) distribution is presented in Appendix 9 and shows change in class frequency after thinning. Mean class values for all plots are presented for pre-thinning and post-thinning in Appendix 15.

An independent samples t-test was used to compare the h/d values of trees removed from plots to those retained, the results of which are summarised in table 3.11. A significant difference [p=0.000] was found between values in plots 2, 3, 5, 6 & 8. No significant difference was found in plots 1 and 4. Mean plot values of h/d decreased in plots 2, 3, 5 and 6 and increased in plot 8. Mean values increased in plot 1 and decreased in plot 4.

Table 3.11 Summary of independent samples t-test carried out to compare h/d ratios of retained to removed trees

Felled trees: 1, Retained trees: 0, Pre-intervention: pre.

plot	felled	N	Mean	Std. Deviation	Std. Error Mean	t	df	Sig. (2-tailed)	ETA squared
1	pre	384	77.27	10.94					
	0	280	77.41	11.68	0.70	0.459	246.5	0.646	0.001
	1	104	76.90	8.69	0.85				
2	pre	402	81.99	11.83					
	0	263	79.38	10.68	0.66	-6.393	400.0	0.000	0.093
	1	139	86.94	12.34	1.05				
3	pre	485	85.18	12.46					
	0	294	82.07	10.08	0.59	-6.702	313.6	0.000	0.085
	1	191	89.98	14.16	1.02				
4	pre	328	64.13	7.30					
	0	237	63.84	7.13	0.46	-1.163	326.0	0.246	0.004
	1	91	64.89	7.72	0.81				
5	pre	374	72.75	11.11					
	0	231	69.95	9.83	0.65	-6.536	372.0	0.000	0.103
	1	143	77.28	11.60	0.97				
6	pre	343	74.40	9.91					
	0	224	72.08	9.10	0.61	-6.269	341.0	0.000	0.103
	1	119	78.76	9.93	0.91				
7	pre	245	84.35	12.16					
	0	0	.	.	.				
	1	245	84.35	12.16	0.78				
8	pre	327	61.16	9.79					
	0	245	63.25	9.86	0.63	8.877	218.3	0.000	0.195
	1	82	54.90	6.32	0.70				

3.4.6.2 Crown : Height Ratio – c/h.

The c/h class (0.1 classes) distribution is presented in Appendix 10 and shows change in class frequency after thinning. Mean class values for all plots are presented for pre-thinning and post-thinning in Appendix 16.

An independent samples t-test was used to compare the c/h values of trees removed from plots to those retained, the results of which are summarised in table 3.12. A significant difference [p=0.000] was found in all thinned plots except 1 and 4. Mean plot values of c/h increased in plots 2, 3, 5 and 6. The mean value if Plot 8 decreased and the values of plots 1 and 4 remained the same.

Table 3.12 Summary of independent samples t-test carried out to compare c/h ratios of retained to removed trees

Felled trees: 1, Retained trees: 0, Pre-intervention: pre.

plot	felled	N	Mean	Std. Deviation	Std. Error Mean	t	df	Sig. (2-tailed)	ETA squared
1	pre	384	0.53	0.09					
	0	280	0.53	0.09	0.01	0.459	246.5	0.646	0.001
	1	104	0.53	0.07	0.01				
2	pre	402	0.55	0.10					
	0	263	0.57	0.09	0.01	-6.393	400.0	0.000	0.093
	1	139	0.52	0.10	0.01				
3	pre	485	0.54	0.10					
	0	294	0.57	0.09	0.00	-6.702	313.6	0.000	0.085
	1	191	0.49	0.10	0.01				
4	pre	328	0.62	0.07					
	0	237	0.62	0.08	0.00	-1.163	326.0	0.246	0.004
	1	91	0.62	0.06	0.01				
5	pre	374	0.56	0.09					
	0	231	0.59	0.08	0.00	-6.536	372.0	0.000	0.103
	1	143	0.53	0.10	0.01				
6	pre	343	0.53	0.07					
	0	224	0.54	0.06	0.00	-6.269	341.0	0.000	0.103
	1	119	0.51	0.07	0.01				
7	pre	245	0.56	0.10					
	0	0	.	.	.				
	1	245	0.56	0.10	0.01				
8	pre	327	0.65	0.09					
	0	245	0.63	0.09	0.01	8.877	218.3	0.000	0.195
	1	82	0.68	0.08	0.01				

3.4.7 Discussion of the Effects of Interventions on Stability Indices

3.4.7.1 Height : Diameter Ratio – h/d

As would be expected, the h/d : diameter relationship takes the form of an inverted height curve with h/d reducing with increasing diameter and plots of lower site index having a lower h/d for a given diameter. The variation of h/d for any given diameter can be seen in Appendix 13, Appendix 15 presenting the mean values.

Changes due to thinning in the h/d curves in Appendix 15 are minimal, the large changes being due to reduction of numbers of individuals within diameter classes. Appendix 9 shows changes in h/d class frequency, changes in higher classes being more evident in low thinned and group plots, even changes in plots 1 and 4 and lower class changes more evident in plot 8.

If the h/d scale proposed by Slodicak & Novak (2006) (<82 = excellent, 83-92 = good, 93-101 = satisfactory, >102 = unsatisfactory) for Norway spruce is used to classify stand stability, all plots appear stable. In all plots, 75% or more of trees before thinning had good stability. Post thinning levels did not drop below this. The percentage of stable trees was considerably higher in plots with lower site index.

Overall change in h/d correlates well with the thinning type applied within plots, determined by the change of diameter distribution from thinning causing a change in the h/d distribution.

Low thinnings (e.g. plots 2 and 3) cause a reduction of h/d whereas crown thinning (plot 8) causes a rise in h/d. Thinning in plots 1 and 4 did not cause a significant shift in h/d as the thinning type was comparatively neutral. The size-effect of the change in h/d is related to the strength of the intervention (e.g. extreme / mild crown thin). A more extreme thinning will cause a greater change in h/d. This is confirmed when change in h/d is plotted against thinning index. A high degree of correlation is found for both SG-ratio ($h/d = 8.443 - 8.774 \cdot SG$; R^2 = 0.97) and S1 ($h/d = -0.617 - 2.498 \cdot SG$; $R^2 = 0.98$).

None of the thinning types caused a very large change in mean plot h/d; change due to creaming thinning was around 2, changes due to low thinning and groups were of the order of 1 to 3.

3.4.7.2 Crown : Height Ratio – c/h

The relationship between c/h and diameter is not as strong as that with h/d and diameter. As can be seen from Appendix 14 there is a weak positive relationship between c/h and diameter, larger trees therefore tending to have proportionately longer crowns.

Changes in the c/h curves in Appendix 16 are small. The large changes are again due to reduction of numbers within diameter classes. Appendix 10 shows changes in c/h class frequency. Changes are not as obviously related to thinning type as those in Appendix 9 for h/d due to the poorer relationship between c/h and dbh.

A high degree of correlation is still found however when change in c/h is plotted against thinning index for both SG-ratio ($c/h = -0.061 + 0.064 \cdot SG$; $R^2 = 0.94$) and S1 ($c/h = 0.005 + 0.018 \cdot SG$; $R^2 = 0.88$).

Low thinnings (e.g. plots 2 and 3) cause an increase in c/h whereas crown thinning (plot 8) cause a decrease in c/h. Thinning in plots 1 and 4 did not cause a significant shift in c/h as the thinning type was comparatively neutral.

Plot mean values of c/h were again little changed by any of the thinning types; change due to creaming thinning was around 0.02, changes due to low thinning and groups were of the order of 0.01 to 0.03.

3.5 CONCLUSIONS

Analysis of the thinning shows that the desired intensity was achieved in the thinning plots, basal area being reduced by a mean of 20.1% and volume by a mean of 20.22%. The residual basal area in all plots remained above 30 m^2/ha however, suggesting that a further intervention will be necessary to secure regeneration (Hale, 2004; Mason *et al.*, 2004a; Page *et al.*, 2001).

Description of intervention type through SG-Ratio and S_I parameter (Gadow & Hui, 1999) suggests that the aims of plot prescriptions and marking were achieved.

Thinning in the frame tree plots was described by SG ratio as a mild crown thinning in plot 1 and neutral in plot 4, although both had S_I values that were fully associated with crown thinning. The mildness of crown thinning was due to the advanced developmental stage of the stand and the need to pick the most stable and generally most dominant trees as frame trees.

The group plots were described by SG-ratio as low thinned, with S_I values highly but not full associated with low thinning. This description is due to the mix of felling all but the most stable trees in groups and the removal of unstable trees in the matrix.

Low thinning was described as such by SG-ratio, plot 5 having a high association and plot 3 being fully associated.

Creaming was described as strongly crown thinning by SG-ratio and had an S_I value fully associated with crown thinning due to the targeting of only the largest trees.

Description of plot diameter distribution diversity by Shannon and Simpson indices found a reduction in all plots with exception of the frame tree plots 1 and 4. This was due to all other thinning types altering diameter distribution skewness, so reducing the diameter range and so index values. In the frame tree plots, skewness was not altered whilst kurtosis was reduced, so making the diameter classes proportionately more similar and increasing index values.

Analysis of felling-class tree characteristics to assess the success of marking objectives found significant differences between classes which agreed with the marking objectives. This suggests that marking picked the "right" trees, matching physical characteristics of trees to those prescribed for each felling class.

Measures of stability h/d and c/h ratios were found to change with thinning type. Crown thinning increased mean h/d and decreased mean c/h. Low thinning decreased h/d and increased mean c/h.

None of the thinning regimes changed the mean values by a large amount however. Plot mean values for h/d increased by 2 for creaming and were reduced by up to 3 for low thinning. Mean values for c/h decreased by 0.02 for creaming and up to 0.03 for low thinning. Plot means all remained at levels that can be regarded as stable after thinning.

CHAPTER 4: SHORTWOOD HARVESTING & TIME STUDY LITERATURE REVIEW

4.1 THE SHORTWOOD SYSTEM

A harvesting system is a combination of methods that enable the felling of trees, the extraction of their produce to roadside and its further transport to market (Hart, 1994). The two main harvesting systems used for timber production are the shortwood system and the tree-length system, each system an umbrella term for a variety of minor working differences that can occur (Hart, 1994; Hibberd, 1991).

The tree-length system extracts the de-limbed stems whole and either comminution takes place at roadside or they are transported whole to mill. Whole-tree harvesting extracts the trees to roadside intact where de-limbing occurs. As with the tree-length system, comminution can occur at roadside or whole stems can be transported to mill.

The increase of interest in renewable energy has also led to a rethink of what constitutes a commercial product and chipping (brash / stem / whole tree), brash baling and stump removal are becoming more common but are poorly defined by traditional nomenclature (Moffat *et al.*, 2006).

4.1.1 Shortwood System Overview

The shortwood system, also known as the cut-to-length system, is differentiated by primary processing taking place at stump i.e. the tree is de-limbed (brashed) and cut into product types at stump. Felling and processing is generally undertaken by chainsaw and / or a harvester and subsequent extraction of the produce is by forwarder. Although it is possible to use other methods such as skidders, forwarders are the most efficient in dealing with the many smaller-volume pieces of product involved (Hart, 1994; Hibberd, 1991).

The shortwood system is efficient over a wide range of tree sizes whereas there is a lower efficiency associated with trees of less than 0.1 m^3 in the tree-length system (Hibberd, 1991). The shortwood system is, however, limited in its ability to deal with very large trees and very steep slopes and these factors may necessitate the use of the tree-length system (Hibberd, 1991).

The shortwood system has a number of commonly quoted advantages over the tree-length system for production of mixed product assortments (Hart, 1994; Hibberd, 1991). Only two phases are involved (harvest & forward) in the shortwood system compared with three phases (fell, skid & process) in the tree-length. The benefit of this is easier control of production, particularly if the harvester and forwarder are evenly matched in productive terms. Whether the capital cost of the machines needed for either system is higher is dependent on the size and type of machines to be used. Kellogg & Bettinger (1994) stated that there was a greater capital cost of machines i.e. harvesters, compared with chainsaws which must be offset by higher productivity. This argument is true if a chainsaw fell, skidder extract, chainsaw process system is to be used. However, feller-bunchers and bed processor-loaders are often used in higher production operations and the cost associated with this machinery is at least comparable with a harvester–forwarder combination.

The need for less stacking space is another cited advantage to the shortwood system compared with the greater area needed for processing in addition to stacking area in tree-length systems.

As produce in the shortwood system is carried rather than dragged, produce remains cleaner, so creating fewer problems in further processing.

The shortwood system is also thought to require a lower roading density and racks and tracks used need not be of a high quality. This view was confirmed by Lanford & Stokes (1996) who found that the shortwood system when compared with a shear feller-buncher and grapple skidder required less roading infrastructure within the stand and could operate on poorer surfaces. The increasing sophistication of skidders may be reducing the need for better racking infrastructure however.

4.1.2 The Change of Harvesting in the UK Towards the Shortwood System

The 20th century saw a huge increase in the mechanisation involved in timber harvesting.

The first electrically-driven bucking chainsaws were introduced by Stihl in 1926 and were followed in 1950 by the first chainsaws operable by one person (Stihl, 2006). By 1959 the chainsaw had not reached predominance over the saw and axe in the UK, a third of all timber still being cross-cut manually, although this had changed by 1969 with a four-fold increase of chainsaws and the majority of bucking performed using them (Rowan & Sawyer, 1971; Huggard & Owen, 1959).

Tractors were used agriculturally from the time of the First World War onwards (Blunden & Curry, 1991) and were soon introduced to work in the forest, performing the work originally undertaken by horse teams, becoming widespread by the time of the

Second World War. Timber was skidded behind tracked and wheeled tractors using winches or a towed sulky (skidding arch) (Mason *et al.*, 2004; Huggard & Owen, 1959).

In the decade from 1960 to 1969, skidding production by tracked tractor decreased from 25% of total to 8.5% and by horse teams from 53% of total to 13%, the work being taken over by wheeled skidders (Rowan & Sawyer, 1971).

During this time the majority of skidding was tree-length. In 1960 only 32% of primary conversion occurred at stump, increasing to 45% by 1969, although often only consisting of removing the butt-log and skidding it separately (Rowan & Sawyer, 1971; Huggard & Owen, 1959).

By 1973, tree-length and long-length skidding still accounted for 90% of production, achieved mainly by farm-type tractors (70%) and an increasing number of purpose-built articulated and other forest skidders. Forwarders were starting to appear and an associated rise in the shortwood system was seen. Cross-cutting performed by chainsaw had increased further and accounted for 80% of production (Rowan, 1974).

The first single-grip harvesters appeared in 1983 produced by S P Maskiner of Sweden, five years after the arrival of their predecessor the grapple processor (Eliasson, 1998). Harvesters did not displace the chainsaw overnight, however, and Hibberd (1986) pays them little attention in describing UK harvesting, although forwarders and the shortwood system were described as being common.

Changes seen in harvesting in the UK are mirrored in other European countries changing from motor-manual to fully mechanised (Lageson, 1996).

The shortwood system now predominates in the UK and vehicle censuses in the past ten years suggest that this is likely to continue at least for the medium-term. The use of purpose-built rather than excavator-based harvesters is increasing with new machines being bought to replace ageing excavator bases. The proportion of purpose-built forwarders is also continuing to increase over tractor-trailer types.

The development of harvesters is a continuing process of improvement and refinement which has led to an increase in machine capability and efficiency. Nurminen *et al.* (2006) noted that in particular, harvester engines, transmissions systems, boom hydraulics and head feeds have improved in efficiency since studies by Eliasson (1998) and Kellogg & Bettinger (1994).

Conversely the use of processors and skidders is reducing and few new machines are being bought. The overall proportion of cableway machinery to other harvesting types has remained the same (8%) although the fleet has aged and overall numbers have dropped, but not to the extent of skidders or processors (Saunders & Jones, 2002; Saunders, 1997).

4.1.3 Harwarders

Harwarders combine the roles of harvester and forwarder into a single vehicle. Examples of production vehicles are the Ponnsse BuffaloDual and WisentDual harwarders and the Valmet 801 Combi (Ponnsse Oyj, 2006; Valmet, 2006).

The advantage of harwarders over conventional harvester-forwarder set-ups is the reduced capital cost of one machine compared with two and the reduction of setup cost for each cutting parcel, particularly important where parcel size is small. Harwarder productivity is linked to factors that affect both harvesters and forwarders due to their dual role (Andersson & Eliasson, 2004; Sirén & Aaltio, 2003; Wester & Eliasson, 2003).

Sirén & Aaltio (2003) investigated the productivity of harwarders compared to thinning and mid-sized harvester–forwarder combinations in Finland. Harwarders were found to be roughly equivalent to conventional systems in unit cost below a mean tree volume of 0.2 m^3. Where two product assortments were cut the harwarder became cheaper when mean stem volume dropped below 0.1 m^3 whereas with five assortments the mean stem volume had to drop below 0.06 m^3. The difference in values is due to harwarders only producing mixed loads, produce being crosscut directly in to the bunk. Complex mixed loads reduce productivity as more time is required in cutting and sorting produce in the bunk. Harwarder extraction distance, as with conventional forwarders, also greatly influences productivity, productivity dropping with distance.

4.2 TIME AND WORK STUDY

The forest is, as noted by Björheden *et al.* (1995), a complex working and production environment far removed from the simpler processes of the factory floor. It is important that terminology regarding definition of actions, methods, analyses and outputs is standardised to allow comparisons to be made. National standard nomenclatures such as those produced by ANSI (1989) and NSR (1978) were used historically but were superseded by the creation of the IUFRO working party S3.04.02 (work study, payment, labour productivity) which produced an international standard authored by Björheden *et al.* (1995).

Work study has been defined by IUFRO as "the systematic study of technical, psychological, physiological, social and organisational aspects or work providing for critical examination of existing and proposed ways of doing work" (Björheden *et al.*, 1995). Work studies are employed in order to establish efficiency and enable improvements to be made if desired (Lageson, 1996; Björheden *et al.*, 1995).

Work studies typically involve work measurements of which a time study is often one. Time study is defined by IUFRO as "the measurement, classification and subsequent systematic and critical analysis of time consumption in work with the purpose of increasing the efficiency of the study object by eliminating useless time consumption" (Björheden *et al.*, 1995).

4.2.1 Classification of Activity

All time studies rely on work classified into *work elements*, sub-divisions of working delimited by *break points*. Identical tasks can be broken down in different ways, however, and the derived work elements often vary from study to study, reflecting national or institutional protocol. An example of differing work elements for the same task can be seen in comparing a study in the USA (Kellogg & Bettinger, 1994) with one in Sweden (Eliasson, 2000) and the UK Forest Research protocol for harvester study (Technical Development, undated (a)). Where Technical Development (undated (a)) classes "fell" as the time from when the boom is moved to reach for the tree to when the head rollers start moving to process, Kellogg & Bettinger (1994) subdivide this into "position to cut" and "felling and dropping" and Eliasson (2000) subdivides to "boom out", "position head", "felling" and "tree fall". Direct comparisons between similar sounding work elements are therefore not always possible.

4.2.2 Time Study Types

Time studies can be performed as a *comparative study*, *correlation study* or a mix of the two (Nurminen *et al.*, 2006; Andersson & Eliasson, 2004; Eliasson, 1998).

Comparative studies compare two or more pieces of equipment, machine or method types under identical conditions whereas correlation studies find relationships between factors influencing forest operations; how changes in conditions affect operational working and output (Eliasson, 1998; Lageson, 1996).

4.2.3 Timing

Time studies can be conducted as either *continuous* studies or as *discontinuous* studies using work sampling (Eliasson, 1998). A number of options exist for the timing of work elements during continuous studies.

Snap-back timing (also fly-back timing) derives from mechanical stopwatch studies where the chronometer is returned to zero with each new work element, so providing element times directly. *Cumulative* timing does not return the chronometer to zero after each element and calculates element duration by sequential subtraction. *Selective* timing stops the chronometer at the end of an element and only starts again if the selected element is repeated whereupon timing carries on from the previous reading (Björheden *et al.*, 1995).

Work (activity) sampling gives only an estimation of proportional time consumption but has the advantage that it requires less intense concentration and that by staggering observations, several processes can be recorded at once by as single observer (Nurminen *et al.*, 2006; Björheden *et al.*, 1995).

4.2.4 Problems Associated with Empirical Studies

A problem with field-based studies is the variation caused by the many factors such as weather and machine component fatigue which can influence results but are in themselves unrelated to the study. Empiric studies have tried to counter these effects by trying to minimise variation in these factors, measure the factors and correct for them and use replicates (Bergstrand, 1987). These attempts at remediation are often difficult and in the case of adding replicates can greatly increase demands on study resources. Simulation studies are therefore the obvious choice for correlation studies to remove this form of variation as stand and machine factors can be kept constant, numerous replications or permutations can be run and resource demands minimised. Simulation studies do however need empiric data on which to base calculations and the assumption is made that operator, machine and stand continue to react and interact in the same way and that a change in factors does not cause entirely new behaviour.

4.2.5 Computer Simulations

Simulation studies have been used extensively as an alternative to empiric time studies. Studies include simulation of harvesters (Wang *et al.*, 2005; Eliasson, 1999;

Eliasson & Lageson, 1999; Eliasson, 1998; Lageson, 1996; Sjunnesson, 1970), feller bunchers (Winsauer *et al.*, 1984; Fridley *et al.*, 1982) and comparisons of different systems and machine combinations (Wang & Greeene, 1999; Wang *et al.*, 1998).

Models can be classed as either deterministic or stochastic. Deterministic models provide the same output in subsequent iterations for a given input and so as Lageson (1996) noted, variance in empiric studies will be greater. Stochastic models can be used to mirror this variation by providing a varying output for a given input, so simulating the randomness of forest working with its inherent delays (Eliasson, 1998).

Model output is, as Eliasson (1998) noted, only as reliable as the simulation itself. Vehicle–environment interactions are based on a number of assumptions and are generally a simplification of real working and should be validated against empiric data.

4.3 MEASUREMENT OF PRODUCTIVITY AND TIME USAGE

The classification of time consumption is central to both understanding working and its analysis. Björheden *et al.*, (1995) provide a classification of all working and its relation to the total time consumption for a job. The conceptual structure is presented in Figure 4.1.

4.3.1 Measures of Performance

The most typical measure of machine performance is productivity, measured as time consumption per unit production (m^3/PMH).

Workplace time (WP) consists of productive work time, supportive work time, disturbance time and work-related delay time (Hånell *et al.*, 2000; Björheden *et al.*, 1995). *Productive work time* is the combination of the *main work time* (equivalent to cyclic work (Technical Development, undated (a))) and *complementary work time* (equivalent to non-cyclic work (Technical Development, undated (a))). WP is also described as productivity per standard machine hour (m^3/SMH) (e.g. Kellogg & Bettinger, 1994).

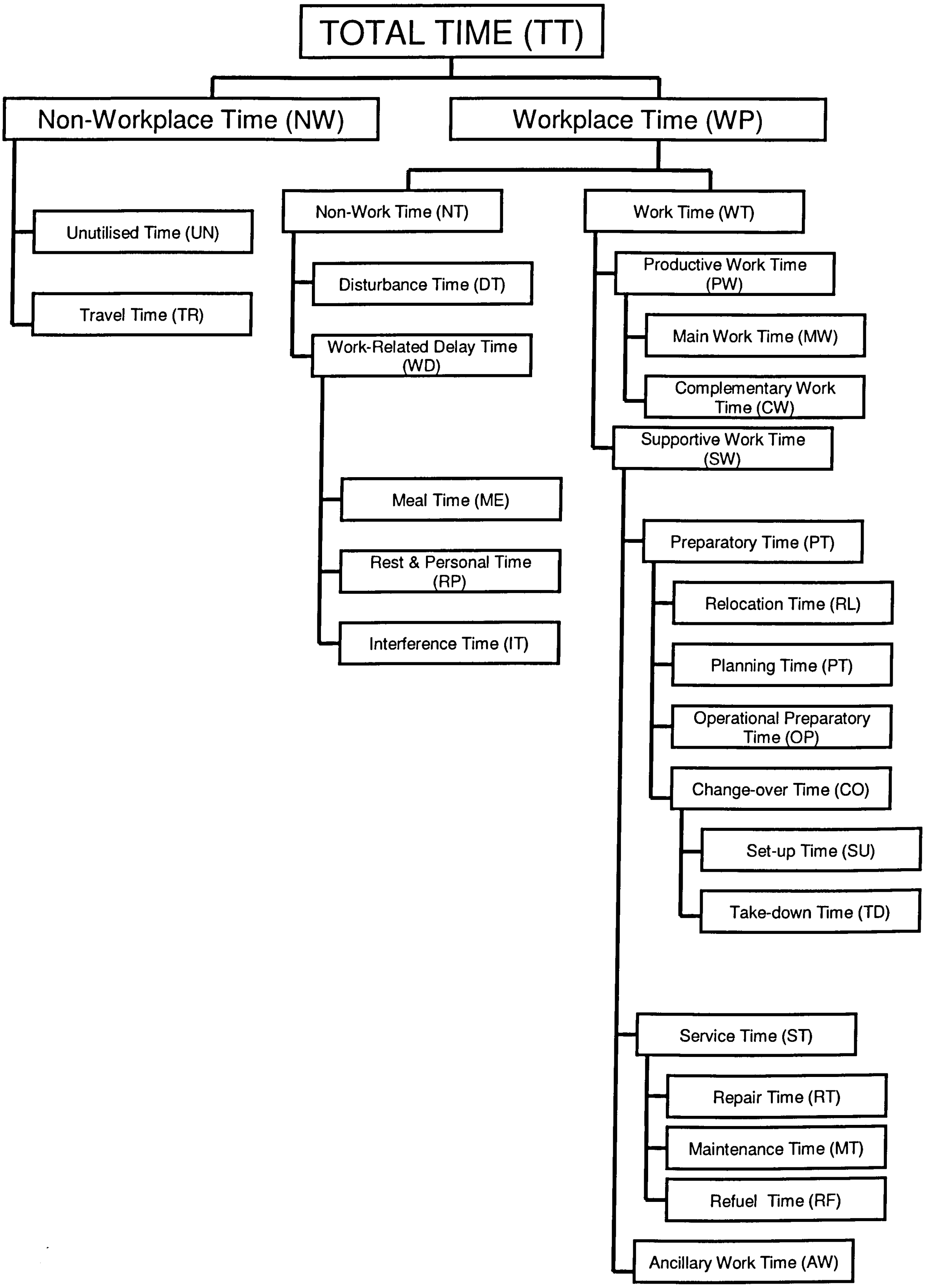


Figure 4.1 Time concepts structure

Reproduced from Björheden *et al.*, (1995) For harvester working, time per tree is a commonly used measure either as a mean value or as time consumption for a given stem size. Time per tree is easily converted to the standard measure of productivity of volume per productive machine hour. Two synonyms are commonly seen for this measure (Stokes *et al.*, 1989; Ford-Robertson, 1971); volume per effective machine hour - $m^3.E_oh^{-1}$ (e.g. Eliasson, 1998) or volume per productive machine hour - $m^3.PMH^{-1}$ (e.g. Lageson, 1996; Kellogg & Bettinger, 1994). Nurminen *et al.* (2006) use a further synonym of delay-free (i.e. only productive cyclic work) productivity – P_e ($m^3.h^{-1}$).

As P_e is delay-free, delays and other non-productive activities must be added to give a value of WP. Kuitto *et al.* (1994) found that $WP = 1.86.E_0$ for single-grip harvesters and $WP = 1.45.E_0$ for forwarders. Nurminen *et al.* (2006) class WP as gross effective productivity (P_{ge}) which includes other work and delays less than 15 minutes. This is analogous to the calculation of *standard hour* times from *basic time* values by the inclusion of 18% rest and 20% other work (Spencer, 1998; Forestry Commission, 1978; Technical Development, undated (a))).

4.3.2 Use of Machinery

Two measures of productivity are routinely used in comparative studies: mechanical availability and mechanical utilisation.

Mechanical availability is defined as "the portion of workplace time that a machine is mechanically fit and able to do productive work" and mechanical utilisation as "the portion of the workplace time that a machine is being used to perform the function for which it was intended" (Björheden *et al.*, 1995).

4.3.3 Cost of Working

Cost per cubic metre or tonne of produce, harvested and transported to roadside, is a commonly expressed measure of the efficiency of a system. The calculation of running costs is a combination of *fixed* and *variable* costs. Fixed costs are time-dependent and include depreciation in use, interest on loans, insurance, administration and non-piecework wages. Variable costs are work dependent and include fuel & lubricants, servicing, machine transfers and piecework wages (Bright, 2001).

The fixed and variable costs are socio-economic variables which will vary both spatially and temporally (country, region and time). Other variables such as machine age and depreciation will vary with the machinery studied. Whilst cost assumptions should be stated and calculations shown, re-calculation is needed if cases are to be compared on an even playing-field. An example of providing a cost per unit volume is given by Kärhä *et al.* (2004) who state that in 2002 the mean cost to roadside for harvester-forwarder shortwood thinnings in Finland was 12.2 US$/m^3 (GB£9.54/m^3 in 2006). This compares to the study by Mederski (2006) who quotes shortwood to-roadside thinning costs at €8.90/m^3 and €10.19/m^3 (GB£6.31/m^3 and GB£7.22/m^3 in 2006) and Kellogg & Bettinger (1994) who quote US$12.49/m^3 (GB£11.38/m^3 in 2006).

4.4 VEHICLE PRODUCTIVITY

There have been many studies made on single-grip harvesters and forwarders to evaluate their productivity, costs, working methods and suitability in the situations and conditions in which they are deployed in the UK and around the world (e.g. Hofsten & Nordén, 2002; Brunberg *et al.*, 2000; Saunders, 2000; Spencer, 1995; Mitchell, 1995; McLaren, 1994).

Production is achieved through the arrangement of *production factors* in a *production system. Productivity* is defined as "the rate of product output per time unit for a given production system" (Björheden *et al.*, 1995).

Eliasson (1998) groups production factors into three classes: stand related, work related and policy related.

Stand related factors include tree species, size, morphology, stocking density, intervention intensity and terrain and ground conditions (climate).

Work related factors include how work is organised and conducted e.g. type of intervention, swathe width, felling pattern, machine type, operator experience and motivation.

Policy related factors include when and how operations are conducted, laws, best-practice guidelines and operational policy of forest companies and landowners.

4.4.1 Production Factor: Tree Size

The most important variable affecting all harvester working productivity is usually tree size (Kellogg & Bettinger, 1994). This is confirmed by Eliasson (1998) who found that all elements associated with felling and processing (position, fell, fall, de-limb and crosscut) were positively correlated with tree size.

Size is a combination of dbh and height and hence volume. Machines have a maximum power with which work is to be accomplished. The amount of work involved in felling and processing trees rises with size as the area to be sawn through by the cross-cut saw rises as the square of the radius and larger trees will also have a greater mass to lift, drag or run through the head. Time consumption will therefore increase with tree size.

Kellogg & Bettinger (1994) reported an increase in the time needed to both position the head onto larger trees and process them. An increase in planning time was also noted for larger trees.

Lageson (1996) also found an increase in the time needed to fell and process trees of larger volume, as did Hånell *et al.* (2000).

Lanford & Stokes (1996) found that time to fell and process was primarily a function of dbh and was not significantly changed by the tree height or number of pieces cut from it whereas Tufts (1997) found that dbh, volume and merchantable length were the most correlated with time to fell and harvester productivity.

Increasing tree size may also have implications for working by exceeding machine limits. Hånell *et al.* (2000) note that large open-grown spruce in particular were too heavy to delimb conventionally using roller-feed. Instead, the harvesting head was moved along the stem of felled trees to delimb and process. Effects of this work method on productivity were not given.

4.4.2 Production Factor: Type of Intervention

The type of intervention dictates the sizes and distribution of removed trees in relation to those retained. Lageson (1996) found that thinning from above increased productivity by 20-40% compared with low thinning, the difference increasing inversely to the thinning ratio. Time per tree was found to be significantly different between high and low thinning, time consumption rising with dbh but proportionally lower than that of the increase in diameter.

Thinning from above will produce a larger mean product than thinning from below as larger trees are harvested. Nurminen *et al.* (2006), Johansson (1996), Kellogg & Bettinger (1994) and Kahala & Kuitto (1986) found that the size of piece has an effect on forwarder load and unload times, handling time decreasing by having to pick up fewer larger volume pieces, so increasing productivity. Andersson & Eliasson (2004) also note that forwarder load efficiency is affected by average piece size as the ratio between solid wood volume and piled wood volume rises with average piece size.

Nurminen *et al.* (2006) found that forwarder productivity correlated best with intervention type (thinning or clearfell), average haulage distance, concentration of produce in the drift and the capacity of the bunk. Kahala & Kuitto (1986) also found that forwarding was quicker per unit volume and hence more efficient in clearfelling compared with thinnings owing to the concentration of produce in clearfelling and Eliasson (1998) showed that vehicle speed along racks remains the same regardless of treatment. Johansson (1996) in a study of agricultural tractor conversions found that driving speed was reduced by 34-45% when loaded. A decrease in purpose-built forwarder loaded driving speed was also found by Nurminen *et al.* (2006), speed dropping from 56 to 44 m/min. Average speeds were also found to be higher over longer travel distances and lower over shorter distances, the vehicle accelerating to higher speeds. Lanford & Stokes (1996), in contrast, found that purpose-built forwarder speed was not altered by load status.

Nurminen *et al.* (2006) also found that increasing forwarder haulage distance from 200 to 400 m led to a reduction of productivity of between 10 and 13% and that an increase in bunk payload from 10 to 14 m^3 caused a 10% increase in productivity over 200 m and 15% over 400 m.

Lageson (1996) noted that Nordberg & Olsson (1988) raised concern over the tendency for operators inexperienced in crown thinning to thin at a greater intensity than intended, so reducing future yield. He noted that the operators studied by him were unused to crown thinning and unable to judge intensity as well, so supporting this view. It is logical to assume, however, that a greater familiarity with crown thinning would ameliorate this risk.

Suadicani & Fjeld (2001) compared harvester working in single tree selection cutting with group selection cutting. For a given removal of volume, the mean dbh removed from the single tree selection, 38% larger than the stand average, was found to be larger than that of the mean dbh removed from group selection. The concentration of working found in group selection increased efficiency however, making both systems comparable in terms of productivity.

Philips (1996) compared clearfelling with shelterwood cutting and found the latter to have around 38% higher unit cost for fell and forward.

Lageson (1996) also describes motor manual felling and tractor processing of pine and states there is a smaller movement time between trees in a low thinned stand, significant at the p=0.005 level. The mean time taken for the chainsaw operator to walk between trees is given 29.93 $cmin.tree^{-1}$ in the low thinned stand compared with 39.72 $cmin.tree^{-1}$ in the crown thinned stand. The mean distance between felled trees in the low thinned stand was 4.97 m compared with 4.92 m in the crown thinned stands. It seems unlikely that the 0.05 m difference is solely accountable for the 10 cmin difference in movement time. The experimental design in this case seems to provide this result as thinning was conducted as feller-select and not pre-marked and the operator was not used to crown thinning. It is therefore likely that the movement time also included "thinking time" which was significantly greater in crown thinning.

4.4.3 Production Factor: Tree Species & Morphology

The shape of a tree is likely to have an effect on its ease of harvesting, and is the result of a number of factors.

Tree species is the primary determinant of tree morphology, with factors such as site, climate and stand spatial inter-relationships likely to dictate further differences. In order to produce low variance correlations between time consumption and tree biometric data it is necessary to differentiate between species and morphologies and to stratify data, as is seen in Nurminen *et al.* (2006) where regressions are calculated separately for all species and felling types. Nurminen *et al.* (2006) found pine and spruce processing time to be approximately equal between stem volumes of 0.2 to 0.9 m^3. Above these volumes time consumption for pine was found to rise at a greater rate than that of spruce, larger trees requiring up to 30% more processing.

Unmerchantable or low value trees such as snags and those of very poor form can reduce productivity if they must be felled in the operation, as comparable or greater work must be performed for little or no return (Kellogg & Bettinger, 1994). Mixed species stands are also more costly to harvest compared with a monoculture of equivalent mean tree volume (unless no sorting is necessary e.g. Norway & Sitka spruce mix). Favreau & Légère (1999) found that harvesting cost rose by 19-73% in mixed species stands owing to changes in working, increase of working complexity and the inclusion of less commercial species which were more difficult to process.

Suadicani & Fjeld (2001) and Klem (1934) stated that decreasing h/d corresponds to an increased relative branch area per m^2 stem area in Norway spruce (*Picea abies*). A lower h/d is also associated with a higher c/h ratio, so suggesting a deeper crown in proportion to the tree height and longer total crown length (Cameron, 2002). Both

Suadicani & Fjeld (2001) and Eliasson (1998) proposed that a change in tree taper could cause changes in de-limbing conditions and its time consumption.

In a similar argument, Lageson (1996) noted that tree morphology can alter time consumption in processing, citing coarse branches as able to slow work and Hånell *et al.* (2000) attributed higher time consumption for trees of a similar size to coarser branching.

4.4.4 Production Factor: Stocking Density & Stand Openness

Eliasson (1998) noted that although the harvester elements of move, boom out and boom in were independent of tree size they decreased with increasing stocking density. Hånell *et al.* (2000) also found a similar effect in machine movement time and boom movement times.

Lageson (1996) goes on to put forward the logical argument that crown thinning, as it removes fewer trees, will make access to successive removed trees more difficult. There has been no empirical study on this specific effect however.

Eliasson (1998) also found that felling time per tree of a given size increased with stand density.

Dense undergrowth and understoreys can have a similar effect to high stocking by restricting boom and vehicle movement and visibility. Tahvanainen (2001) found that dense undergrowth can be responsible for a 13-38% drop in productivity and an increase in damage to the stand, 9% of trees being damaged compared with 5.3% in an open stand.

4.4.5 Production Factor: Intervention Intensity

Machine productivity is positively correlated with the intensity of an intervention. Increasing the removed proportion of a stand *-ceteris paribus-* will increase the concentration of working and hence productivity in both cutting and forwarding (Eliasson *et al.*, 1999; Siren, 1998). Hånell *et al.* (2000) found this to be true as movement time per tree decreased and number of trees per conversion site (harvester stop to fell and process) increased with an increase in the number of trees harvested.

4.4.6 Production Factor: Terrain

Like any other form of ground-based vehicle, harvesters and forwarders are limited in the terrain they can travel over. The classification of terrain is covered for the UK by a three-part numerical code produced by the Forestry Commission (Hibberd, 1991). The code grades ground conditions (soil type and drainage), ground roughness, and slope, between most favourable (1) and least favourable (5). A site with ironpan soil (average), obstacles of 50 cm high at 3 m spacing (rough) and 15% gradient (gentle) would be classed as 3:4:2. Whilst vehicles will have ultimate operating limits, productivity will decrease before they are reached. Kellogg & Bettinger (1994) note that as wheeled harvesters and forwarders must travel perpendicular to the contour for stability, steep slopes will reduce vehicle speed and ultimately traction will be lost. Vehicles will therefore have different uphill and downhill slope limits which must be specified for vehicle load and soils (e.g. McLaren, 1994). Rough sites are also a cause of reduced production as operators must spend more time manoeuvring around obstacles (Kellogg & Bettinger, 1994).

Traction aids such as chains and band-tracks are routinely used to provide increased traction, although floatation on softer sites is only improved by band-tracks. Specialist steep-slope harvesters such as the Silvatec Sleipner "mountaineer" and the Valmet 911.3 X3M have recently appeared. The Sleipner is equipped with band-tracks on all four wheel pairs and rated to work up to 30 degree slopes, and the Valmet has had its four wheel pairs replaced with four caterpillar tracks (Silvatec, 2006; Valmet, 2006). Purpose-built forestry zero-tail-swing excavator-type tracked harvesters such as the Tigercat LH830C and the John Deere 759G are also very capable on steep slopes due to their tilting ability; the 759G is quoted as being able to forward tilt 27 degrees, rear tilt 10 degrees and side tilt 20 degrees (Tigercat, 2006; John Deere, 2006).

4.4.7 Productivity Factor: When and How Operations are Conducted

The organization of working is important in maintaining operational efficiency. Working manner can be affected by pertinent laws, best-practice guidelines and operational policy of forest companies and landowners. Otherwise work should be conducted in the most efficient manner for the site and conditions.

Forwarder working can take the form of *single pass* or *multiple pass*, although working can switch between the two during a job. Single pass forwarding entails the operator loading all assortment types during a pass through the stand, so producing a mixed load. Multiple pass forwarding entails the operator only loading with a single product type during each pass (Nurminen *et al.*, 2006; Kellogg & Bettinger, 1994). Loading time was found to decrease with mixed loading but the benefit was lost due to the considerably longer time taken to unload and sort produce at the stacks (Kellogg & Bettinger, 1994). Nurminen *et al.* (2006) found that pure sawlog loads were around 40% more productive than pulpwood loads and 7 to 25% more than mixed loads in thinnings and clearfells.

An increase in the number of products cut has been shown to increase harvester processing time consumption. Nurminen *et al.* (2006) found increased time consumption for 0.3 to 0.8 m^3 pine, spruce and birch, of 3 to 10%, 3 to 11% and 2 to 9% respectively, for each new assortment. The number of products cut will also affect productivity as it affects the concentration of products in the drift and so dictates the efficiency of single loads (Kellogg & Bettinger, 1994; Kuitto *et al.*, 1994).

Nurminen *et al.* (2006) also noted that in the studies of the 1990s often only a very limited number of product types were cut (e.g. Kellogg & Bettinger (1994) cut 5.4 m log and 6.1 m pulp). Product assortments cut have become more varied to meet the more specific demands of timber processors, with knock-on effects on the structure of the drift.

4.4.8 Productivity Factor: Rack Spacing & Swathe Width

Extending rack spacing or swathe width can lead to greater concentration of working at conversion sites and less total vehicle travel, so increasing productivity.

Mederski (2006) noted that Bort *et al.* (1993) and Forbrig *et al.* (1996) had concluded that extending the distance between racks decreased productivity and so increased costs. This conclusion seems largely due to the poor organisation of working in their studies rather than inherent flaws in the concept and method; the reduction in productivity being due to work organisation making the harvester travel the rack network twice.

In his study, Mederski (2006) compared conventional racking density with 18-20 m between racks (526 m/ha in 44 year old stand and 465 m/ha in 72 year old stand) where the harvester can reach the entirety of the matrix from the racks with a wider rack spacing of 35-38 m between racks (286 m/ha in 44 year old stand and 267 m/ha in 72 year old stand) where a chainsaw operator must fell trees that are unreachable from the racks for subsequent processing by the harvester. Both Mederski (2006) and Johansson

(1996) conclude that wider racking leads to higher productivity due to concentration of working i.e. more trees harvested and processed at each conversion site and hence a greater product concentration which leads to higher forwarder productivity.

Wider racking is not universally applicable however. Rack spacing is reliant on the boom reach of the machinery used and the height of the trees felled, both of these likely to change with the development of the stand. Where trees are felled by chainsaw towards the rack for the harvester to process, the harvester will have to start processing from the tree tip. Harvester processing from the tip of the tree down might be problematic in larger trees as the small diameter of the stem might not be able to support the tree weight. Processing from the crown down might also pose problems for the head in gaining initial purchase on the tree. In stands with a dense shrub layer or understorey the harvester could also miss pre-felled trees. Stand density, tree size and species will also affect chainsaw productivity.

Another investigation into increasing the distance between racks by Hallonborg & Nordén (2001) studied a Timberjack 1270B harvester with a specially lengthened 11 m boom. The study found that harvesting time per tree was comparable to conventional machines and that the method did not lead to greater stand damage or poor selection. Productivity was increased however, as the harvester moved less than in conventional systems.

Another aspect of increasing the distance between racks is the increased volume of brash deposited per unit area of rack and hence a better brash mat over which to extract (Saunders & Ireland, 2005), although this is to be balanced against more intense use.

A point of note concerning both Mederski (2006) and Hallonborg & Nordén (2001) is the size of the trees studied. In both studies the mean tree volume is small, 0.3 m^3 and 0.1 m^3 respectively. With increasing tree size it is reasonable to believe that the methods employed would either become less feasible or unworkable.

The swathe width cut when clearfelling can also affect productivity. Spencer (1998) studied the effect of cutting 4, 6, 8 or 10 rows in a Sitka spruce crop spaced at 1.45 m. At the mean tree volume of 0.27 m^3, felling 6 or 8 rows increased output by around 12% compared with 4 rows, and this increased to 17% for 10 rows. When mean tree volume was increased to 0.6 m^3 the difference in output between 4 and 6 or 8 rows was still around 12%, although the output rose by 19% for 10 rows.

4.4.9 Productivity Factor: Felling Pattern

The pattern of felling is an extension of how work is organized and so has an effect on productivity. Suadicanii & Nordfjell (2003) investigated the effect on productivity due to row thinning from racks as opposed to conventional selective thinning. This form of row thinning where the harvester did not travel along the row of trees to be thinned but instead reached through from a rack was found to reduce harvester productivity. The working method required the harvester to spend more time associated with boom movement, both reaching toward the trees and then pulling them into the rack for processing. Forwarder working was not compromised however. This can be compared with the findings of Dhubháin *et al.* (1989) who found that in chainsaw first thinnings, selective low thinning was less productive than a 1 in 4 row thinning and 1 in 4 row and chevron thinning.

4.4.10 Productivity Factor: Machine Type & Specification

The type and size of machine have a great bearing on productivity. Larger harvesters will have the power and capacity to handle larger trees and larger forwarders will be able to extract a higher volume during each working cycle.

Mederski (2006) demonstrates this well in his study of thinning flat pine sites of 44 and 72 years old and mean tree volume of around 0.30 m^3 and 0.35 m^3 respectively. A Timberjack 770 harvester (4 wheel 11,550 kg) and Vimek 606 6WD forwarder (capacity 3000 kg) were used in the 44 year-old stands with a Timberjack 1270B harvester (6 wheel 17,500 kg) and Timberjack 1010B forwarder (capacity 10,000 kg) used in the 72 year-old stands. The increase in machine size, coupled with a greater mean tree size, nearly doubled the volume cut and transported per hour, although this came at the price of higher running costs which resulted in approximately equal cost to roadside for both vehicle pairings.

Low revenue is a common problem with first thinnings due to small stem size ($\approx$0.075 m^3 in Kärhä *et al.*, 2004), low volume removals and dense stands. Kärhä *et al.* (2004) found that in early thinnings, small thinning harvesters could run at the same productivity as medium-sized harvesters for a lower operating cost, so increasing net revenue. The stem volume : processing time relationship was found to be linear and nearly identical for both machine types in smaller trees. The curve steepened sharply at around 0.5 m^3 for smaller harvesters but not until around 1.1 m^3 for the larger harvesters indicating the greater capacity of the larger machines and their ability to work in later thinnings or small final fellings.

With regard to forwarders, Tufts (1997), Gullberg (1997) and Väätäinen *et al.* (2005) all proposed that grapple size and pile size in the drift may be more important to productivity than mean removed tree volume.

Harvesting head calibration and accuracy also has an effect on productivity as inaccurate cutting can cause produce to fail to meet buyer specifications and so be rejected and remain unsold. Makkonen (2001) splits harvesting head error into two; inaccuracy and imprecision. Inaccuracy is caused by poor calibration and leads to a consistent error. Imprecision derives from variable factors such as irregular stem shape, branching and bark texture and operator input and component condition.

Makkonen (2001) notes that the measuring wheel is particularly sensitive to error as bark softness can cause the effective diameter of the wheel to change. Obstacles in the measuring wheel path and sharp taper can also cause length underestimation. Loose bark can also cause the wheel to mis-measure as can poor condition and maintenance of the wheel. Diameter measurement errors caused by poor stem form and insufficient roller pressure are largest, however smaller errors can be attributed to bark peeling and poor delimbing.

Kärhä *et al.* (2004) checked and calibrated the head of the studied harvester against calliper measurement before each study to a claimed accuracy of ± 0.0001 m^3. This seems overly hopeful as the volume of a 496 cm log of top, middle and base diameters 250 mm, 268 mm and 305 mm will drop from 0.288 m^3 to 0.287 m^3 if the length is miss-recorded as 495 cm; a level of measuring inaccuracy commonly found in harvesting (Makkonen, 2001).

4.4.11 Productivity Factor: Operator Experience and Motivation

There is general agreement that operator skill, experience and motivation plays an important part in determining the level of productivity (e.g. Ovaskainen *et al.*, 2004; Lageson, 1996; Kellogg & Bettinger, 1994). Kärhä *et al.* (2004) found this to be true with differences in machine productivity of as much as 40% caused by operators.

Commenting on operator experience is common in time studies, for example Johansson (1996) compares the relative working experience of his three operators and Lageson (1997) notes that both his operators have equivalent competency, so inferring that their work is comparable.

Operator fatigue, both mental and physical, is another important aspect closely linked with motivation. Berger (2003) observes that mental stress in harvester operators can be a problem. Although removed from the direct physical stress experienced by for example chainsaw operators, long working hours at high levels of concentration, coupled with poor rest periods and often the financial responsibility for expensive machinery, can lead to operator stress and a decrease in effectiveness.

4.5 STAND EFFECTS OF MECHANICAL HARVESTING

4.5.1 Residual Stand Damage

Jäghagen & Lageson (1996) note that, for a given thinning intensity, crown thinning will remove fewer trees within a stand, so necessitating fewer boom movements and reducing the chance of damage. Conversely, more trees will be retained in crown thinning so providing less space in which to manoeuvre the boom. Crown thinned trees are also larger, increasing the likelihood they will damage other trees as they are removed and causing the boom to swing more when loaded during felling, again increasing the likelihood of damage. The disadvantages of both thinning types were thought to be roughly equivalent and likely to create similar amounts of damage. This was confirmed by their findings from a study of damage occurring in Scots pine caused by harvester thinning. Damage was grouped into three size classes (<20 cm^2, 20-100 cm^2, >100 cm^2), three location classes (root and stump, root collar to 2 m, >2 m), and two damage severity types (bark peel off, damage to wood). No significant differences were found in damage size and type caused by high and low thinning.

Lageson (1996) reported in a similar situation that again no significant difference was found for damage size and type caused by crown and low thinning. Damage was found to be located higher up the stem for low thinning, the effect thought to be caused by the crown-thinned trees being heavier and therefore more likely to be moved and processed at a lower level than lighter low-thinned trees.

Sirén (2001) found that the mean contact point (not necessarily damaging) was at 450 cm above root collar whereas mean damage height was only 275 cm above root collar. Sirén also found that a mean of 19.3% (range 14.5-25.4%) of tree felling cycles (i.e. the process of felling and processing a tree) involved contacts with other trees. Of the struck trees, one third were removed and of the residual two thirds, 28.2% were damaged.

Factors found to influence the likelihood of contacts were operator, felled tree volume (and hence weight and height) and stand density. The likelihood of damage being caused by a contact was related to season and felled tree volume.

Sirén (2001) also found that the percentage of damaged residual trees varied from 0 to 8.6%, with a mean of 3.4%. Sirén compared this to Swedish mean values (Fröding, 1992) of 5.9% and the Finnish mean (Hartikainen, 1996) of around 4%. He noted that damage levels in North America were often recorded as being higher and accredited this to the use of other harvesting systems and particularly the use of skidders.

Jäghagen & Lageson (1996) and Lageson (1996) both noted that damage is affected by season due to summer sap flow making bark more likely to peel. This was confirmed by Sirén (2001) who found that the likelihood of a blow causing damage to a tree was 1.5 times greater in the summer and that damage area was likely to be the smallest in winter, intermediate in spring and autumn and largest in summer.

4.5.2 Silvicultural Considerations

Elliason (1998) noted that shelterwoods can potentially pose problems to harvesters as retained trees will continue to grow in diameter, (and also height and volume) so nearing or even exceeding machine capabilities.

The development of regeneration within the shelterwood matrix will also place different demands on the harvester if damage to young trees is to be minimised (Eliasson, 1998).

Westerberg & Berg (1994) found that the proportion of seedlings damaged in shelterwood cutting and shelter tree removal was as much as 65%. Similar findings have been published by Glöde & Silkström (2001) who found that around 40% of seedlings were lost in both directional felling methods used although the spatial distribution of damage did change.

Hånell *et al.*, (2000) found that compared with clearfelling, time consumption per tree in establishing shelterwoods was 11-16% greater for harvesters and 5.5-6% higher for forwarders mainly due to the dispersed working. The total harvesting cost for a 15 ha stand was calculated as 11-13% greater in shelterwood cutting, although this difference increased with decreasing stand size.

Eliasson *et al.* (1999) found that harvester productivity of 53.8 and 40.9 m^3 per productive machine hour (m^3/PMH) in shelterwood establishment cutting when removing 58% and 38% of stems from a stand of $\approx$605 trees/ha was 16-36% lower than in comparable clearcuting. These figures compare with those by Hånell *et al.* (2000) in which a 50% reduction in density from ≈600 trees/ha gave productivity 35% lower than that in clearfelling.

CHAPTER 5: HARVESTER STUDY

5.1 INTRODUCTION

The harvesting at Trallwm was organised and supervised by UPM harvesting with work carried out by a harvester–forwarder team sub-contracting to UPM harvesting. The machines began work at Trallwm on the 14th June 2004 and study in the plots commenced on the 15th June 2004.

The harvester studied was a Silvatec 82665TH "Sleipner" equipped with a Loglift 220V/83 crane, providing a nominal reach of 8.3 m with a stated 188 KNm of lifting torque and 43.6 KNm of slewing torque. The harvesting head used was the Silvatec 560, the largest head specified by Silvatec for the Loglift crane and was coupled with the TM2000 measuring and optimisation system, optimising on value (Silvatec, 2006). The Sleipner is a very capable machine, comparable in terms of power and specifications to the Ponsse Ergo and John Deere 1270D & 1470D, and can be used with equal effect in clearfells and large diameter thinnings (Ponsse Oyj, 2006; John Deere, 2006). The harvester was fitted with wheel chains on the rear wheels of each bogie to aid traction.

The machine at time of study was around six months old and the experienced operator was fully adjusted to it.

5.1.1 Aims

5.1.1.1 Study of Harvester Head Accuracy

- To investigate the accuracy of product measurements recorded by the harvester
- To assess the effects of recording error

5.1.1.2 Harvester Study

- To identify differences in harvester working between treatments
- To identify if possible the causes of treatment differences
- To relate harvester working as far as possible to stand parameters

5.1.1.3 Study of Products Cut

- To investigate treatment effects on cut product assortment

- To identify if possible the causes of treatment differences
- To investigate tree primary comminution

5.1.1.4 Study of Rack Use

- To investigate rack use by the harvester
- To assess differences in spatial coverage of the plot by the harvester
- To investigate treatment differences in brash coverage

5.1.2 Literature Review

The literature pertinent to harvester working is reviewed in Chapter 4.

Studies of harvesters are more abundant than those of forwarders. The work of Nurminen *et al.* (2006) is the most current and comprehensive work which can be seen as the successor to that of Brunberg (1997) and Brunberg *et al.* (1989).

Scandinavian studies are numerous including those by Brunberg *et al.* (1989), Lageson (1997), Brunberg (1997), Eliasson (1998), Hanell *et al.* (2000), Siren and Aaltio (2003) and Nurminen *et al.* (2006).

There is also a good selection of North American studies including those by Kellogg & Bettinger (1994), Lanford and Stokes (1996) and Tufts (1997).

5.2 HARVESTING HEAD CALIBRATION AND MEASUREMENT CHECK

5.2.1 Introduction and Method

In order to estimate the accuracy of measurements made by the harvesting head and hence the accuracy of the data in the vehicle data-log, check measurements were made on products cut. Confirmation of the accuracy of the harvester data-log enables the data to be used in volume calculations for both harvester and forwarder and negates the need to manually measure and count produce.

Sample trees, manually measured for calibration checking, were chosen at random by using a timer set to count-down from a random number of minutes and re-measuring the next tree to be cut. Only one to two trees per hectare in thinning plots were sampled as the process led to a disruptive break which, although unlikely to have a follow-on effect on working practice, certainly ceased production for a few minutes. Five trees were re-measured in the clearfell. Sampling was in addition to daily system calibration by the harvester operator. The products cut from the sample tree were identified in the drift and their lengths measured with a tape measure to the nearest centimetre and top diameters measured with calliper (mean of two measurements at right angles) to the nearest millimetre. Measurements were compared against those recorded in the vehicle data-log.

5.2.1.1 Product Specifications

The products cut during the study were defined by the markets open to the harvesting contractors UPM-Tilhill.

A total of six products were cut in the plots and are presented in Table 5.1 with the price per tonne received by the forest owner (£/tonne standing). Although product specifications changed during the thinning operations at Trallwm due to different demands from the sawmill, only the six listed products were cut in the plots so as to maintain continuity and allow comparison.

5.2.2 Data Gathered

The target of two trees sampled per thinning plot was achieved in all except plots 3 and 4 where only one tree was measured. Five trees were measured in the clearfell. Check measurements are presented in Appendix 17.

Table 5.1 Product codes and dimension specifications for harvester time study

Product	Vehicle-log product code	Time study product code	Length (cm)	maximum base diameter (cm)	minimum top diameter (cm)	Sale value to owner (£/tonne)
Log	111	1	495	60	18	£16.90
Small Log	112	2	315	60	18	£14.00
Bar	113	3	375	-	14	£8.65
Small Bar	114	4	254	-	14	£6.70
Stake	115	6	172	13	7.5	£8.00
Pulp	127	5	300	-	8	£0.25

5.2.3 Error

The differences between length and top-diameter values recorded by the harvester and those measured by check measurement are presented in Table 5.2. Negative values represent under-measuring by the harvester and positive values over-measuring.

Mean values show 495 cm log and 375 cm bar lengths were under-recorded on average by 3.1 cm and 0.8 cm respectively. All other products were on average over-recorded with mean values ranging between 0.4 cm in 315 cm logs and 2.0 cm in 254 cm bars.

The highest under-recording of length was by 87 cm for a 495 cm log from tree 672 in plot 7. The highest over-recording of length was by 10 cm for a 172 cm stake from tree 505 in plot 1.

Mean values for diameter show 300 cm pulp and 172 cm stake top diameters were under-recorded on average by 2.4 mm and 0.1 mm respectively. All other products were on average over-recorded with mean values ranging between 0.3 mm in 315 cm logs and 5.0 mm in 254 cm bars.

The highest under-recording of top diameter was by 33 mm for a piece of 300 cm pulp from tree 761 in plot 2. The highest over-recording of top-diameters was by 8 mm for a 172 cm stake from tree 543 in plot 7 and for a piece of 300 cm pulp from tree 573 in plot 5.

No significant differences were found between product types in length recording error [F(5,79)=.615, p=0.689] or in top diameter error [F(5,79)=1.162, p=0.335].

Table 5.2 Summary of the differences between product lengths and top-diameters recorded by the harvester and check measurements

Product		No.	Minimum	Maximum	Mean	Std. Deviation
Log 495cm	Difference in Length (cm)	31	-87.0	4.0	-3.1	16.1
	Difference in Top Diameter (mm)	31	-4.0	6.0	0.8	2.3
Log 315cm	Difference in Length (cm)	9	-1.0	2.0	0.4	0.9
	Difference in Top Diameter (mm)	9	-3.0	4.0	0.3	1.9
Bar 375cm	Difference in Length (cm)	12	-8.0	2.0	-0.8	2.8
	Difference in Top Diameter (mm)	12	-2.0	5.0	1.4	2.4
Bar 254cm	Difference in Length (cm)	2	2.0	2.0	2.0	0.0
	Difference in Top Diameter (mm)	2	4.0	6.0	5.0	1.4
Stake 172cm	Difference in Length (cm)	21	-6.0	10.0	1.0	2.8
	Difference in Top Diameter (mm)	21	-18.0	8.0	-0.1	4.9
Pulp 300cm	Difference in Length (cm)	10	0.0	8.0	1.6	2.6
	Difference in Top Diameter (mm)	10	-33.0	8.0	-2.4	11.6
Total	Difference in Length (cm)	85	-87.0	10.0	-0.7	10.0
	Difference in Top Diameter (mm)	85	-33.0	8.0	0.3	5.0

5.2.4 Proportional Error

The difference between length and top-diameter values recorded by the harvester and those measured by check measurement are presented as a proportion of recorded values in Table 5.3. Under-measurement is again represented by negative numbers and over-measurement by positive numbers.

Mean proportional values show 495 cm log and 375 cm bar lengths were under-recorded on average by 0.62% and 0.22% respectively. All other products were on average over-recorded with mean length values ranging between 0.14% in 315 cm logs and 0.79% in 254 cm bars.

The highest proportional under-recording of length was by 17.54% for a 495 cm log from tree 672 in plot 7. The highest over-recording of length was by 5.81% for a 172 cm stake from tree 505 in plot 1.

Mean values show 300 cm pulp and 172 cm stake top diameters were under-recorded on average by 3.84% and 0.22% respectively. All other products were on average over-recorded with mean values ranging between 0.15% in 315 cm logs and 2.97% in 254 cm bars.

The highest under-recording of top diameter was by 37.93% for a piece of 300 cm pulp from tree 761 in plot 2. The highest over-recording of top-diameters was by 6.25% for a 172 cm stake from tree 543.

Table 5.3 Summary of the proportional differences between product lengths and top-diameters recorded by the harvester and check measurements

Product		No.	Minimum	Maximum	Mean	Std. Deviation
Log 495cm	Length Error %	31	-17.54%	0.81%	-0.62%	3.24%
	Top Diameter Error %	31	-1.91%	3.26%	0.35%	1.06%
Log 315cm	Length Error %	9	-0.32%	0.63%	0.14%	0.28%
	Top Diameter Error %	9	-1.23%	2.00%	0.15%	0.89%
Bar 375cm	Length Error %	12	-2.13%	0.53%	-0.22%	0.74%
	Top Diameter Error %	12	-1.31%	3.33%	0.89%	1.52%
Bar 254cm	Length Error %	2	0.79%	0.79%	0.79%	0.00%
	Top Diameter Error %	2	2.72%	3.23%	2.97%	0.36%
Stake 172cm	Length Error %	21	-3.49%	5.81%	0.58%	1.61%
	Top Diameter Error %	21	-15.52%	6.25%	-0.22%	4.23%
Pulp 300cm	Length Error %	10	0.00%	2.61%	0.52%	0.84%
	Top Diameter Error %	10	-37.93%	4.15%	-3.84%	12.46%
Total	Length Error %	85	-17.54%	5.81%	-0.02%	2.19%
	Top Diameter Error %	85	-37.93%	6.25%	-0.17%	4.88%

5.2.5 Further Analysis

By plotting machine data against check data, two pieces were identified as outliers for length (495 cm log, tree 672, plot 7 and 495 cm log, tree 572, plot 1) and two others as outliers for diameter (300 cm pulp, tree 761, plot 2 and 172 cm stake, tree 672, plot 7). On removal of these outliers the coefficient of determination (R^2) for length increased from 0.9943 to 0.9996 and for diameter from 0.9948 to 0.9984.

Figure 5.1 presents changes in mean and standard deviation of length after the removal of outliers and 5.2 the changes in diameter.

Error data was combined with recorded plot assortment volumes to provide adjusted volume production values for comparison with that recorded in the harvester log. The mean errors for each assortment and their standard deviations were used to calculate adjusted volumes and 95% confidence intervals for each cut piece recorded in the harvester vehicle log.

Volume calculation was achieved through Newton's formula and using the harvester log as described in 5.5.3.5. Newton's formula is defined as:

$$v = \frac{\pi L(d_1^2 + 4d_2^2 + d_3^2)}{24}$$

v = volume of piece (m^3)

L = length of piece (m)

d_1 = diameter of base of log (m)

d_2 = mid-diameter of log (m)

d_3 = top diameter of log (m)

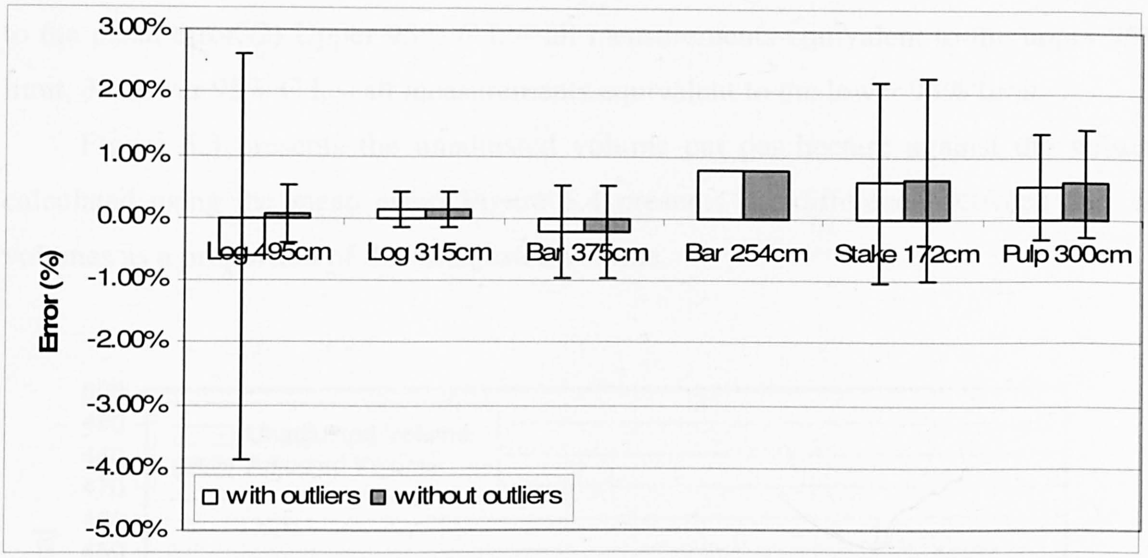


Figure 5.1 Mean percentage error of length measurement before and after removal of outliers. Boxes represent mean values and bars a standard deviation from the mean.

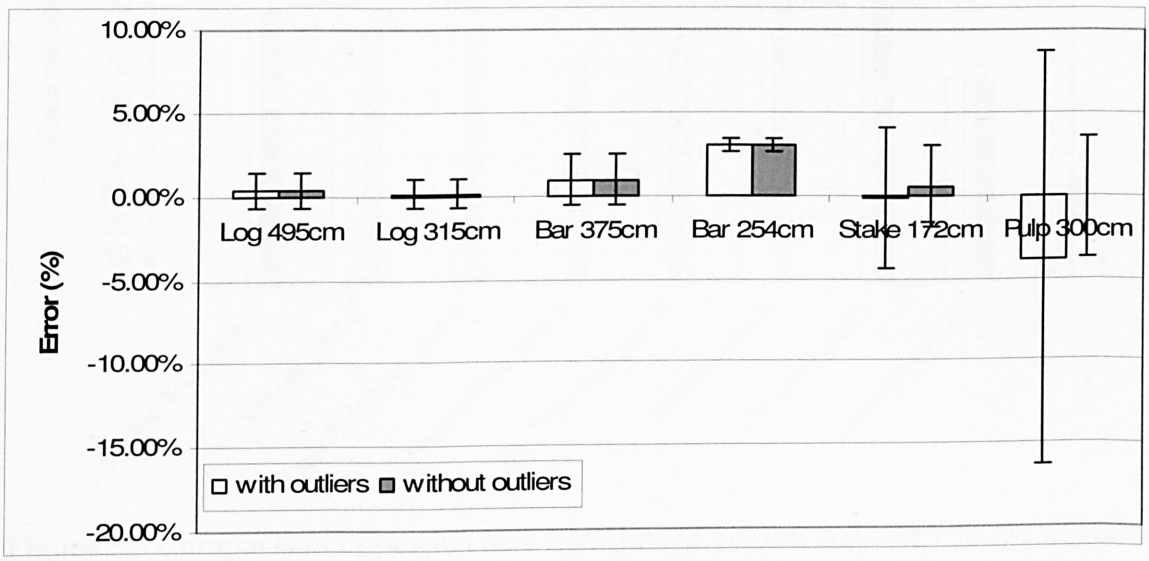


Figure 5.2 Mean percentage error of diameter measurement before and after removal of outliers. Boxes represent mean values and bars a standard deviation from the mean.

Top, middle and base diameters were all adjusted with the top diameter % error and piece length with the length % error (both errors including outliers). The diameters and lengths corresponding with upper and lower 95% confidence intervals were then calculated using 1.96 standard deviations from the mean.

Three volumes were calculated; 1) Mean Volume – all measurements equivalent to the mean error, 2) Upper 95% C.I. – all measurements equivalent to the upper 95% limit, 3) Lower 95% C.I. – all measurements equivalent to the lower 95% limit.

Figure 5.3 presents the unadjusted volume cut per hectare against the volume calculated using the mean error. Figure 5.4 presents the difference between the two volumes as a proportion of the unadjusted volume.

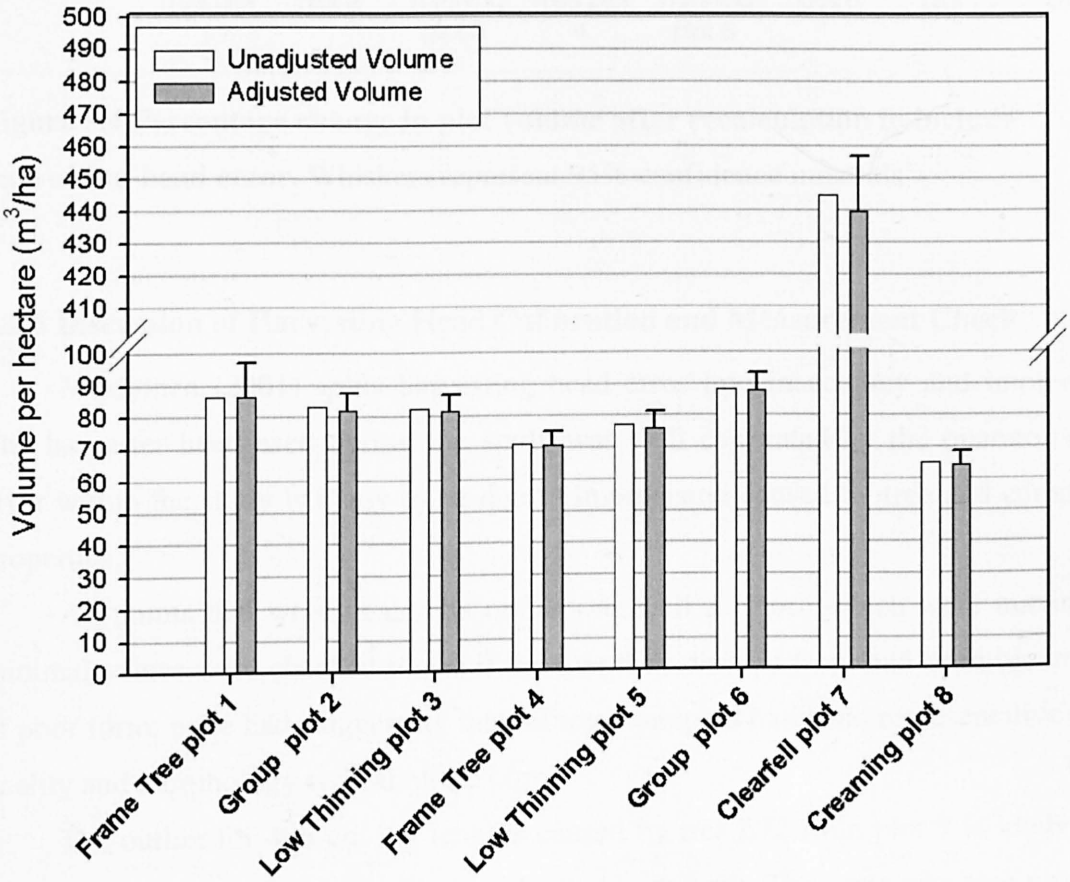


Figure 5.3 Comparison of per-hectare unadjusted volume against volume adjusted for error. Whiskers represent 95% confidence intervals.

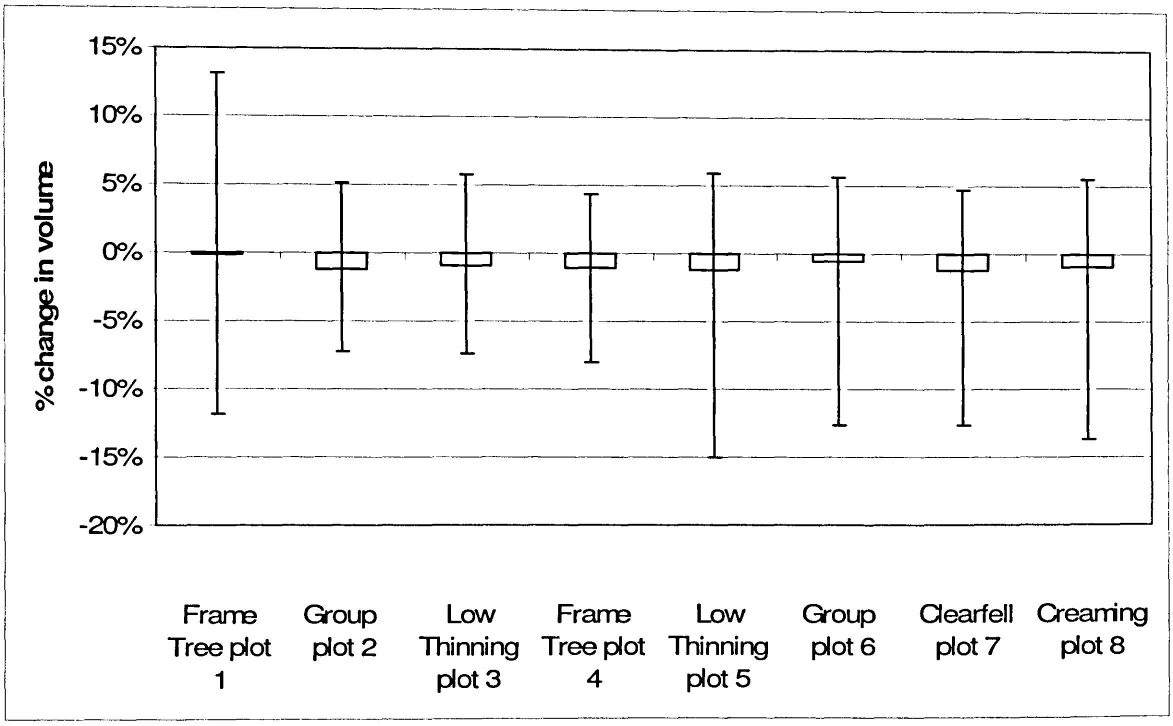


Figure 5.4 Percentage change in plot volume after recalculation to include harvesting-head error. Whiskers represent 95% confidence intervals

5.2.6 Discussion of Harvesting Head Calibration and Measurement Check

Makkonen (2001) splits harvesting head error into inaccuracy and imprecision. The harvester head used during the study was well calibrated by the operator so the error within the study is likely to be due to imprecision caused by tree and component properties.

All points that were treated as outliers as well as those which were maximal or minimal values were checked to see if the tree they derived from had been recorded as of poor form; none had, suggesting that all trees sampled had been representative of the quality and morphology typical of the crop.

The outlier for 495 cm log lengths caused by tree 672 from plot 7 is likely to be due to the measuring wheel becoming clogged with bark. The same tree also produced the 172 cm stake outlier for diameter and although different sensors are involved in diameter measurement, this may be a linked problem.

The measuring wheel had been replaced due to its tendency to clog with bark before plot 1 was thinned: the second 495 cm log outlier should therefore be due to another problem. The measuring wheel is however, as noted by Makkonen (2001), very sensitive to errors caused by tree morphology.

The second diameter outlier was caused by a piece of pulp. As pulp is only cut where no higher quality product is possible the pieces are often rough and it is therefore of little surprise that some measurements were thrown off.

Mean errors in all produce types were within working tolerances for the situation, product values ranging between 0.14% and 0.79% for length and 0.5% and 3.84% for diameter. Variance was higher than desirable due to the previously described outliers.

Product length was measured to within ±5 cm in 92% of cases and confidence intervals suggest that 95% of length measurements were within ±8.39 cm of target values and diameter measurements within ±8.87 mm. The limits on length given by BSW sawmilling is ±5 cm from the product specification e.g. 490 – 500 cm for a 495 cm log. The maximum standard product length sawn is 480 cm which provides 10 cm of buffer from specified values. Whilst head accuracy could have been better, no rejections of loads or complaints were made by the sawmill or other markets, leading to the conclusion that errors lay within acceptable working tolerances.

The mean volume error throughout the plots is 0.89%, varying between 0.14% in plot 1 and 1.22% in plot 5; equivalent to only 0.1 to 0.8 m^3/ha in the thinning plots and around 4.5 m^3/ha in the clearfell.

The error is certainly greater than the head accuracy of ±0.0001 m^3 claimed by Kärhä *et al.* (2004) but as stated in Chapter 4, this claimed accuracy seems too high. The mean error does compare well with those described by Makkonen (2001) and also with those of Nieuwenhuis & Dooley (2006), although variance was greater in the Trallwm study.

5.3 PRODUCTS CUT

5.3.1 Summary of Products Cut

A summary of products cut within the plots is presented in Appendix 18. The number of pieces of each product cut is presented in Figure 5.5, volume cut per hectare is presented in Figure 5.6 and revenue per hectare is presented in Figure 5.7.

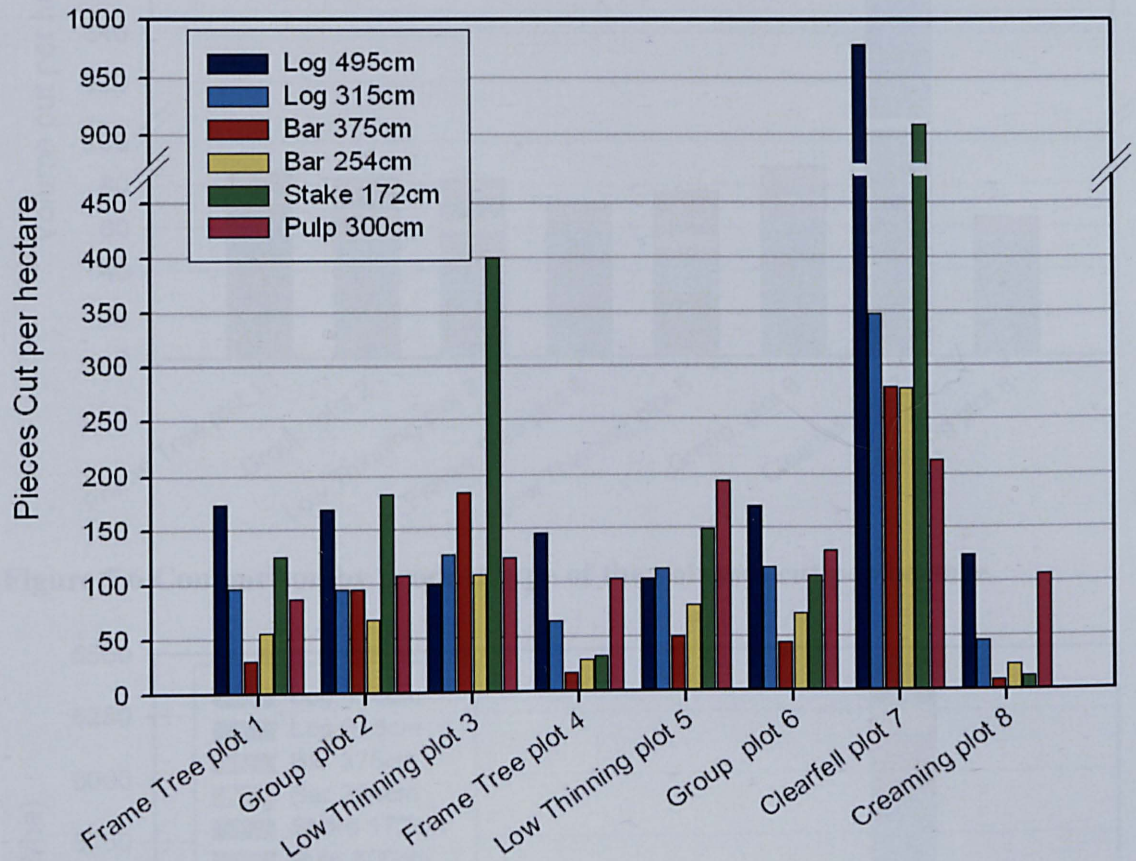


Figure 5.5 Comparison by product type of the number of pieces cut per hectare

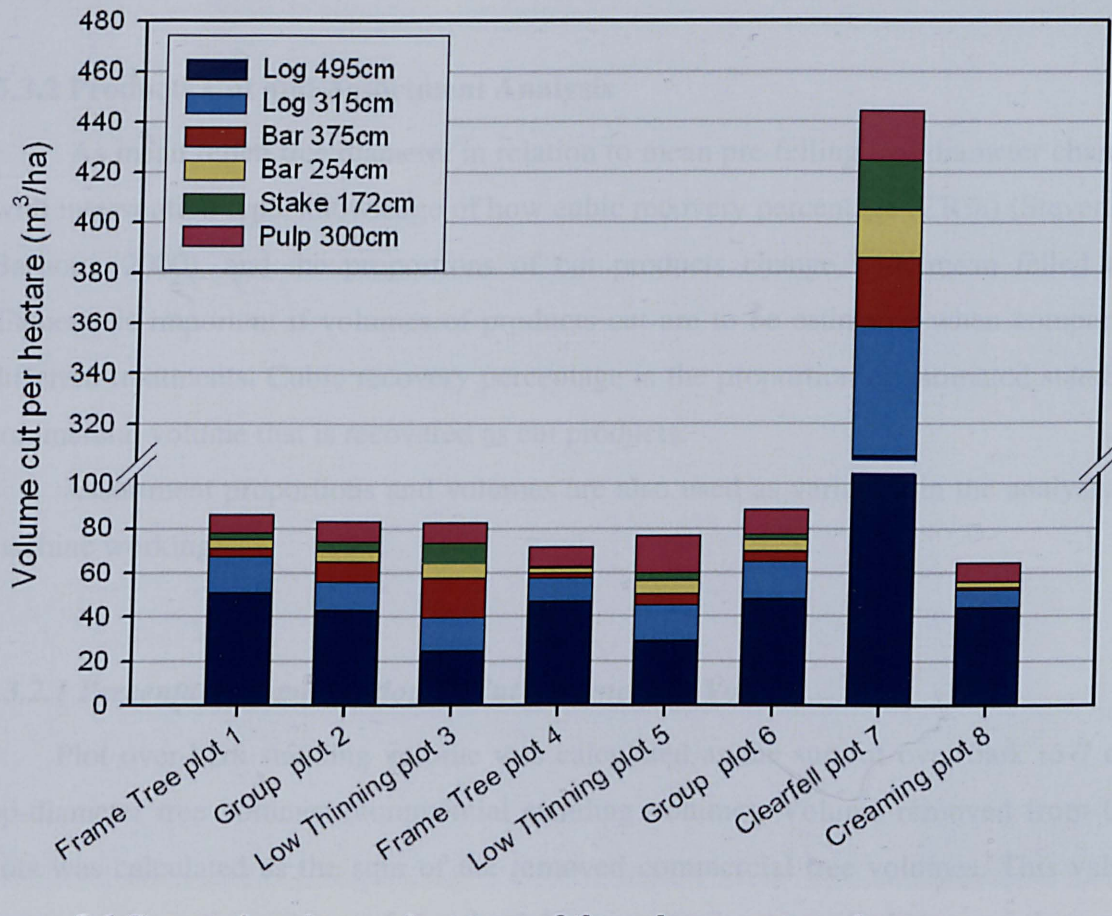


Figure 5.6 Comparison by product type of the volumes cut per hectare

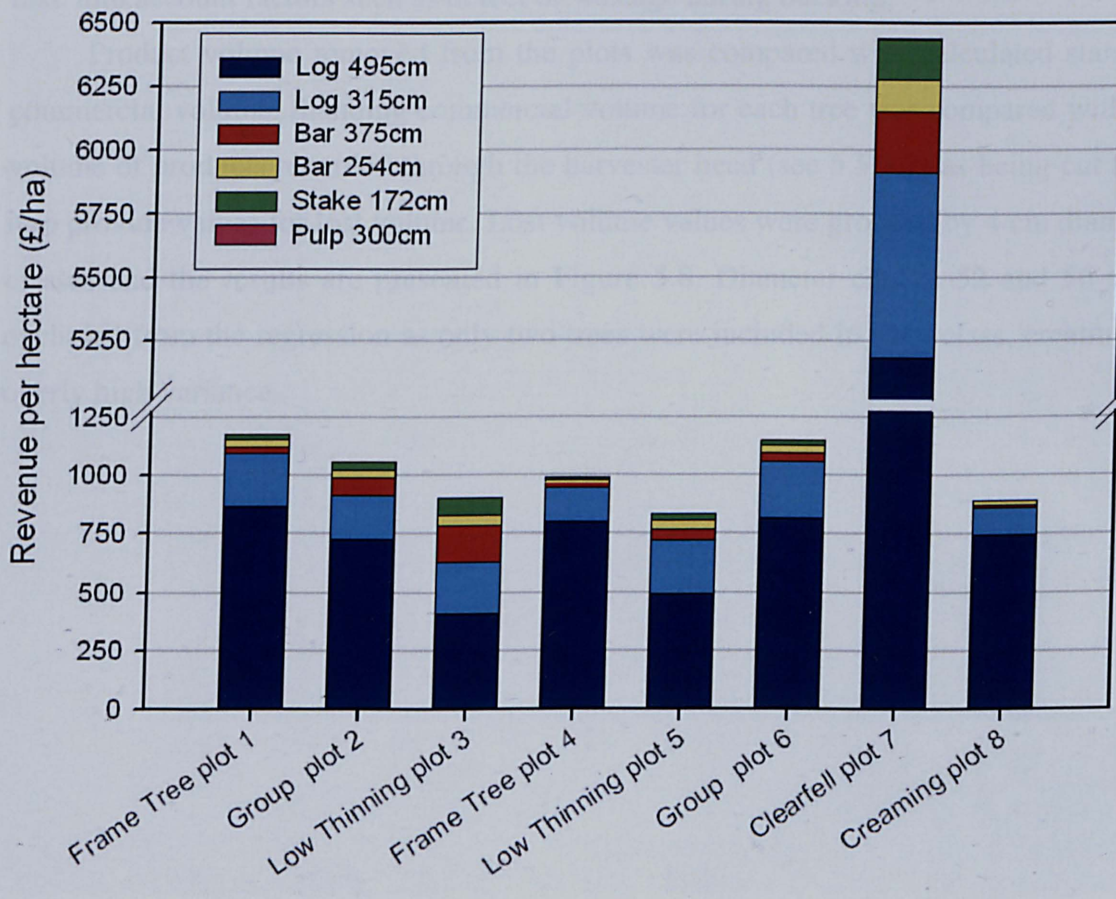


Figure 5.7 Comparison by product type of revenue per hectare

5.3.2 Products Cut and Assortment Analysis

As mean felled tree diameter in relation to mean pre-felling tree diameter changes with intervention type, knowledge of how cubic recovery percentage (CR%) (Stevens & Barbour, 2000), and the proportions of cut products change with mean felled tree diameter is important if volumes of products cut are to be estimated when comparing different treatments. Cubic recovery percentage is the proportion of estimated standing commercial volume that is recovered as cut products.

Assortment proportions and volumes are also used as variables in the analysis of machine working.

5.3.2.1 Percentage Comminution of Cut Commercial Volume

Plot over-bark standing volume was calculated as the sum of over-bark to 7 cm top-diameter tree volumes (commercial standing volume). Volume removed from the plots was calculated as the sum of the removed commercial tree volumes. This value represents the entire volume of merchantable size (to 7 cm top-diameter and does not take into account factors such as defect or wastage during bucking.

Product volume removed from the plots was compared with calculated standing commercial volume. Standing commercial volume for each tree was compared with the volume of products recorded through the harvester head (see 5.5.3.2) as being cut from it to provide values for lost volume. Lost volume values were grouped by 4 cm diameter classes and the results are presented in Figure 5.8. Diameter classes 52 and 56 were excluded from the regression as only two trees were included in each class, creating an overly high variance.

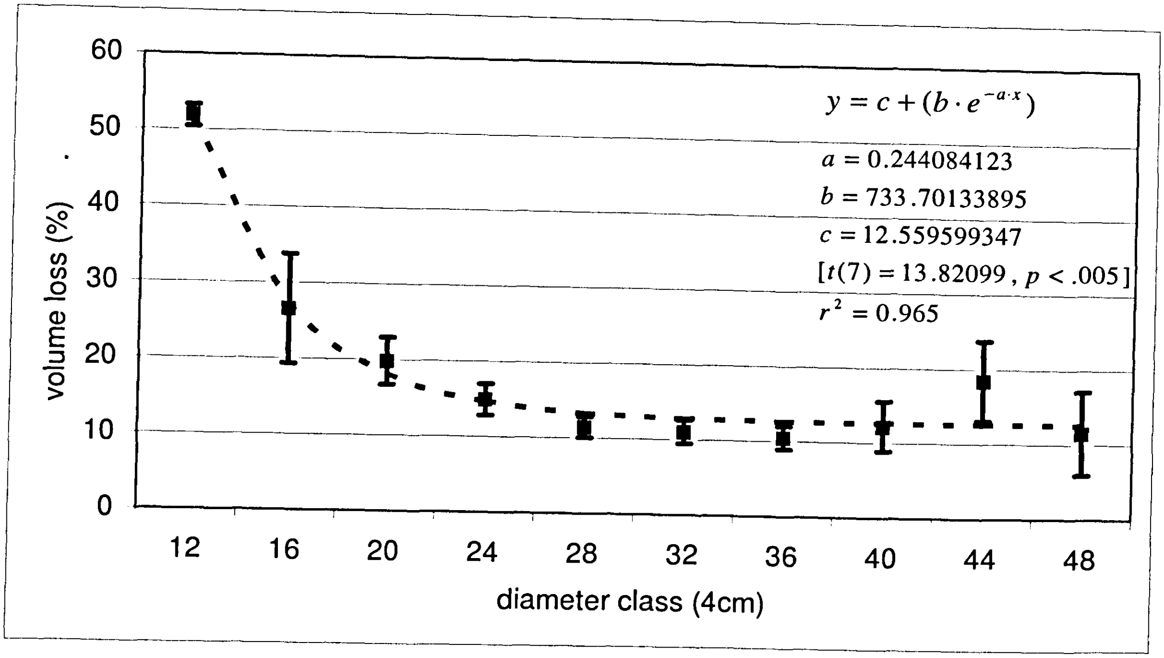


Figure 5.8 Calculated proportional loss of commercial standing volume during primary processing

Mean values are presented with 95% confidence intervals, dotted line represents regression

Figure 5.8 shows that with increasing diameter and hence tree volume, percentage loss of volume decreases, stabilising at around 12.5%. Volume loss per tree in absolute terms actually increases with diameter as can be seen in Figure 5.9, rising from around 0.075 m^3 in the smaller diameter classes to around 0.25 m^3 in the larger ones. Mean plot values of proportional and per-tree volume loss are presented in Table 5.4.

Table 5.4 Plot mean proportional and absolute volume loss

	Frame 1	Group 2	Low 3	Frame 4	Low 5	Group 6	Clearfell 7	Creaming 8
Mean removed tree dbh (cm)	32.1	27.2	23.8	33.6	27.4	30.6	32.0	36.2
Mean volume loss per tree (%)	6.0	7.7	19.2	10.2	13.1	12.1	15.9	11.6
Mean volume loss per tree (m^3)	0.06	0.05	0.09	0.09	0.08	0.10	0.16	0.11
Plot volume loss (m^3/ha)	5.74	6.64	17.64	8.33	11.02	12.20	53.26	8.61

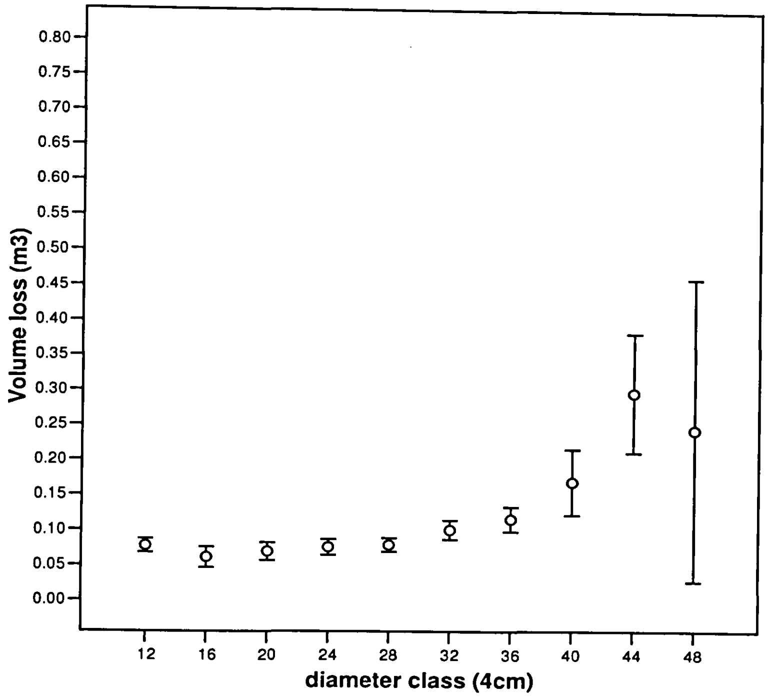


Figure 5.9 Calculated loss of commercial standing tree volume during primary processing

Mean values are presented with 95% confidence intervals

5.3.2.2 Proportional Distribution of Product Types

As has been discussed in chapter 2, the plot diameter distributions were significantly different, the plots had differing site indices and differing stocking densities. This disparity in plot attributes means that the plots and their outputs – the initial results in 5.3.1 - cannot be compared simply. As a method of mediating plot differences, volume of products cut are presented as a proportion of total plot cut volumes in Figure 5.10, although this still does not fully mediate for the significant differences in diameter distributions.

When the proportion of log material ($P_v^{495+315}$) (495 cm + 315 cm) is compared to thinning types as described by SG ratio a significant relationship is found ($P_v^{495+315} = 1.257 - 0.4967\text{SG}$), [F(6)=13.83, p=0.01) indicating a strong link that explains 69.7% of variance.

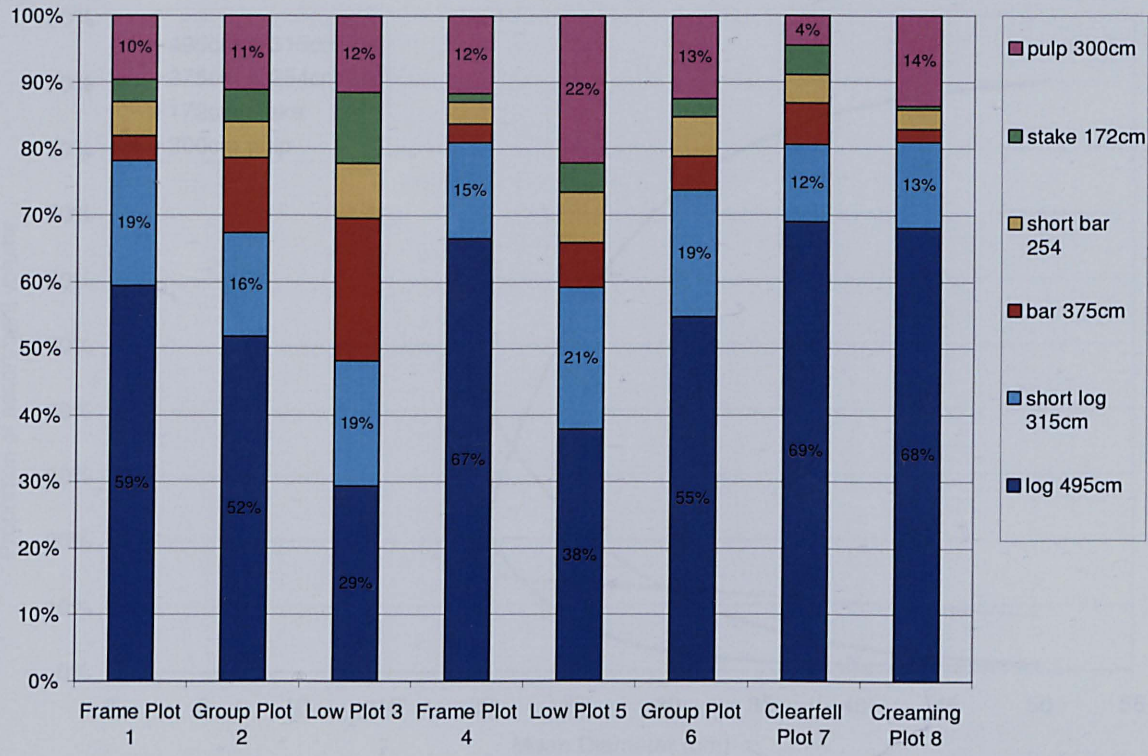


Figure 5.10 Comparison by product type of volume cut as a percentage of total volume cut

5.3.2.3 Proportional Distribution of Product Types in Relation to Felled Tree Characteristics

Individual tree assortment data were pooled by plot and 5 cm tree dbh classes. Arithmetic mean cut-tree diameter ($\overline{d}_{thin}$) was calculated for each plot diameter class as the independent variable and the proportion of total cut volume from the plot diameter class for each product type ($_{dclassY}\,p_v^{productX}$) was calculated as a dependent variable. Total log proportion (495 cm + 315 cm; $P_v^{495+315}$) and total bar proportion (375 cm + 254 cm; $P_v^{375+254}$) were also calculated as dependent variables. Raw distributions can be found in Appendix 18.

Curves were fitted to the distributions through non-linear and linear regressions. Both amalgamated log and bar data provided better regressions over those of individual product types and so were selected in preference. Curves generated from the regressions are presented in Figure 5.11 and the regression functions, parameters and statistical significance presented in Table 5.5. Raw data points can be found in Appendix 19.

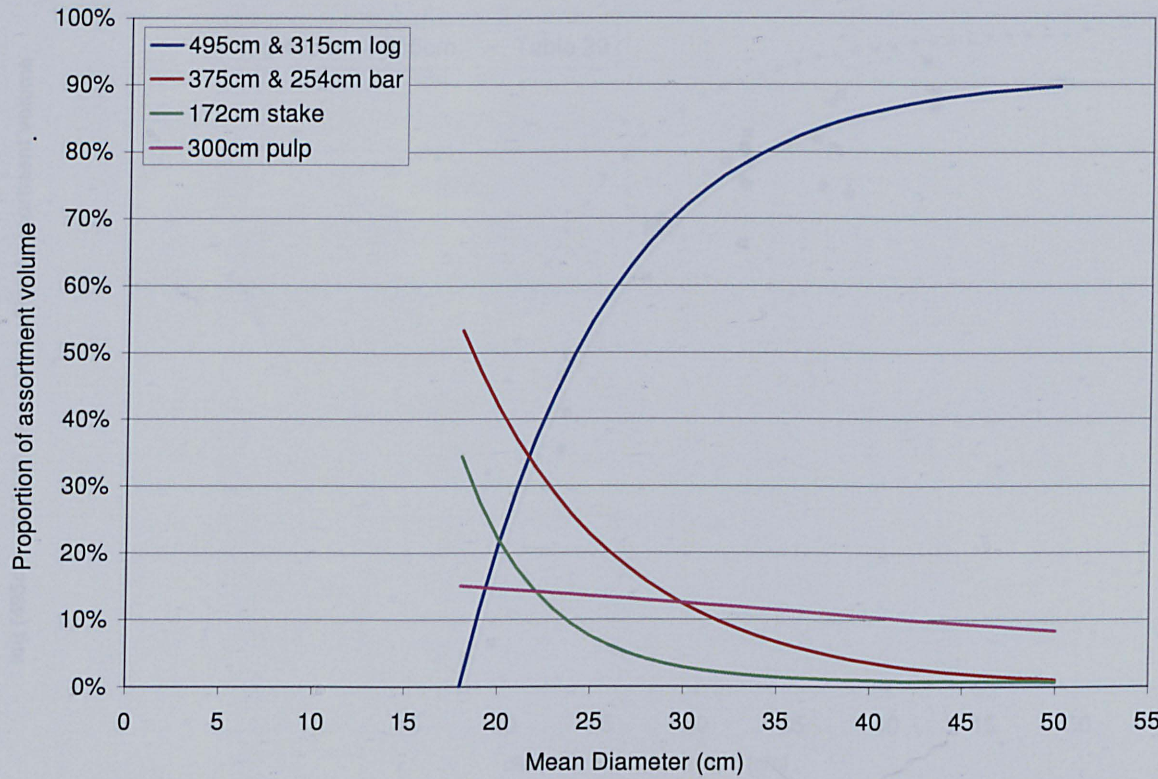


Figure 5.11 Calculated volume assortment curves

Due to the poor regression gained between pulp proportion and mean felled tree diameter class, mean felled tree height ($\bar{h}_{thin}$) was investigated as an alternative independent variable and a multiple regression was then performed using $\bar{d}_{thin}$ and $\bar{h}_{thin}$ as the independent variables as a replacement for volume to take into account differing site indices.

The results were compared to find the best predictor variables using the Akaike Information Criterion (AIC) (Burnham & Anderson, 2002; Akaike, 1981). Results are presented in Table 5.6. The presented Akaike weight values (w_i) describe the reliability of the regression models, smaller values of residual sum of squares and fewer model parameters increasing Akaike scoring (w_i). The highest w_i values indicate the most statistically robust models, showing the best fit for the fewest parameters used.

The calculated log curve was plotted against published figures for single tree overbark volume assortment tables (Matthews & Mackie, 2006; Hamilton, 1975) as a comparison of output. Data were drawn from Table 29 of the Forest Mensuration Handbook for total log volume (no minimum length) as a percentage of total overbark volume to a specified overbark top diameter of 18 cm, the minimum top diameter of log material. The comparison is presented in Figure 5.12.

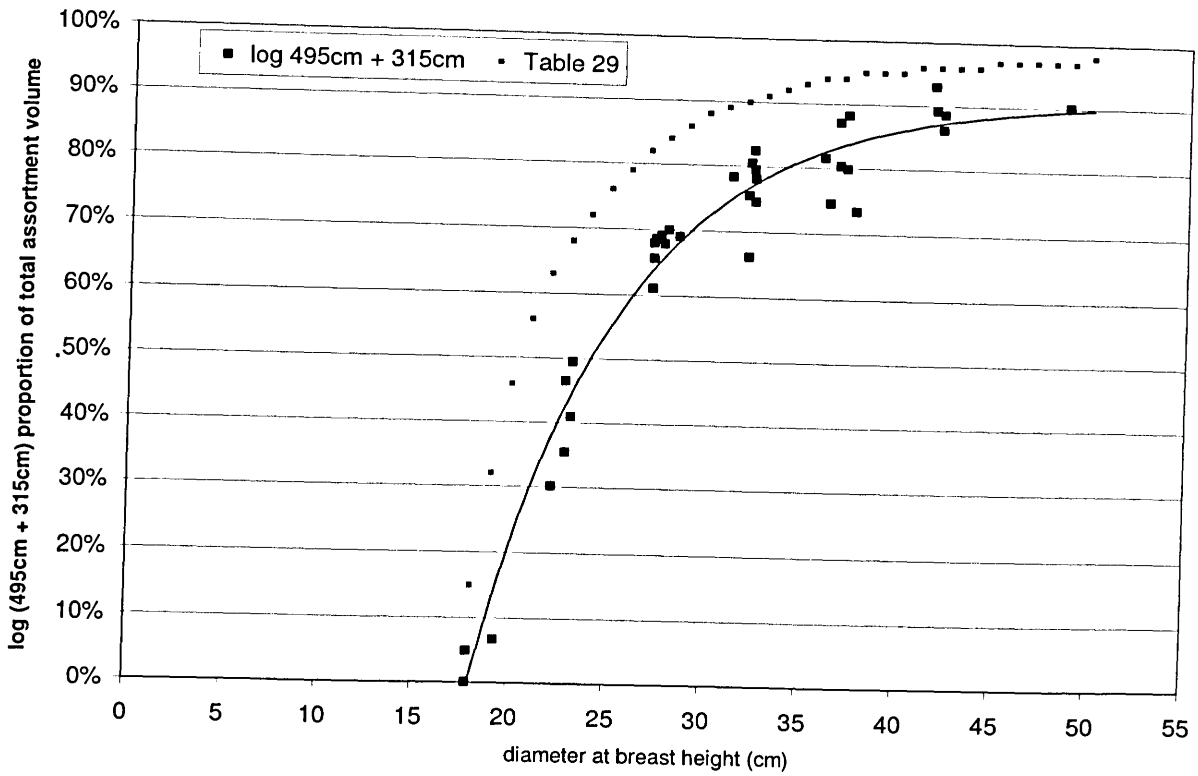


Figure 5.12 Comparison of derived log proportion relationship to generic published data

Table 5.5 Volume assortment regression function summary

DEPENDENT VARIABLE	INDEPENDENT VARIABLE	FUNCTION	PARAMETERS		R^2	Sig.
$p_v^{495+315}$	$\bar{d}_{thin}$	$y = a \cdot (1 - e^{-b \cdot (x+c)})$	a b c	0.9114 0.1305 -17.9751	0.9674	<.005
$p_v^{375+254}$	$\bar{d}_{thin}$	$y = b \cdot e^{-a \cdot x}$	a b	0.1216 4.7602	0.9365	<.005
p_v^{172}	$\bar{d}_{thin}$	$y = c + (b \cdot e^{-a \cdot x})$	a b c	0.2272 20.9174 0.0082	0.9642	<.005
p_v^{300}	$\bar{d}_{thin}$	$y = a \cdot x + b$	a b	-0.0021 0.1875	0.0660	0.124

Table 5.6 Summary of univariate and bivariate linear regressions for proportional volume of 300cm pulp in relation to mean cut diameter and height

Dependent Variable	Independent Variable	R^2	D.F	F	Sig.	Intercept	Slope	Slope $\bar{d}_t$	Slope $\bar{h}_t$	Residual Sum of Squares	n	p	AIC	Delta AIC	Akaike Weights (Wi)
p_v^{300}	univariate														
	$\bar{d}_{thin}$	0.066	35	2.490	0.124	0.1880	-0.0021			0.131	36	4	-194.18	11.19	0.00
	$\bar{h}_{thin}$	0.315	35	16.088	0.000	0.3800	-0.0110			0.096	36	4	-205.37	0.00	0.65
	bivariate														
	$\bar{d}_{thin}$ $\bar{h}_{thin}$	0.332	2,34	8.444	0.001	0.3880		0.001	-0.014	0.094	36	5	-204.13	1.24	0.35
	$\bar{d}_{thin}$	0.017			0.359										
	$\bar{h}_{thin}$	0.265			0.001										

5.3.2.4 Product Volume in Relation to Tree Diameter

The relationship between piece volume and tree size was investigated to facilitate forwarder analysis as piece volume is an important variable in the forwarder study.

For each plot, felled tree data were separated into 5 cm dbh classes and the arithmetic mean diameter of each class was calculated. The mean volumes of the six products produced in each class were then calculated and plotted against class diameter. This was also carried out with combinations of logs (both 495 cm and 315 cm) and bars (375 and 254 cm). Plotted data are presented in Appendix 20 and the eight linear regressions are summarised in Table 5.7. All regressions were highly significant and showed that mean product volume rises with tree diameter.

Table 5.7 Summary of linear regressions of piece volume as a function of felled tree diameter

Dependent Variable	R^2	D.F	F	Sig.	Intercept	Slope
log 495	0.969	31	963.78	0.000	-0.1240	0.0131
log 315	0.735	33	91.50	0.000	0.0069	0.0045
bar 375	0.528	35	39.22	0.000	0.0635	0.0014
bar 254	0.408	35	24.16	0.000	0.0423	0.0009
stake 172	0.235	34	10.47	0.003	0.0183	0.0001
pulp 300	0.413	35	24.66	0.000	0.0360	0.0015
log 495 + 315	0.972	33	1150.84	0.000	-0.1124	0.0109
bar 375 + 254	0.197	35	8.56	0.006	0.0700	0.0005

5.3.3 Discussion of Products Cut and Assortments

Cubic recovery percentage (CR%) (Stevens & Barbour, 2000) was found to increase with tree diameter. Published work (e.g. ChungMin *et al.*, 2006; Lowell & Green, 2001; Stevens & Barbour, 2000) agrees that CR% increases with tree diameter but tends to focus on recovery after secondary or tertiary processing by sawing and milling. No published data has been found on CR% after primary processing i.e. cutting of products by the harvester. Lowell & Green (2001) present an increasing non-linear relationship of CR% to log top diameter of a similar form to that given in 5.3.2. Whilst the regression for CR% in primary processing shows an increase with diameter which levels at around 30 cm, some doubt exists over the validity of extrapolation. The regression was only carried out for diameter classes to 48 cm as there were too few samples in larger classes. The form of the curve for diameters in excess of 50 cm is uncertain. In current British working there is likely to be a decrease in CR% as trees approach and exceed 60 cm due to butt-log end diameter exceeding the British 60 cm limit for sawmilling and butt trimming being used to produce merchantable logs. It should also be noted that whilst CR% increases with diameter and percentage wastage decreases, the absolute wastage volume increases.

The proportional assortment volume distributions shown in figure 5.11 and the significant relationship described between the proportion by volume of log produced from a plot and its thinning index, show that thinning type does have an effect; crown thinning producing a greater proportion of log than low thinning.

Thinning type does not fully explain product assortment however, as is very obvious when the "neutral" intervention (SG=1) of the clearfell is compared with the extreme crown thin of plot 8 (SG=.74), both plots producing the same proportion of log material. This effect is likely to be due to the different plot diameter distributions.

Mean felled tree diameter is a much better predictor of product assortment than thinning type as can be seen in Table 5.4 by the significant regressions achieved with high R^2 values.

Amalgamating within log and bar types provided a single expression for each type of better fit than either of its two components. The cutting of 315 cm logs and 254 cm bars was only carried out when the more profitable 495 cm logs and 375 cm bars could not be cut instead. The combination of the products improves the estimation of the proportion of the stem of greater than 18 cm or 14 cm diameter, the minimum top diameter for logs and bars respectively, by effectively reducing the minimum piece length from 495 cm to 315 cm for logs and from 375 cm to 254 cm for bars.

The reason for proportional assortment output being highly correlated with thinning index is that it describes the mean felled tree diameter in relation to pre-felling mean diameter. As there were statistically significant differences between plot diameter distributions, the regression was not as well defined as with purely diameter, but plots were similar enough to produce an R^2 of 0.697.

Figure 5.11 shows that with increasing mean felled tree diameter, proportion of log increases whilst all other products decrease. The rise in log proportion is due to tree height:diameter ratios tending to decrease with size. As log proportion rises, all other assortment proportions must fall.

The yield of pulp is the most poorly defined of the products, probably reflecting its random nature. Pulp can be produced from nearly any part of the tree, being more associated with stem defect rather than diameter. Although the pulp proportion does decline with increasing diameter, it does so at a slower rate than bar and stake proportions.

Comparison in Figure 5.12 of calculated log proportion to published figures (Matthews & Mackie, 2006; Hamilton, 1975) shows lower values throughout the diameter range in this study. The relationship represents log proportion of productively cut timber and so does not include any trimming or unproductive portions of cut stems (i.e. CR% is included in the volume value). In contrast the published curve represents the proportion of total tree commercial volume with a diameter greater than 18 cm, and no account is made for CR%. This would logically lead to the calculated line being above that of the published data. The published data does not have a minimum piece length however, meaning that all stem volume below 18 cm top diameter is included. The calculated curve in comparison can only include lengths of stem divisible by 495 cm or 315 cm, so reducing proportional values. It can therefore be concluded that flexibility in cutting to length was a more important factor than unproductive volume loss. The form of the two curves is very similar and both have similar x intercepts, of 17.00 cm and 17.97 cm diameter respectively. The published data are generic for all conifer crops so differences may also be partly attributed to species and stand differences.

Mean piece volume rose significantly with diameter for all product types. The rise is understandably largest in the logs; being cut from lower in the tree, changes in diameter are likely to have a greater effect. All other product types were found to rise as well, although the rate of rise was not as high as for logs. This suggests that diameter increase has a significant effect even in cutting products such as stakes from the tree tip. The secondary products, 315 cm logs and 254 cm bars, show poorer relationships with diameter than the primary products, 495 cm logs and 375 cm bars. This is probably due to the secondary products being cut when defect made it impossible to cut the higher revenue primary products, the defect adding a degree of stochasticity to the diameter : proportion relationship. The relationship between mean stake volume and tree diameter is also likely to be poorer than that for 495 cm logs due to the stakes being cut from the tip of the tree, far removed from diameter at breast height.

5.4 RACK USAGE AND SURVEY

Study of rack usage by the harvester allows spatial analysis of working to be carried out and treatment differences to be compared. Ineffective brashmat production is named in the literature as being a problem in CCF working (e.g. Mason *et al.*, 1999). Analysis of brashmat production allows comment on the effect of treatment on this operational aspect. Plot rack-use values are also used as variables in the analysis of vehicle working. Forwarder movement distance is covered in 6.5.1.

5.4.1 Introduction and Method

As described in 2.3.2 the racks within the plots were surveyed prior to harvesting. Rack usage and brash lay-down was recorded to investigate harvester movement in relationship to treatment. Vehicle movement was measured as it has a large influence on productivity.

After the harvester had passed through the plot and before forwarding had begun, rack usage was recorded. Existing racks were surveyed from their starting point for harvester use, identified by the tyre tracks left by the vehicle. A measuring wheel was used to measure along the rack to the nearest metre and a record was made of rack use and brash-mat cover. Rack usage was divided into four classes: Used Process, Used Access, Not Used and Rack Crossing. Used Process was rack that had been travelled on for the purpose of harvesting whereas Used Access was rack travelled only in order to gain access to a neighbouring plot. Where two racks crossed the one with the lowest identification number was given precedence and counted in full with any brash mat allocated to it, the section of the other which was common to both was classed as Rack Crossing and was counted only for length.

Brash-mat cover was defined as brash covering the width of the travelled rack to a depth that fully obscured a view of the ground beneath and was recorded as absent or present.

Where the harvester had travelled in the matrix the resultant path was classified as a track. The point at which a track joined with a rack was noted during the measuring wheel survey and a sketch-map annotated. Where tracks did not join two racks, the bearing of the track from its start point was noted. Tracks were measuring-wheel surveyed in the same manner as racks for brash coverage.

Re-survey of the clearfell plot was not possible as all survey points were lost during the operations leaving no reference points.

Rack use information was used to create an ArcView theme based on the rack maps described in section 2.3.2. The rack use theme shows used racks, rack sections and newly created tracks.

5.4.2 Summary of Rack Usage

Rack and track usage within the plots is presented in Table 5.8 as absolute and per hectare values. Rack use and track creation is presented by maps in Appendix 21.

As no re-survey of the clearfell plot was possible, all existing rack within the plot was classified as unused and no estimation was made on the length of track created.

Rack use ranges from 557 m/ha in plot 2 to 735 m/ha in plot 1, with a mean value of 646 m/ha and standard deviation of 65.7 m/ha. Plots 1 and 2 lie 1.36 and 1.35 standard deviations away from the mean respectively and plot 8 lies 1.07 standard deviations above the mean, all other plots lie within a standard deviation from the mean.

Tracks were used in all plots except plot 4, the greatest use being in plot 1 where 126 m/ha were used and the least being in plot 6 where 15 m/ha were used. The mean length of track used was 42 m/ha, standard deviation 42.7 m/ha, with all plots being within a standard deviation of the mean with the exception of plot 1 which had a value 1.97 standard deviations higher.

Table 5.8 Summary of plot rack and track usage and of brash lay-down

Absolute values presented above per hectare values in brackets

all figure in metres	Frame Tree plot 1	Group System plot 2	Low Thinning plot 3	Frame Tree plot 4	Low Thinning plot 5	Group System plot 6	Clearfell plot 7	Creaming plot 8
Plot Area	1.00	1.00	0.94	1.00	0.99	1.00	0.68	1.00
Total Rack Length (per ha)	1284 (1284)	1080 (1080)	1192 (1266.1)	1124 (1124)	1037 (1047.4)	1109 (1109)	760 (1117.2)	1133 (1133)
Unused Rack (per ha)	549 (549)	523 (523)	611 (649)	468 (468)	386 (389.9)	527 (527)	760 (1117.2)	417 (417)
Total Used Rack (per ha)	735 (735)	557 (557)	581 (617.1)	656 (656)	651 (657.5)	582 (582)		716 (716)
Used Rack: Mat Present (per ha)	258 (258)	242 (242)	329 (349.4)	291 (291)	290 (292.9)	322 (322)		297 (297)
Used Rack: Mat Not Present (per ha)	477 (477)	315 (315)	252 (267.7)	365 (365)	361 (364.6)	260 (260)		419 (419)
Total Track (per ha)	126 (126)	57 (57)	53 (56.3)	0 (0)	21 (21.2)	15 (15)		19 (19)
Track: Mat Present (per ha)	45 (45)	20 (20)	21 (22.3)	0 (0)	16 (16.2)	4 (4)		0 (0)
Track: Mat Not Present (per ha)	81 (81)	37 (37)	32 (34)	0 (0)	5 (5)	11 (11)		19 (19)

5.4.2.1 Proportional Rack Use

The proportion of racks used within plots varied between 63% in plot 8 and 49% in plot 3, the mean being 56% with a standard deviation of 6%. The proportions used in plot 8 and plot 6 were 1.22 and 1.15 standard deviations above the mean respectively with plot 3 using 1.35 standard deviations less. All other plots lay within a standard deviation. Values are presented in Table 5.7.

5.4.2.2 Analysis of Rack Usage

Total rack usage (L_{used}^{rack}) is not well correlated with the length of rack existing in plots before the intervention (L_{total}^{rack}) ($L_{used}^{rack} = 0.2989 L_{total}^{rack} + 302.4$, R^2=0.17).

A significant relationship [F(1,6)=8.408, p=0.027] does exist however, between total rack usage (L_{used}^{rack}) and intervention type as described by the SG ratio ($L_{used}^{rack} = 966.062 - 284.592SG$, R^2=0.584). The effect of the relationship is considerable, suggesting a decrease in rack use of 182 m/ha for a change in SG from 0.74 to 1.38 (crown thin to low thin).

A strong trend was also found between proportional rack usage ($L_{\%used}^{rack}$) and SG ratio ($L_{\%used}^{rack} = 0.751 - 0.170SG$, R^2=0.441) although it is not significant [F(1,5)=3.942, p=0.104]

There is no significant relationship between the length of track used per hectare (L_{total}^{track}) and the length of rack used per hectare (L_{used}^{rack}) ($L_{total}^{track} = 0.2002 L_{used}^{rack} - 87.23$, R^2=0.0949), or the thinning type as described by the SG ratio ($L_{total}^{track} = -8.688SG + 51.192$, $R^2 = 0.002$).

5.4.3 Plot Area Coverage

In order to assess the area of the plots effectively covered by the harvester during working, the rack-use theme in ArcView, which included tracks used by the harvester, was buffered to the distance of the harvester boom (8.3 m) to create a polygon which was then trimmed to the plot boundary. Area coverage maps are presented in Appendix 22, and Figure 5.13 presents the area of each plot effectively covered by the harvester. The area consists of both plot matrix and rack area. The mean coverage was 89.9% with a standard deviation of 2.9%. Plot 1 has the lowest coverage of 85.3%, 1.56 standard deviations below the mean and plot 3 has the highest coverage of 92.6%, 0.96 standard deviations above the mean. Plot 2 has a coverage of 1.30 standard deviations below the mean whilst all other plots are within a standard deviation.

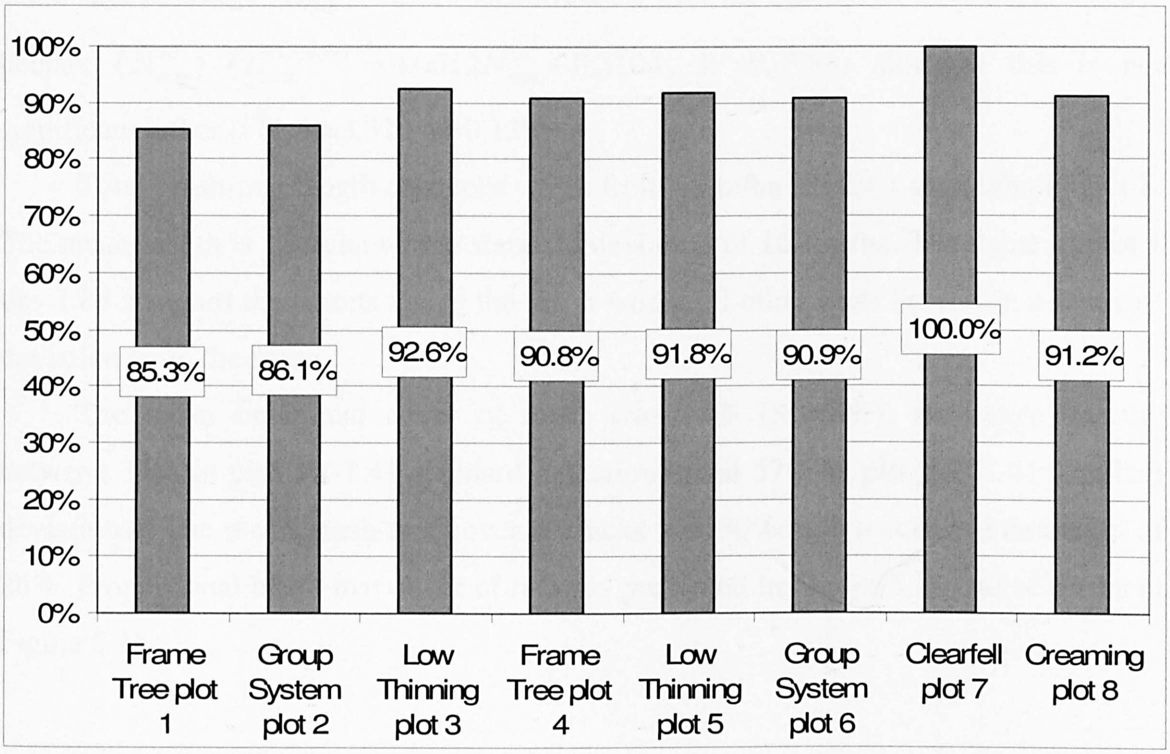


Figure 5.13 Effective percentage area coverage of plots by the harvester during harvesting

5.4.4 Analysis of Brash Lay-down

A one-way analysis of variance was used to compare the length of brash-mat segments between plots and no statistically significant difference was found at the $p<.05$ level [$F(6,377)=1.106, p=0.358$].

This was repeated, analysing rack and track data separately and again no significant differences were found; Rack (after logarithmic transformation) [$F(6,356)=1.401, p=0.213$] (M=5.59m, SD=4.25m, range 1-34m) and Track [$F(6,17)=2.533, p=0.091$] (M=3.17m, SD=2.533m, range 1-9m).

Total length of rack brash-mat varies from 349 m/ha in plot 3 to 242 m/ha in plot 2. The mean plot length of brash-mat is 293 m/ha with a standard deviation of 36.2 m/ha. Plot 3 and plot 2 values lie 1.55 and 1.41 standard deviations from the mean whilst all other plots are within a standard deviation.

Total length of brash mat ($L_{total}^{brashmat}$) is best correlated with the number of trees harvested per hectare (N_{thin}^{ha}) ($L_{total}^{brashmat} = 0.4089N_{thin}^{ha} + 241.65$, R^2=0.2148), although this relationship is not significant [F(1,6)=1.368, p=0.409]. The proportion of rack brash-mat coverage ($L_{rack}^{\%brashmat}$) is best correlated with the number of trees harvested per hectare (N_{thin}^{ha}) ($L_{rack}^{\%brashmat} = 0.0012N_{thin}^{ha} + 0.3104$, R^2=0.3983) although this is not significant either [F(1,5)=3.310, p=0.129].

Total brash-mat length on tracks varies from 45 m/ha in plot 1 to 0 m/ha in plot 8. The mean length is 15 m/ha with a standard deviation of 16.1 m/ha. The value of plot 1 lies 1.84 standard deviations above the mean whilst all other plots lie within a standard deviation from the mean.

The mean brash-mat cover of racks was 46% (SD=8%), the range varying between 35% in plot 1 (-1.41 standard deviations) and 57% in plot 3 (+1.41 standard deviations). The mean brash-mat cover of tracks was 30% with a standard deviation of 26%. Proportional brash-mat cover of racks is presented in Figure 5.14 and of tracks in Figure 5.15.

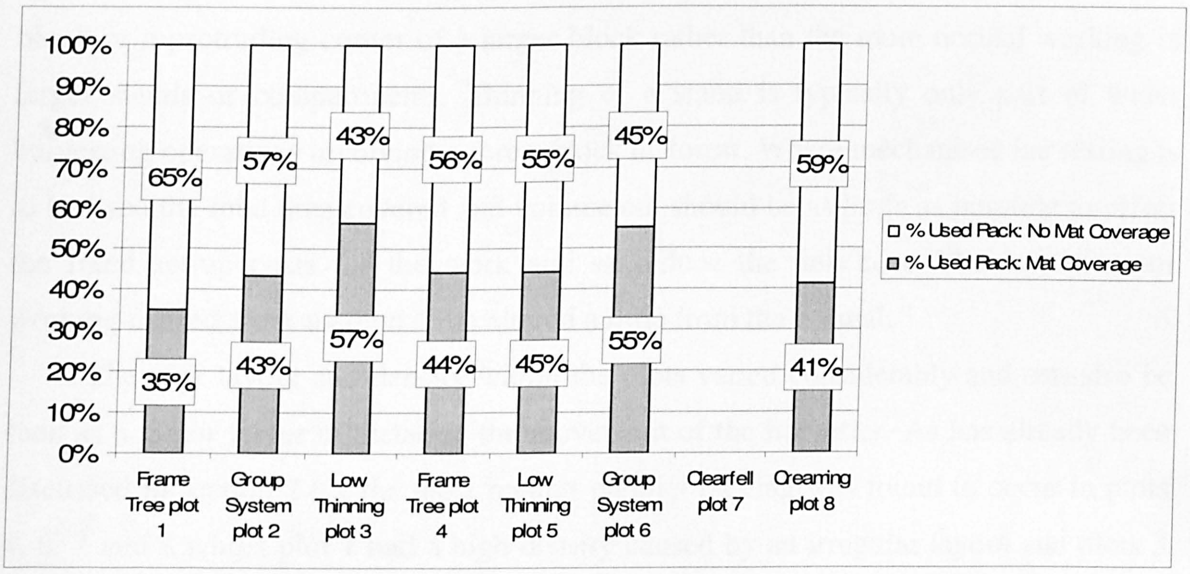


Figure 5.14 Proportional brash-mat cover on racks

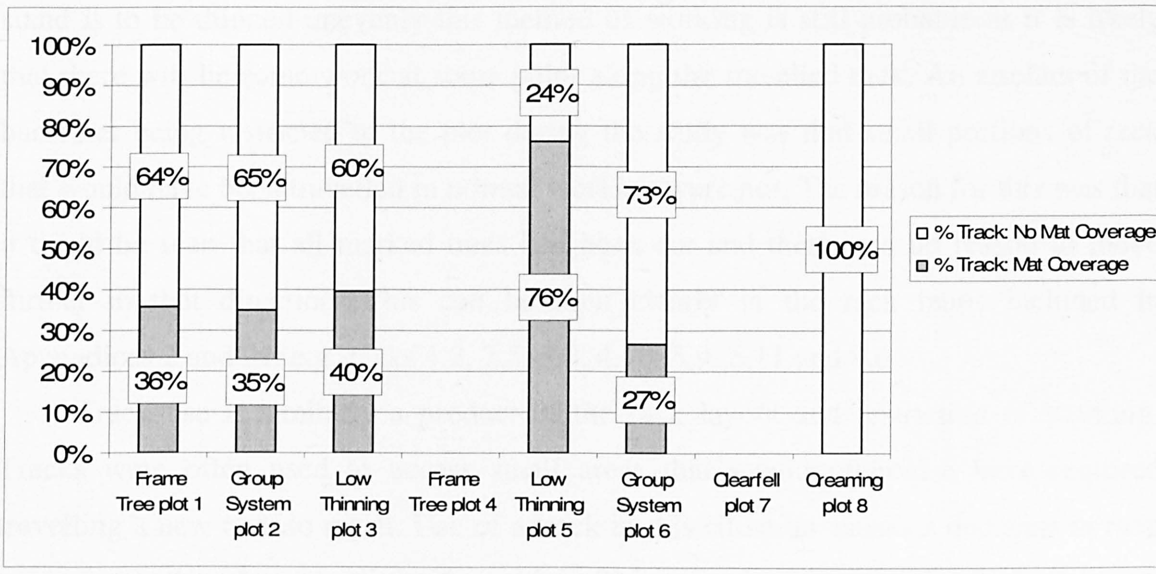


Figure 5.15 Proportional brash-mat cover on tracks

5.4.5 Discussion of Rack Usage and Brash Lay-down

To some extent the results gained from the study of rack usage are an artefact of the manner in which the time study was conducted. The time study was restricted to the square hectare plots and so was comparable to harvesting in a very small woodland block or a protruding corner of a larger block rather than the more normal working in larger stands or compartments. Thinning of a stand is typically only part of wider harvesting operations involving a forest block or forest. Where mechanised harvesting is to be used the total area covered and volume cut should be as large as possible to offset the fixed set-up costs for the work and so reduce the unit cost. The restriction of working caused work method to be altered a little from the normal.

The rack layout and density within the plots varied considerably and can also be seen as a major factor in dictating the movement of the harvester. As has already been discussed in section 2.6.2 the most regular parallel racking was found to occur in plots 4, 6, 7 and 8 whilst plot 1 had a high density caused by an irregular layout and plots 3 and 5 had adaptations to topography which caused high and low density respectively.

Typical organisation of shortwood thinning would involve the harvester entering a rack from the forest road or ride and working to its end which is again caused by another road or ride. The harvester would then travel along the road or ride and turn into the next rack to be used which is determined by the rack spacing and the vehicle reach and capability. The ideal situation would involve parallel racking where each newly thinned swathe would neatly abut to the previous. If a stand is to be thinned evenly the harvester must travel sufficient racks so as to be able to reach the entire stand area. If a stand is to be thinned unevenly this method of working is still probable as it is likely that there will be some work at some point along the travelled rack. An artefact of the harvester being restricted to the plot during the study was that small portions of rack that would have been travelled in normal working were not. The reason for this was that it could be seen that all marked trees had been cut and there was no reason to move further in that direction. This can be seen clearly in the rack maps included in Appendices 2 and 21. e.g. racks 1.2, 2.5, 3.2, 4.10, 5.9 ,6.11 and 8.6.

Track use is similarly a product of the rack layout and restriction of working. Tracks were often used to access small areas that would otherwise have required travelling a new rack to reach. Use of a track in this situation causes a decrease in rack use compared with unconstrained working. This can also be seen clearly in the rack maps included in Appendices 2 and 21. e.g. tracks 1.42, 2.22, 3.22 and 5.31.

The other main use of tracks was to travel from the end of one rack to start another. As stated earlier, moving between racks is normally achieved by travelling along a road or ride and so the use of tracks in this situation is again an artefact of the study. This again can be seen clearly in the rack maps included in Appendices 2 and 21. e.g. tracks 1.40, 2.25, 3.23, 6.20 and 8.32.

The correlations found between thinning type as expressed by the SG ratio and rack length used suggest that harvester movement in the plots was influenced by treatment. The value of SG explains 58% of total variance in per-hectare rack usage. The decrease in R^2 value between per-hectare rack use and proportional rack use is due to the differences in racking density between plots. The remaining variation is thought to be due to the different layouts of the plot rack networks; the positions of racks in relation to other racks and to the plot boundary.

The purpose of using racks and tracks within the plots was to gain access to the trees within them. A telling indicator of the efficacy of rack and track use is therefore the area that was effectively covered by the harvester during working. The marking in all the plots identified trees for felling throughout the entire plot. Whilst the marking in the matrix of the group plots (2 & 6) was more irregular and diffuse than in the other plots, marked trees were still scattered throughout the plot up to its boundary.

The calculation of covered area shows that access was gained or possible to the majority of trees in all plots.

Whilst the analysis of area coverage by the harvester shows all plots to have been evenly covered, the analysis of rack usage suggests that this coverage was dependent on rack use which varied with thinning type.

A hypothesis is that as crown thinning removes proportionately larger trees the harvester must fell at a closer distance so as to maintain control thus requiring more extensive use of racking. Whilst this cannot be proven by this study, further work could investigate the harvester-to-tree distance at felling in relation to thinning prescription or tree size.

The analyses of variance performed suggest that there is no difference in the pattern of brash lay-down between plots. Total length of brash-mat also appears to be unrelated to plot prescription or rack usage. The total length of brash mat can be partially explained by the number of trees felled per hectare (21.5% of variance) however this relationship is not significant at the $p>.05$ level ($t=1.17$, $n=7$, d.f.$=5$).

The lack of brash on a number of the tracks e.g. track 8.2, was due to them being used solely to move between racks and not to gain access to trees.

The brash-mat survey used a simple assessment technique where presence of an effective brash-mat was indicated by the mat obscuring the ground beneath it over the width of the rack running surface. The harvester operator was conscientious and ensured that trees were delimbed in front of the vehicle to maximise the brashmat. The assessment did not estimate the depth of brash over its length, however, and so no calculation of volume can be made to test correlation between brash volume produced and plot prescription.

5.5 HARVESTER TIME STUDY

5.5.1 Harvester Time Study Preamble & Rationale

5.5.1.1 Introduction

The aim of the Trallwm study, to ascertain differences in working in different transformation scenarios, requires the isolation of working activities and the assessment of whether they are attributable to intervention type.

Figure 5.16 is presented as a concept of the stratification of working activities; the feasibility of their assessment and their relevance.

5.5.1.2 Long Term and Short Term Effects

The long term effects on harvester maintenance and running costs caused by different intervention types could not be investigated with this study. It is conceivable that the different working practices used might increase or decrease vehicle component wear, be more or less fuel efficient, or cause some unforeseen maintenance side-effect. However, unless the harvester was studied for an extended period carrying out a single working type and started each period of study with exactly equally worn components (e.g. all new saw chains, hydraulic hoses etc), the long-term effects cannot be studied. In reality the harvester carried on thinning in stands other than the plots when not involved in the research, and components were installed and maintained when necessary. The effect of this is that the time-study could only assess short-term working and effects.

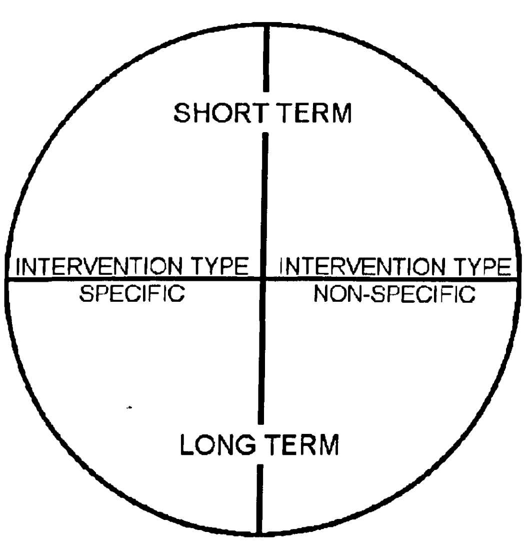


Figure 5.16 Conceptual diagram study observations and relevance

5.5.1.3 Differentiation of Plot Working

The time study needed to differentiate work and movement outside the plots from that within them. Movement of the harvester from its start-up point, along roads, rides and racks before entering the plots is all considered irrelevant to intervention type and merely a function of woodland infrastructure layout.

General preparation and before-shift maintenance was not influenced by intervention type as the activity was not reacting to any aspect of the plot that was to be harvested, but to miscellaneous factors more likely to be influenced by previous working in other plots or the surrounding stands. Time allotted to these codes is therefore not attributable to any aspect of working in the plots.

Working was therefore divided into "preparation and travel to plot" and "working in plot".

5.5.2 HARVESTER TIME STUDY METHOD

5.5.2.1 Time Study

The harvester time study was carried out by the author using the protocol set out in Technical Development (undated (a)) which is included in full in Appendix 2.12. The protocol contains descriptions of all work elements with their relevant break-points. The study was recorded using a Husky FS2 data-collector installed with Forestry Commission Technical Development software.

The author conducted the study from the cab of the harvester sitting on the passenger shelf behind the operator thus giving a safe vantage point with a good view of working and of the vehicle display. The major benefits of sitting in this position were the ability to ask the operator questions over working technique and being able to view the display and so confirm which product type was being cut.

5.5.2.2 Changes in Protocol

The study differed from the protocol only in the use of the fell code "C" – fell unbrashed tree. The protocol calls for "C" to be suffixed with the diameter (d) of the tree cut in rounded-down centimetres e.g. "C25" = fell unbrashed tree of d=25 cm. The use of a diameter suffix is required by the Forest Research program TDB MENU which analyses time-study data-sets and provides summary data. Due to its limitations, TDB MENU was not used for data analysis.

The "**C**" code was suffixed with the tree identification number instead which allowed the relevant sections of study time series be associated to mensuration data.

5.5.2.3 Product Specifications

The products cut during the study were defined by the markets open to the harvesting contractors UPM-Tilhill.

A total of six products were cut in the plots and are presented in Table 5.1 in section 5.2.1.1, with the price per tonne received by the forest owner. Although product specifications changed during the thinning operations at Trallwm due to different demands from the sawmill, only the six listed products were cut in the plots so as to maintain continuity and allow comparison.

The time study protocol allows the studier to group together cut pieces if they are of the same product type e.g. two 495cm logs cut can be recorded separately as E1, E1 or together as E21. The decision was made to record all pieces cut singly so as to be able to associate the data fully with the vehicle data log.

5.5.2.4 Defining Working in Plots

As described in 2.3.1.4 (Defining Edges), plot boundaries had been marked by spraying paint dashes along the ground. Prior to the time study the boundary marks were resprayed and particular attention given to points on the boundary crossed by racks so as to enable easy recognition of entry into the plot by the vehicles.

The recordable plot time was started and finished when the harvester head crossed the plot boundary entering and leaving the plot.

5.5.3 Harvester Time Study Data Analysis

5.5.3.1 Data Files

The harvester study produced two data files; a vehicle log and Husky log. Both are delimited text files and were imported into EXCEL to be edited and used in further analysis.

5.5.3.2 Vehicle Data Log

The Silvatec Sleipner uses the TM2000, a Windows based optimisation system which runs on a tablet style computer. The tablet is positioned in front of the operator and displays cutting information and suggests products to be cut. The optimisation programme records the information produced by the harvesting head sensors (length wheel & delimbing knives width sensors) and produces a downloadable data-log of all head activity.

Sample output, downloaded as a comma-delimited text file is included in Figure 5.17. Each line of the data-log records the cutting of a product or the unproductive trimming of the stem. Information recorded consists of, from left to right, cutting unit name (Trallwm), date, time of saw actuation, binary productive or unproductive cut (1 or 0), product code (as in Table 5.1), piece length (cm) and top middle and bottom diameters (mm).

```
trallwm, 02/07/04, 10:38:18, 0000, 0, 0111, 0171, 0098, 0058, 0058
trallwm, 02/07/04, 10:39:14, 0000, 1, 0111, 0497, 0369, 0353, 0336
trallwm, 02/07/04, 10:39:22, 0000, 1, 0111, 0497, 0336, 0308, 0279
trallwm, 02/07/04, 10:39:29, 0000, 1, 0112, 0314, 0279, 0246, 0215
trallwm, 02/07/04, 10:39:34, 0000, 1, 0127, 0305, 0215, 0166, 0124
trallwm, 02/07/04, 10:40:45, 0000, 0, 0111, 0140, 0399, 0399, 0399
trallwm, 02/07/04, 10:40:54, 0000, 1, 0111, 0497, 0399, 0383, 0373
trallwm, 02/07/04, 10:42:07, 0000, 1, 0111, 0496, 0359, 0339, 0308
trallwm, 02/07/04, 10:42:14, 0000, 1, 0112, 0314, 0308, 0271, 0246
trallwm, 02/07/04, 10:42:19, 0000, 1, 0127, 0306, 0246, 0210, 0160
trallwm, 02/07/04, 10:42:22, 0000, 0, 0115, 0127, 0160, 0138, 0125
```

Figure 5.17 Sample of vehicle log text file

5.5.3.3 Husky Time Study Data Log

The Husky data logger downloads a data log in text file format. The log consists of an activity code and time stamp delimited by an = sign for each activity observation. Sample output is included in Figure 5.18. The first line of the file records the study file identification number, in this case processor file 1010 (PR1010).

```
1010                     PR
02B1=085781
02B4=085818
02B4=090446
02C1=093266
02B4=093283
02C2=093310
01A=093340
01A=093351
02C9=093360
03C29=093410
02E1=093438
02E1=093448
02E4=093463
01E=093476
02A3=093480
02E5=093486
02E5=093491
01F=093501
01A=093515
03C30=093543
```

Figure 5.18 Sample of Husky log text file for harvester

5.5.3.4 Husky Data Log Handling

The comma-delimited Husky data-log was imported directly into EXCEL. The initial import into EXCEL split the activity code from the time stamp (See Figure 5.19). The time stamp was then broken into hours, minutes and centiminutes which allowed the calculation of the split time taken for each recorded activity. The data-set was then prepared for checking and editing by colour coding of rows. Cyclic work was coloured yellow and green and alternated in colour to aid in the identification of the time series relevant to each felled tree. Non-cyclic work was coloured blue and memos were coloured red. Memos were then removed from the time series (although kept for reference), so that all time stamps ran sequentially and the split times calculated. This initial review of the time study logs allowed for identification of erroneous codes and other problems in the sequence. The activity codes were separated from their numerical prefix and presented in a new column called ACTION (See Figure 5.20).

			HOUR	MINUTE	CENTI
1010	PR				
02B1	085781	85781	8	57	81
02B4	085818	85818	8	58	18
05MLCMP		0	0	0	0
08MOVRCAST		0	0	0	0
08MDRIZZLE		0	0	0	0
07M170604		0	0	0	0
11MTIMEON0903		0	0	0	0
02B4	090446	90446	9	4	46
02C1	093266	93266	9	32	66
02B4	093283	93283	9	32	83
02C2	093310	93310	9	33	10
01A	093340	93340	9	33	40
01A	093351	93351	9	33	51
02C9	093360	93360	9	33	60
04C762	093410	93410	9	34	10
02E1	093438	93438	9	34	38
02E1	093448	93448	9	34	48
02E4	093463	93463	9	34	63
01E	093476	93476	9	34	76
02A3	093480	93480	9	34	80
02E5	093486	93486	9	34	86
02E5	093491	93491	9	34	91
01F	093501	93501	9	35	01
01A	093515	93515	9	35	15

Figure 5.19 Sample of pre-editing Husky Excel file

A cyclic work sequence is presented in Figure 5.20 where tree 762 is felled and processed as an example of typical working. Cyclic work associated with the tree is presented in green with the next cycle, felling tree 761, in yellow. The harvester can be seen to move along the rack (A) for a total of 41 cmin and then manoeuvre (C9) for 9 cmin which is non-cyclic time marked in blue. Acquiring and felling tree 762 (C762) took 50 cmin and is followed immediately by the processing of two 495 cm logs (E1) and a 254 cm bar (E4) taking 28, 10 and 15 cmin respectively. The remaining stem is processed through the head (E) for 13 cmin and then the butt-end trimmed (A3) taking 4 cmin. Two further pieces are cut by the harvester, both pulp (E5), taking 6 and 5 cmin respectively. The final cyclic work element is the dropping the top onto the brash matt in front of the machine (F) which took 10 cmin.

ACTION CODE	ACTION	TIME STAMP	TIME STAMP 2	HOUR	MIN	CENTIMIN	SPLIT		
05MLCMP									
08MOVRCAST									
08MDRIZZLE									
07M170604									
11MTIMEON0903									
1010	PR								
02B1	B1	085781	85781	8	57	81	53781	B1	0
02B4	B4	085818	85818	8	58	18	37	B4	0
02B4	B4	090446	90446	9	4	46	628	B4	0
02C1	C1	093266	93266	9	32	66	2820	C1	0
02B4	B4	093283	93283	9	32	83	17	B4	0
02C2	C2	093310	93310	9	33	10	27	C2	0
01A	A	093340	93340	9	33	40	30	762	0
01A	A	093351	93351	9	33	51	11	762	0
02C9	C9	093360	93360	9	33	60	9	C9	0
04C762	C762	093410	93410	9	34	10	50	762	0
02E1	E1	093438	93438	9	34	38	28	762	1
02E1	E1	093448	93448	9	34	48	10	762	1
02E4	E4	093463	93463	9	34	63	15	762	1
01E	E	093476	93476	9	34	76	13	762	0
02A3	A3	093480	93480	9	34	80	4	762	0
02E5	E5	093486	93486	9	34	86	6	762	1
02E5	E5	093491	93491	9	34	91	5	762	1
01F	F	093501	93501	9	35	01	10	762	0
01A	A	093515	93515	9	35	15	14	761	0

Figure 5.20 Sample of edited Husky log text file

5.5.3.5 Vehicle Data Log Handling

The initial import into EXCEL populated ten columns using the delimiting commas to split the rows of text (See Figure 5.21). The data-set was then prepared for checking and editing by colour coding of rows. Successive trees were identified and coloured yellow and green corresponding to the colouring in the Husky data to aid in cross-referencing. Piece volume was calculated through Newton's formula as shown below.

$$v = \frac{\pi L(d_1^2 + 4d_2^2 + d_3^2)}{24}$$

v = volume of piece (m^3)

L = length of piece (m)

d_1 = diameter of base of log (m)

d_2 = mid-diameter of log (m)

d_3 = top diameter of log (m)

wood	date	time		productive	p code	length	butt D	mid D	top D	TREE NO.	Volume
trallwm	17/06/04	10:47:01	0	1	111	497	284	272	260	762	0.289
trallwm	17/06/04	10:47:07	0	1	111	496	260	246	228	762	0.235
trallwm	17/06/04	10:47:16	0	1	114	255	228	222	207	762	0.097
trallwm	17/06/04	10:47:30	0	1	127	306	206	193	157	762	0.087
trallwm	17/06/04	10:47:34	0	1	127	305	157	143	98	762	0.046
trallwm	17/06/04	10:47:36	0	0	115	123	98	98	98	762	0.009
trallwm	17/06/04	10:48:18	0	1	112	315	290	287	270	761	0.201
trallwm	17/06/04	10:48:30	0	1	114	254	270	265	263	761	0.141
trallwm	17/06/04	10:48:47	0	0	114	94	263	263	263	761	0.051
trallwm	17/06/04	10:48:51	0	1	115	173	263	263	263	761	0.094
trallwm	17/06/04	10:48:55	0	1	115	171	263	113	110	761	0.030
trallwm	17/06/04	10:48:58	0	1	115	171	110	99	99	761	0.014
trallwm	17/06/04	10:48:59	0	0	115	218	99	79	68	761	0.011
trallwm	17/06/04	10:50:38	0	1	112	314	213	213	200	6	0.110

Figure 5.21 Sample of edited vehicle log Excel file

5.5.3.6 Data Checking and Editing

Data checking and editing consisted of comparing the vehicle data log with the time study time series. The vehicle log was used as a firm source of types, sequence and pieces of produce cut to which the time study could be compared and edited against. The time study series provided the identification numbers of cut trees which were then added to the vehicle log data so that each row was associated with a tree. Editing was carried out manually, the wide range of forms taken making non-manual checks unfeasible.

When edited fully, the time study data set had two columns added to aid in data-sorting. The first was populated with the corresponding tree number of cyclic data and the code of non-cyclic data.

The second was populated with a binary field indicating productive cutting of produce (1) and non-productive work (0) which matched the vehicle log binary field.

Vehicle data-log and time study were then married by sorting each by tree number, productive/unproductive and time fields. The combining of time study and vehicle data-logs also acted as a useful last data-check as discrepancies caused the files to miss-match.

5.5.4 Harvester Time Study Results

5.5.4.1 Total Time Usage

Total observed time is summarised for all plots in Appendix 23. Total observed time was also compared against the sum of all element times and no difference was found, indicating that all time was accounted for in the study.

Total time consumption per plot is presented in Figure 5.22 with per-hectare equivalent values.

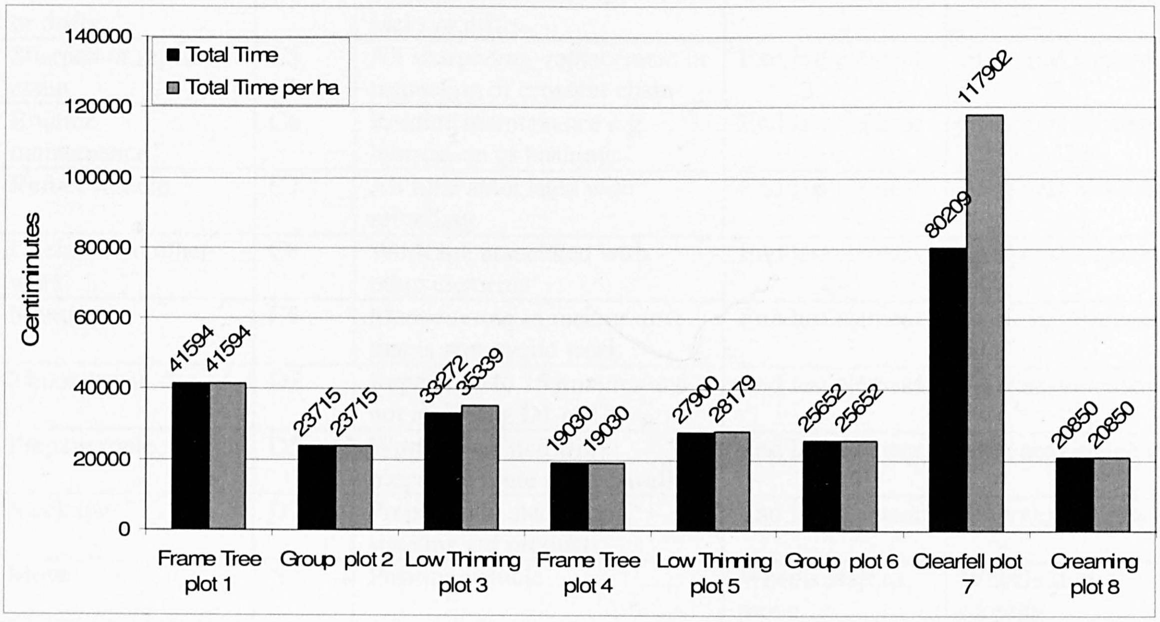


Figure 5.22 Total time taken per plot and total time taken per hectare

5.5.4.2 Use and description of elements

Table 5.9 presents the elements studied, their use and their breakpoints. Time consumption associated with the elements is presented in 5.5.5.3 and 5.5.4.4. The full time-study protocol (Technical Development, undated (a)) is presented in Appendix 2.12.

Table 5.9 Studied element descriptions and breakpoints

Operation	Code	Element	Breakpoint	
			Start	**Stop**
General preparation	B2	Includes getting & replacing tools	End last element	Start next element
To and from camp	B4	Visits to camp at shift start and end and in breaks	End last element	Start next element
Rest and personal	B9	No IPE related work	End last element	Start next element
Wait for or talk to work study	C1	Delays caused by work study	End last element	Start next element
Inspect and consider	C2	Pause work to consider work approach	End last element	Start next element
Move between racks or drifts	C3	Vehicles movement between racks or drifts	End last element	Start next element
Sharpen or replace chain	C5	All sharpening, replacement or inspection of crosscut chain	End last element	Start next element
Routine maintenance	C6	Routine maintenance e.g. lubrication of bushings	End last element	Start next element
Refuel vehicle	C7	All time associated with refuelling	End last element	Start next element
Unclassified other work	C8	Work not associated with other elements	End last element	Start next element
Manoeuvre	C9	Manoeuvring in rack or drift that is non-cyclic work	End last element	Start next element
Minor repair	D2	Repairs up to 15 minutes and not including D1 or C5	End last element	Start next element
Prepare route	D5	Work associated with preparing route to be travelled	End last element	Start next element
Stack logs	D7	Preparing to stack and stacking cut products	End last element	Start next element
Move	A	Position vehicle	Wheels start to move	Wheels stop moving
Trim butt	A3	Use cross-cut saw to trim	Saw starts	Saw stops and retracts
Fell unbrashed tree	C	Reach for tree, fell, take down	Start to reach for tree	Feed rollers start or start G
Process	E	Delimb & measure	Feed rollers start	Start of A3 to zero measurement
Process products	E1 - E5	Delimb, measure, position & cross cut	Feed rollers start	Piece cut and saw retracts
Aside & cut up top	F	Cut up un-commercial top and drop in rack	Last piece cut and saw retracts	Top drops from head
Re-process	G	Move vehicle to facilitate take down or tree positioning	Start to reach for tree	Release tree
Fell & aside unmarketable tree	A8	Reach for tree, fell, take down	Start to reach for tree	Release tree

5.5.4.3 Non-Cyclic Work Elements

Table 5.10 summarises used non-cyclic element duration for all plots whilst fuller details can be found in Appendix 23.

Table 5.10 Summary of non-cyclic work element duration for all plots All values in centiminutes and summarise element occurrences.

ELEMENT DESCRIPTION	GENERAL PREPARATION	TO AND FROM CAMP - WALKING	REST AND PERSONAL	WAIT OR TALK WORK STUDY	INSPECT AND CONSIDER	MOVE BETWEEN RACKS OR DRIFTS	SHARPEN OR REPLACE CROSS-CUTTING CHAIN	ROUTINE MAINTENANCE	REFUEL MACHINE	UNCLASSIFIED OTHER WORK	MANOEUVRE	MINOR REPAIR	PREPARE ROUTE	STACK LOGS
CODE	B2	B4	B9	C1	C2	C3	C5	C6	C7	C8	C9	D2	D5	D7
MEAN	2063.5	235.8	2664.5	715.7	72.3	264.0	656.1	261.4	105.0	48.9	56.5	1580.3	48.6	56.9
STD. DEV	1083.9	222.2	2472.9	1843.9	229.0	457.3	605.1	565.4	0.0	230.4	175.5	2612.4	186.5	99.4
MIN	597	17	82	4	3	2	28	3	105	4	3	27	3	9
MAX	3440	682	5428	14147	2407	2182	1940	3053	105	2385	1828	5823	2693	719

5.5.4.4 Cyclic Work Elements

Table 5.11 summarises cyclic element duration for all plots whilst fuller details can be found in Appendix 23.

Table 5.11 Summary of cyclic work element duration for all plots All values in centiminutes and summarise element occurrences.

ELEMENT DESCRIPTION	MOVE	CONTINUATION OF MOVE	TRIM BUTT	FELL BRASHED TREE	FELL UNBRASHED TREE	CONTINUATION OF FELL	PROCESS	PROCESS LOG 495CM	PROCESS LOG 315CM	PROCESS BAR 375CM	PROCESS BAR 254CM	PROCESS PULP 300CM	PROCESS STAKE 172CM	ASIDE AND CUT UP TOP	RE-PROCESS	FELL AND ASIDE UNMEASURABLE UNMARKETABLE
CODE	A	A1	A3	B	C	D	E	E1	E2	E3	E4	E5	E6	F	G	A8
MEAN	33.0	NOT USED	12.0	NOT USED	35.0	NOT USED	40.1	21.3	20.1	17.9	19.5	18.8	11.9	17.0	23.5	52.8
STD. DEV	183.6		99.3		16.8		267.3	201.3	117.0	104.0	102.9	108.6	116.6	114.0	71.0	114.0
MIN	1		1		9		1	2	2	1	1	1	1	1	1	3
MAX	2567		3137		165		5918	7158	2461	1899	1993	1771	3880	2515	685	831

5.5.5 Harvester Time Study Analysis

5.5.5.1 Approach of Analysis

Whilst total plot time consumption has been presented in 5.5.4, little about treatment effects can be concluded from this. Analysis of harvester time consumption investigates whether increased time consumption is caused by variables that can be attributed to treatment effect or if it is due to an unaffected stand or working parameter.

Analysis of work elements first assesses differences in element duration between plots, comparing the mean length of individual element observations. In addition, time consumption for each element (e.g. per-tree consumption, total per-plot or per-treatment consumption, consumption per unit volume) can be compared against tree, plot or treatment parameters and other element values.

Avenues of investigation were identified using a correlation matrix as well as through logical deduction from studying machine working methods.

The analysis aims to associate cyclic and non-cyclic time consumption with intervention and stand parameters.

5.5.6 Non-cyclic Elements

5.5.6.1 Analysis of Non-cyclic Elements

5.5.6.1.1 C2 – Inspect and Consider

The duration of individual pauses to *inspect and consider* were compared between treatments with a one-way analysis of variance. Significant differences were found between treatments [$F(4,156)=4.482$, $p=0.002$], post-hoc Tukey analysis indicating that mean duration in Low (78.38 cmin) was significantly higher than in Frame (28.20 cmin), Clearfell (23.19 cmin) and Creaming (18.46 cmin), but not Group (31.65 cmin).

Significant difference in element duration was also found between plots [$F(7,153)=4.165$, $p=0.000$], post-hoc Tukey analysis showing that plot 3 (104.69 cmin) had a significantly higher mean duration than that of the other plots, which ranged from 18.5 to 38.2 cmin.

No correlation was found relating C2 plot time consumption per tree to *numbers of trees felled*, *total felling time* or to *total processing time.* As the consideration time is associated in the literature with felling and movement, this suggests that the vast majority of this activity was used in planning vehicle movement.

Inspect & consider time consumption per tree was found to be highly positively related to total movement time (T_{total}^{A0}) and total manoeuvre time (T_{total}^{C9}), the sum of the two ($T_{total}^{A0} + T_{total}^{C9}$) providing the best predictor variable. The linear regression of inspection time per tree (T_{tree}^{C2}) is presented in Table 5.12.

5.5.6.1.2 C3 – Move Between Racks

No significant relationship could be found to explain plot *movement between rack* time consumption and no significant difference was found between *movement between rack* treatment element duration [F(4,98)=2.436, p=0.052]. The best relationship found was with *total used rack* and track in the negatively trending linear relationship $T_{total}^{C3} = -2.3572 \cdot L_{used}^{rack+track} + 3460.8$, [F(1,6)=4.114, p=0.089], R^2=.407.

5.5.6.1.3 C9 – Manoeuvre

A one-way analysis of variance found no significant difference of *manoeuvre* duration between treatments [F(4,195)=1.621, p=0.170].

No correlation was found between mean felled tree volume and *plot total manoeuvre time*. Instead, a strong positive correlation between the *length of new track* created by the harvester (L_{total}^{track}) and the *total time spent manoeuvring* was identified. The regression is included in Table 5.12.

The code is also often seen in association with route preparation (D5) although there was no correlation found between the C9 and D5 codes.

5.5.6.1.4 D5 – Prepare Route

No significant differences were found between treatments for element duration in a one-way analysis of variance [F(4,274)=1.207, p=0.308].

No relationship was found between plot time consumption and *used rack* or *track length*. When *prepare route* time consumption per metre of used rack and track was calculated, plot 3 and 7 values were found to be far greater than the others. Time consumption was 1.95 cmin/m and 3.54 cmin/m in plots 3 and 7 respectively compared with a mean of 0.74cmin/m for other plots (SD=0.11, range 0.59-0.89).

5.5.6.1.5 D7 – Stack Logs (stack all assortments)

In a one-way analysis of variance, element duration was found to be significantly different between treatments [F(4,52)=3.094, p=0.023]. The mean value of Low (47.9 cmin) was found, through post-hoc Tukey analysis, to be significantly higher than that of Clearfelling (25.68 cmin) but not that of Frame (39.45 cmin), Group (32.6 cmin) or Creaming (17.67 cmin).

Plot total D7 time consumption was found to be significantly correlated with total felling time (T_{total}^{C0}), the regression is presented in Table 5.12.

Mean stacking duration was found to be significantly positively correlated with the combined percentage by volume of stakes and pulp ($P_v^{300+172}$) ($T_{mean}^{D7} = 8.882 + P_v^{300+172} \cdot 168.217$, R^2=.565, [F(1,6)=7.781, p=0.032]), although $P_v^{300+172}$ was found to be non-significant as a co-variate in describing total time consumption.

Table 5.12 Summary of regression analysis of non-cyclic work elements. All time consumption values in centiminutes

Work phase model	Dependent variable	R^2	F-test	Term		Constant / Coefficient		t-test	
						Estimate	Std. Error	t-value	p
Inspect and consider (all plots)	T_{tree}^{C2}	0.812	[F(1,6)=25.856, p=.002]	Constant		-6.860	2.443	-2.808	0.031
				$T_{total}^{A0} + T_{total}^{C9}$	x_1	0.004	0.001	5.085	0.002
Manoeuvre (thinning plots)	T_{total}^{C9}	0.800	[F(1,5)=19.955, p=.007]	Constant		156.648	168.648	0.928	0.396
				L_{total}^{track}	x_1	13.154	2.945	4.467	0.007
Stack logs (all plots)	T_{total}^{D7}	0.896	[F(1,6)=51.829, p=.000]	Constant		-184.379	63.594	-2.899	0.027
				T_{total}^{C0}	x_1	0.079	0.011	7.199	0.000

5.5.6.2 Discussion of Non-cyclic Work Elements

5.5.6.2.1 C2 – Inspect & Consider

Time taken by the harvester operator to pause and consider the working situation was found to be directly related to movement within the stand and not to felling. This is an interesting finding as it indicates that the extra felling consideration time required for larger trees as described by Kellogg & Bettinger (1994) was either absent in this study or of little overall importance.

The correlation between movement and consideration time suggests that the high values produced by plots 1 and 3 are likely to be caused by challenges to movement, so necessitating greater thought towards vehicle movement. The irregular rack layouts within the two plots and steep slope working and high stocking density found in plot 3 are likely to be the challenges to movement which have caused the high recorded values.

The high element duration mean value for low thinning is heavily influenced by plot 3 which, whilst not having a high number of occurrences (23) compared to other plots, did have a high mean (104.7 cmin) and median value (37.0 cmin). The ANOVA using plot instead of treatment shows this well, as plot 3 has a significantly higher mean duration than all other plots. The high time consumption identified in plot 1 was due to the opposite situation of a similar mean duration to other plots (31.4 cmin) but a higher number of occurrences (37).

The irregularity of a racking network can therefore be seen to influence inspect and consider time-consumption. A sensitivity analysis using parameters equivalent to typical plot values was carried out to investigate this effect. In a hectare stand where 650 m of rack is used, 40 m of track installed and 125 trees thinned, an additional 10 metres of track would lead to an increase of 0.53 cmin per tree and 50 m of rack would lead to 1.18 cmin per tree.

5.5.6.2.2 C3 – Move Between Racks

No significant difference was found in C3 element duration between treatments suggesting that travelling between racks was performed in a manner which was not affected by treatment or plot. The identified trend suggests that between-rack movement time-consumption, and hence between rack movement, decreases with increasing rack and track use. This indicates that the need to change racks decreased with increasing irregularity of the racking system.

More regular racking has a lower overall time consumption associated with move between racks (C3), move (A0) and manoeuvre (C9). Whilst move between rack time consumption increases with regularity, there is an overall reduction in time consumption as A0 and C9 fall at a greater rate; an increase of 600 cmin for C3 corresponding to a decrease of 1300 cmin or more for A0 and C9.

5.5.6.2.3 C9 – Manoeuvre

The analysis suggests that, like inspect and consider (C2), manoeuvring is not closely associated with felling but with travel. Total time consumption was found to show a strong positive correlation with the length of track travelled by the harvester. This correlation seems plausible as tracks were classified as movement by the harvester through the matrix of the plot and hence required a great deal of manoeuvring to work around trees. The high values for plots 1 and 3 are again likely to be due to the irregular racking network and terrain, forcing the harvester operator to travel through the matrix more. This agrees with the findings of Kellogg & Bettinger (1994) who found that difficult sites required more manoeuvring time.

The identified relationship was calculated for the thinned plots as the clearfell had high total time consumption and no tracks, indicating that manoeuvring in clearfells may be due to other factors.

During observation of working, it was noted that the harvester was often manoeuvred closer to trees, particularly larger individuals, in order to better control felling. Inspection of the time study files shows, at least subjectively, that C9 is often associated with C0 (fell) and D5 (prepare route). However, mean felled tree diameter was not found to be a good variable or covariate to describe C9 time consumption and no relationship could be identified linking C9 to D5 time consumption. Variation in the dependent variable is 80% explained by track use, the remaining 20% may be associated with felling.

Several studies have been published on the effect of rack spacing on harvesting productivity, e.g. Mederski (2006) and Hallonborg & Nordén (2001), generally concluding that productivity rises as racking intensity decreases due to the increased concentration of working at higher spacing. The difference in racking regularity between the plots provides a similar effect to different spacing, the less regular rack layouts being equivalent to a narrower rack spacing. Analysis has also shown that a regular rack network not only concentrates working and minimises travel but also reduces other work types such as manoeuvre and pause to inspect.

5.5.6.2.4 D5 – Prepare Route

It is interesting to note that time consumption associated with D5 is not correlated with rack or track length. The analysis of variance suggests that there is no significant difference in element duration and that the activity takes a similar form in all treatments.

Plots 3 and 7 do have very high time consumption values per used rack metre due to a greater number of occurrences. This is probably due to the difficult ground conditions found in plot 3 and maximising brash-mat construction in plot 7 due to the expected higher rack usage and soft ground conditions.

5.5.6.2.5 D7 – Stack Logs (stack all assortments)

The stacking of produce, although a non-cyclic work element, can be seen to be directly related to cyclic work and is also important in the interaction between harvester and forwarder. The regression shows that stacking total time consumption increases linearly with felling total time-consumption. Mean element duration was also found to be positively correlated with combined percentage of pulp and stake. This may be explained by the relative sizes of the six products and the relative assortment percentages between tree sizes. High pulp and stake percentages will occur in smaller tree diameter classes which will also include a larger proportion of bar material and have a smaller mean product size. Larger diameter classes will have a larger proportion of logs which, due to their size, rarely need repositioning in their pile. Sorting products in smaller diameter classes will be likely to involve a greater number of product types and so a greater number of piles to rearrange. Smaller size products will also have a greater tendency to spin and deflect when being processed onto a pile and so require repositioning. Although this study concerned only one species, six products were cut compared with a maximum of four in Nurminen *et al.* (2006) with a follow-on increase in working complexity, which as noted by Favreau & Légère (1999), can lead to reduced productivity.

5.5.6.2.6 Other Work Elements

Other work elements in the study were little used or completely absent from many of the plots, however, some useful information can still be gained from them.

During the clearfell a measuring wheel with two sets of teeth which had been fitted at the previous work site to increase measuring accuracy of smaller trees was still installed in the harvesting head. Due to the time of year the tree bark was very prone to peeling off and the wheel had a tendency to peel off thin ribbons and become bound. The wheel could often be un-bound from the cab by pressing a foot pedal which caused the wheel to push out from the head: time taken in this process was allocated to C8 –

unclassified other work. On one occasion the clogging was so bad as to require manual clearance, this being classed as a minor repair (D2) which lasted 178 cmin. The wheel was swapped after the clearfell for a single-toothed version which did not suffer so badly from this problem. The time consumption which can be associated to what was a somewhat minor component choice was equivalent to 7 cmin/tree in the clearfell compared to 1 cmin/tree or less in other plots and shows how minor factors can have a large influence on time consumption.

The other potentially serious implication of this problem is that of the head sensors, the measuring wheel is the most susceptible to error (Makkonen, 2001) and measurement errors could lead to produce rejection by buyers and volume miscalculation.

5.5.7 Cyclic Elements

5.5.7.1 Analysis of Cyclic Work Elements

5.5.7.1.1 A – Move

A one-way analysis of variance was conducted to investigate if there was a difference in element duration between treatments. Statistically significant differences were found between treatments [F(4,967)=29.530, p=0.000]. Post-hoc Tukey analysis indicates that mean time for the Clearfell (9.27 cmin) is significantly less than all for other treatments. Frame (22.91 cmin) is significantly different from all other treatments with the exception of Creaming (19.91 cmin). Group (15.71 cmin) is not significantly different from Low (18.19 cmin).

Harvester movement time per tree (T_{tree}^{A0}) was found to be most influenced by the *number of trees removed* (N_{thin}^{ha}) per hectare and the *length of rack* (L_{used}^{rack}) used in the plot. The bivariate linear regression describing T_{tree}^{A0} is presented in Table 5.13.

5.5.7.1.2 C0 – Fell Un-brashed Tree

To examine the effect of treatment on the time taken to fell, a one-way analysis of variance was conducted. Treatment means were found to be significantly different [F(4,1202)=9.043, p=0.000]. Post-hoc analysis suggests that felling in Frame (40.51 cmin) took significantly longer than in all other treatments except in Creaming (39.33 cmin) and significantly longer in Creaming than in both Low (32.77 cmin) and Clearfell

(33.75 cmin). Mean time consumption for Group (34.04 cmin) was not significantly different from that for Low or Clearfell.

Using individual tree data, *diameter squared* was found to be the best predictor of *felling time consumption*, the highly significant linear regression of $T_{tree}^{C0} = 0.021d_{thin}^2 + 15.035$ explaining 25.9% of variation [F(1205)=420.56, p=0.000].

Using plot data, *time consumption per tree* was best described using the *mean crown:height ratio of felled trees* ($\overline{CH}_{thin}$) and the sum of the *relative spacing of trees removed* (RS_{thin}) and the *mean diameter of felled trees* ($\overline{D}_{thin}$). The bivariate linear regression is presented in Table 5.13.

5.5.7.1.3 E0 – Process

In a one-way analysis of variance, *process* element duration was found to vary significantly between treatments [F(4,1269)=22.473, p=0.000]. Post-hoc Tukey analysis indicated that the element duration in Creaming (32.91 cmin) was significantly higher than in all other treatments. Duration in Frame (22.12 cmin) was found to be significantly higher than in Group (16.23cmin) but not in Low (18.40 cmin) or in Clearfell (19.34 cmin).

Time consumption per tree (T_{tree}^{E0}) was found to be highly related to *mean felled tree crown:height ratio* ($\overline{CH}_{thin}$). The linear regression is presented in Table 5.13.

5.5.7.1.4 E1 – Process 495 cm Log

A highly significant difference was found in the mean duration of processing element time between treatments in a one-way analysis of variance [F(4,1641)=6.39, p=0.000]. Post-hoc Tukey analysis indicated that mean duration for Group (9.70 cmin) was significantly less than for Frame (11.09 cmin), Low (10.86 cmin), Clearfell (10.76 cmin) and Creaming (11.89 cmin).

Time consumption per tree (T_{tree}^{E1}) was found to be highly positively correlated with *mean felled tree volume* ($\bar{v}_{thin}$) and the highly significant linear regression is presented in Table 5.13.

5.5.7.1.5 E2 – Process 315 cm Log

A one-way analysis of variance was used to compare the duration of E2 occurrences between plots. No statistically significant difference was found between mean treatment duration [F(4,880)=1.232,p=0.296].

No significant relationship could be found between E2 time consumption per tree (T_{tree}^{E2}) and any stand or harvesting parameters.

When combined with time consumption for E1 to form a total for log products (T_{ree}^{E1+E2}), mean felled tree volume ($\bar{v}_{thin}$) was found to be the best descriptor variable and the regression is presented in Table 5.11.

Total plot log volume percentage ($P_v^{495+315}$) was also found to be a good and highly significant descriptor variable and the regression is included in Table 5.13.

5.5.7.1.6 E3 – Process 375 cm Bar

Treatment effect on duration of 375 cm bar processing time was investigated in a one-way analysis of variance and found to be significant [F(4,608)=4.989, p=0.001]. Tukey post-hoc analysis indicates that mean time consumption for Clearfell (9.99 cmin) was significantly greater than for both Group (8.65 cmin) and Low (8.35 cmin) but not for Frame (9.98 cmin) or for Creaming (9.10 cmin).

Time consumption per tree (T_{tree}^{E3}) was found to be best described by *percentage of 375 cm bar by volume* (P_v^{375}) and the linear regression is presented in Table 5.13.

5.5.7.1.7 E4 – Process 254cm Bar

A one-way analysis of variance was used to compare the duration of E4 between treatments. No statistically significant difference was found at the p<.05 level [F(4,613)=2.133,p=0.075].

Mean time consumption per tree (T_{tree}^{E4}) was also found to increase with the *percentage of product by volume* (P_v^{254}) although the regression presented in Table 5.13 is not significant. Combining both bar types was not found to improve function utility.

5.5.7.1.8 E5 – Process 300 cm Pulp

In a one-way analysis of variance, duration of pulp processing occurrences was found to vary significantly with treatment [F(4,981)=8.870, p=0.000]. Post-hoc Tukey analysis indicates that mean element duration in Clearfell (11.83 cmin) was significantly higher than all other treatments; Frame (9.15 cmin), Group (8.80 cmin), Low (9.61 cmin) and Creaming (8.24 cmin).

Plot pulp percentage by volume (P_v^{300}) was found to be the best descriptor variable for *time consumption per tree* (T_{tree}^{E5}), the significant regression being presented in Table 5.13.

5.5.7.1.9 E6 – Process 172 cm Stake

A one-way analysis of variance was used to compare the duration of E6 between treatments. Post-hoc analysis showed that Creaming (6.70 cmin) had a mean value greater than those for all other treatments - Frame (6.31 cmin) Group (5.96 cmin) Low (5.44 cmin) Clearfell (6.28 cmin), but the difference is only significant between Creaming and Low.

Product percentage by volume (P_v^{127}) was again found to be the best descriptor variable for *E6 time consumption per tree* (T_{tree}^{E6}), the significant regression presented in Table 5.13.

5.5.7.1.10 F0 – Aside and Cut Up Top

Significant differences were found between treatments in a one-way analysis of variance [F(4,1202)=8.355, p=0.000]. Post-hoc analysis indicates that mean element duration was significantly lower in Clearfell (7.44 cmin) than Frame (9.55 cmin) and Low (9.33 cmin) but not Group (8.29 cmin) or Creaming (8.48 cmin).

Total F0 time consumption per plot (T_{total}^{F0}) was found to be best described by the *relative spacing of felled trees* (RS_{thin}) and the regression is presented in Table 5.13.

5.5.7.1.11 A3 – Trim Butt / Rot

A one-way analysis of variance was used to compare the duration of A3 between treatments and significant differences were found [F(4,1428)=20.936, p=0.000]. Tukey analysis indicates that the duration in Clearfell (8.43 cmin) was significantly longer than in all other treatments and that duration in Frame (6.24 cmin) was also significantly greater than in Low (4.836cmin) but not in Creaming (4.84 cmin) or in Group (4.91 cmin).

Trimming time per tree (T_{tree}^{A3}) was found to be best described by *mean felled tree volume* ($\overline{v}_{thin}$). The linear regression is presented in Table 5.13.

Table 5.13. Summary of regression analysis of cyclic work elements. All time consumption values in centiminutes

Work phase model	Dependent variable	R^2	F-test	Term		Constant / Coefficient		t-test	
						Estimate	Std. Error	t-value	p
Move (all plots)	T_{tree}^{A0}	0.889	[F(2,5)=20.035, p=.004]	Constant		-7.279	7.820	-0.931	0.395
				N_{thin}	x_1	-0.043	0.007	-6.148	0.002
				L_{used}^{rack}	x_2	0.047	0.012	3.735	0.014
Fell Tree (all plots)	T_{tree}^{C0}	0.853	[F(2,5)=14.509, p=.008]	Constant		17.878	6.039	2.960	0.032
				$\overline{D}_{thin} + RS_{thin}$	x_1	1.001	0.223	4.497	0.006
				$\overline{CH}_{thin}$	x_2	-37.478	18.856	-1.988	0.104
Process (all plots)	T_{tree}^{E0}	0.852	[F(1,6)=34.473, p=.001]	Constant		-63.384	14.986	-4.230	0.006
				$\overline{CH}_{thin}$	x_1	157.389	26.806	5.871	0.001
Process 495cm log (all plots)	T_{tree}^{E1}	0.961	[F(1,6)=149.246, p=.000]	Constant		-7.395	1.826	-4.050	0.007
				$\overline{v}_{thin}$	x_1	26.234	2.147	12.217	0.000
Process 495cm & 315cm log (all plots)	$T_{tree}^{E1\&2}$	0.953	[F(1,6)=122.193, p=.000]	Constant		-1.741	2.197	-0.793	0.458
				$\overline{v}_{thin}$	x_1	28.566	2.584	11.054	0.000
	$T_{tree}^{E1\&2}$	0.924	[F(1,6)=73.272, p=.000]	Constant		-12.817	4.106	-3.122	0.021
				$P_v^{495+315}$	x_1	48.765	5.697	8.560	0.000
Process 375cm bar (all plots)	T_{tree}^{E3}	0.777	[F(1,6)=20.857, p=.004]	Constant		1.665	0.636	2.620	0.040
				P_v^{375}	x_1	30.629	6.707	4.567	0.004
Process 254cm bar (all plots)	T_{tree}^{E4}	0.339	[F(1,6)=3.071, p=.130]	Constant		2.844	1.141	2.491	0.047
				P_v^{254}	x_1	35.567	20.296	1.752	0.130
Process 300cm pulp (all plots)	T_{tree}^{E5}	0.699	[F(1,6)=13.932, p=.010]	Constant		3.349	1.505	2.225	0.068
				P_v^{300}	x_1	43.377	11.621	3.733	0.010
Process 127cm stake (all plots)	T_{tree}^{E6}	0.601	[F(1,6)=9.047, p=.024]	Constant		2.993	1.456	2.056	0.085
				P_v^{127}	x_1	88.883	29.551	3.008	0.024
Aside top (all plots)	T_{total}^{F0}	0.944	[F(1,6)=100.954, p=.000]	Constant		3750.925	251.103	14.938	0.000
				RS_{thin}	x_1	-285.947	28.459	-10.048	0.000
Trim butt (all plots)	T_{tree}^{A3}	0.897	[F(1,6)=52.271, p=.000]	Constant		0.160	0.983	0.162	0.876
				$\overline{v}_{thin}$	x_1	8.361	1.156	7.230	0.000

5.5.7.2 Discussion of Cyclic Work Elements

5.5.7.2.1 A – Move

The number of felled trees per hectare can be seen as a measure of the density of felling and so the average distance between processing points. Increasing the number of felled trees will decrease the distance between processing points and also decrease the movement time of each tree, the net effect being an inverse relationship with rising N. The racking infrastructure can also be seen to have an effect on the movement time as it will dictate the total distance to be moved and so influence the time taken. Irregular systems will increase the total distance travelled and so increase time taken.

The findings agree well with previously published studies. Both Eliasson (2000) and Lageson (1996) found the number of trees harvested per hectare to be the greatest influence on movement time-consumption. Lageson also noted the effect of terrain class which can be seen as a determinant of racking efficiency. Nurminen *et al.* (2006) calculated a mean time per stem of 10.0 cmin for thinnings and 7.7 cmin for clearfell. This compares to the mean thinning value of 17.07 cmin/tree (st.dev = 4.98, range = 12.01-23.08) and 6.39 cmin/tree for the clearfell in this study.

Used racking density in the study by Nurminen *et al.* was much lower, around 475 m/ha compared with 614 – 861 m/ha in this study. Whilst the removed stems per hectare were similar between study clearfells (489/ha to 497/ha), thinning removals were much more numerous in the study by Nurminen *et al.* (335/ha to a mean of 126/ha).

The identified relationship for movement time-consumption appears to hold true as published figures for thinnings when compared to this study show a greater number of felled trees per hectare and lower racking density and a lower movement time per tree. A comparison of figures for clearfelling suggests that the harvesters studied by Nurminen *et al.* (2006) were slower than the one studied in this study, however, as the published movement time per tree is higher.

Unfortunately, the protocol used to study the harvester had no facility for measuring the distance moved as in the forwarder study. It would be interesting to see if the same differences between treatments for the forwarder apply to the harvester for distance moved, and have the same effect on speed.

5.5.7.2.2 C – Fell Un-brashed Tree

The activity described by the fell code can be seen to be less specific than in some other studies, for example that by Eliasson (1998) where boom in and boom out are separated and that of Kellogg & Bettinger (1994) where head positioning time was separated. Nevertheless the results produced compare well with other studies.

Time consumption for felling was found to be most highly correlated with mean felled tree diameter although using this as the sole variable provided a poorer description (R^2=.615, [F(6)=9.59, p=0.021]) than when combined with other parameters. Tree size, be it described through diameter or volume, is widely published as being the most important variable in felling time-consumption (e.g. Nurminen *et al.*, 2006; Eliasson, 1998; Tufts, 1997; Lanford & Stokes, 1996; Kellogg & Bettinger, 1994), the analysis agreeing with other studies that time consumption rises with diameter.

The relative spacing of felled trees was found to improve the description of time consumption when combined with diameter (R^2=.737, [F(6)=16.80, p=0.006]). This can be seen as describing the boom movement, wider spaced trees requiring greater time to be reached by the head. Nurminen *et al.* (2006) found no relationship between number of removed trees per hectare and boom movement to acquire the tree. In the analysis performed here, the best regression was obtained using felled tree relative spacing (including that of the clearfell) and not retained tree density or relative spacing of the retained stand, suggesting that the effect was due time taken to reach to and from trees and not the effect of increasing stand density restricting boom movement and so increasing time consumption e.g. Hånell *et al.* (2000) and Eliasson (1998).

Whilst the effects of crown:height ratio have been noted by several authors (e.g. Hånell *et al.*, 2000; Lageson, 1996) as increasing time consumption in processing by providing more de-limbing resistance, the effect of tree branchiness has not been covered with regard to felling time. Whilst c/h was not found to be significant as a variable (t=-1.988, p=0.104), its inclusion did increase the R^2 value of the regression from 0.737 to 0.853 and increased Akaike Information Criteria values (Burnham & Anderson, 2002; Akaike, 1981). The inclusion of c/h within the function leads to a decrease in time consumption with increasing crown depth; a tree of 30 cm diameter felled at a relative felling spacing of 9 m will require 5% less felling time (around 2 cmin) with an increase in c/h of 0.05. An explanation for this could be that the increased crown weight due to higher c/h will help falling trees push through canopy gaps better and avoid hanging-up, so avoiding the time required to free them. This certainly agrees with anecdotal evidence from speaking to machine operators and from personal felling experience.

5.5.7.2.3 E0 – Process

Time consumption for processing, the running of a tree through the harvester head to remove branches and allow more accurate measurement during product cutting, was largely explained by mean crown:height ratio of the felled trees. This finding agrees with both Hånell *et al.* (2000) and Lageson (1996) who noted that coarse branching can slow processing. Separate delimbing was not always used, the majority of working carrying out delimbing and product cutting in one pass. The findings correspond well with the reasons for using the different work method, where coarser branching and / or poor stem form would pose measurement problems in a one-pass method. The rise in time consumption per tree is very high for comparatively small rises in c/h; an increase from 15.3 to 46.8 cmin/tree occurring with the rise of c/h from 0.5 to 0.7. As noted by Cameron (2002) and Suadicani & Fjeld (2001), tree c/h values are likely to increase with decreasing h/d ratio and as h/d decrease is an effect of increasing diameter, larger trees are more likely to have deeper crowns and increasing relative branch area per stem area. Crown thinning is therefore more likely to fell trees with larger crowns than low thinning with a follow-on increase of processing time-consumption per tree. As crown thinning will for a given intensity fell fewer trees per area than low thinning, the total time consumption may not be greater. As can be seen from the analysis, although crown thinning has a tendency to increase per-tree time-consumption and element duration, only when the extreme crown thinning of the Creaming plot is applied does total time consumption rise noticeably above that of other treatments; by 6.24 minutes/ha or approximately 22% of thinning plot average.

5.5.7.2.4 E1-E6 – Process Products

Both element mean duration and time consumption per tree had a tendency to differ between treatments owing to mean felled tree diameter effects. As felled diameter increases, so does mean product volume (see 5.3.2.4 concerning this relationship). Product diameters will therefore tend to rise with increasing tree diameter so requiring extra work and time to cross-cut, a result also found by Eliasson (1998).

It seems reasonable that time consumption per tree for 495 cm logs is, of the six cut products, the best described in regressions using mean felled tree volume. The 495 cm log is cut from the base of the tree and so the most closely related to measured tree size. 495 cm logs and 375 cm bar regressions show better fit than those for 315 cm logs and 254 cm bars in a manner strikingly similar to the diameter to product proportion relationship (section 5.3.2.3) and the diameter to mean product volume relationship (section 5.3.2.4). This is likely to be due to 315 cm logs and 254 cm bars being the "secondary" product which is only cut when the preferred "primary" product (495 cm or 375 cm) is not possible – often due to defect. The greater stochasticity involved with cutting secondary products is likely to be the cause of the poor regression fit.

5.5.7.2.5 F0 – Aside & Cut-up Top

As total time consumption rises with the number of felled trees and per-tree time consumption decreases, intensity of working has an effect on this element. No significant differences were found between the mean element durations recorded in the thinning plots, suggesting that thinning intensity was not sufficiently different between treatments to cause an effect. The mean duration recorded in the clearfell was 1-2 cmin lower (per tree) than in thinning due to the higher intensity of working. Higher intensity of working will cause a higher concentration of product piles in the drift. When processing a tree, a higher concentration of piles will decrease the mean distance moved by the boom to process products onto the relevant piles. As the boom is likely to be closer to the harvester when processing products is completed, there will be a lower mean distance, and hence less time, to move the boom in order to drop the unmerchantable top onto the brash mat in front of the harvester.

Tree size was not a factor in F0 time consumption as the unmerchantable top is be very similar in dimensions regardless of the size of tree it was cut from.

5.5.7.2.6 A3 – Trim Butt

Time consumption associated with trimming was found to be best described by mean felled tree volume. As noted before, tree size is the most important factor in felling and processing, and studies such as that by Eliasson (1998) have shown cross-cutting time to be positively correlated with tree size. Butt-rot was not generally evident within the trial stands and so trimming was used to reduce log butt-diameter to maintain product specification, to cut out sections of stem defect to optimise production and to re-zero the length measurement after rough delimbing. Per-tree butt-trimming time consumption can be seen to rise steeply with tree volume. An increase in mean felled tree volume, equivalent to that from low to crown thinning at Trallwm (0.55 m^3 to 0.95 m^3) would increase time consumption by 70% (4.8 to 8.1 cmin/tree). Total time consumption is not particularly different between plots or treatments however as per-tree increases are cancelled out by the reduction in number of felled trees.

5.5.8 Cyclic Per-tree

5.5.8.1 Regression Analysis of Time Consumption

Whilst plot mean time-consumption data could be compared with a wide range of stand parameters (e.g. used rack density, RS of thinned trees and plot product proportions) to investigate relationships, the diameter range offered by the mean plot data is quite constrained – approximately 25 cm to 36 cm. Using individual tree data increases the understanding of the relationship between time consumption and diameter above and below these limits. The analysis assumes independence of observations (trees), however this may not be truly the case as the felling of one tree may influence the felling of another, by creating a canopy gap for instance. The use of individual tree data is widespread (e.g. Eliasson, 1998; Lageson, 1996), but the assumption should be borne in mind.

Time consumption was calculated for each tree for four cyclic work phases:

- Total: all cyclic time associated with a tree
- Total less movement (A & G): Total time minus movement elements A and G
- Fell: fell tree element C
- Process: process elements E0, E1-E6, A3 and F0

Regressions of work-phase time-consumption against tree diameter were performed with quadratic curves selected as the optimal balance of best fit and curve simplicity defined through Akaike scoring (Burnham & Anderson, 2002; Akaike, 1981). Quadratic curves have also been used to describe per-tree time consumption by Karha *et al.* (2004) and Nurminen *et al.* (2006).

The calculated curves are presented in Figure 5.23 with goodness of fit and the details of parameters in Table 5.14. The curves for all-plot data are presented together in Figure 5.24 to enable easier comparison. The curves for all-plot data are shown with their data points in Appendix 28.

In all regressions, clearfell time-consumption is lower than of thinning. All-plot data shows a relationship between thinning and clearfell.

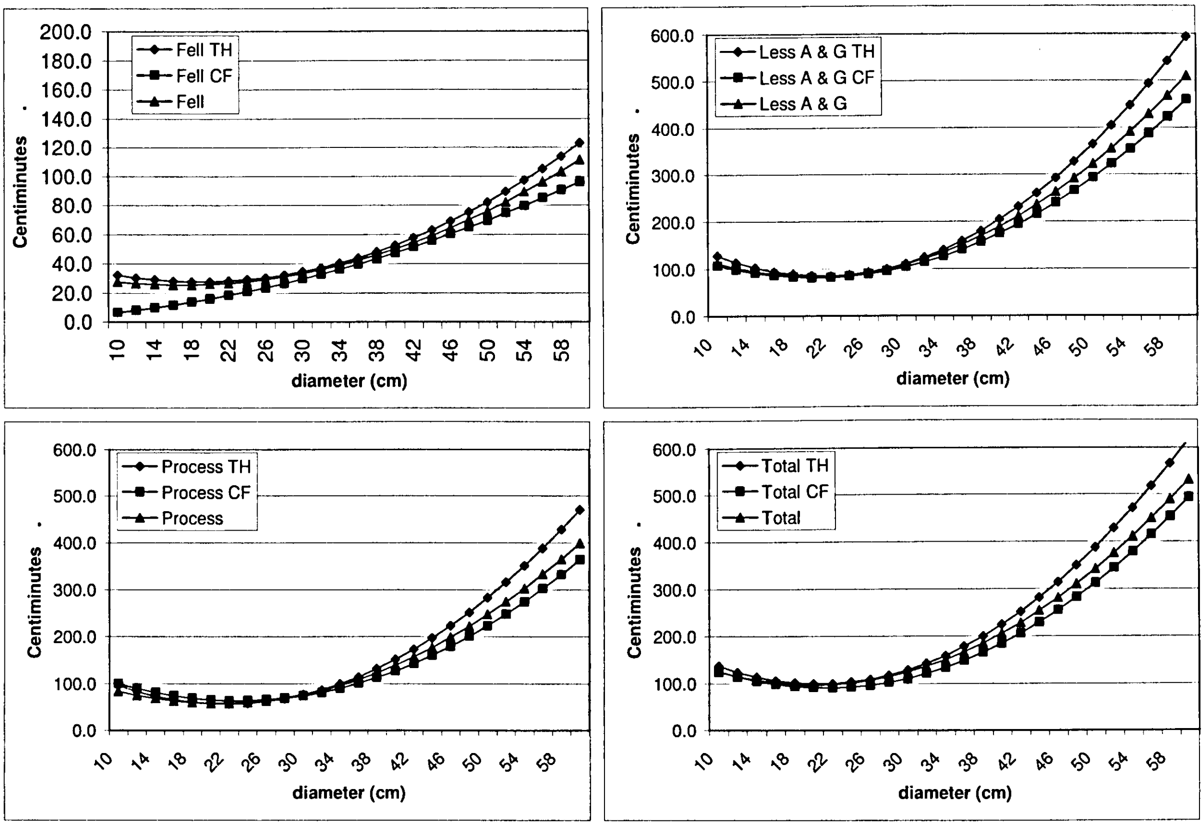


Figure 5.23 Fitted curves for time consumption in relation to tree diameter for work elements; Fell, Total less movement (A & G), Process and Total

Curves are presented for all plot data, for thinned plots (TH) and the clearfell (CF)

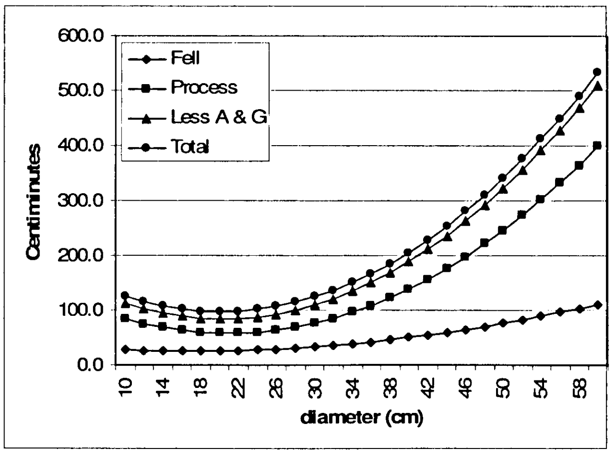


Figure 5.24 Time consumption in relation to tree diameter for work elements; Fell, Total less movement (A & G), Process and Total

Curves are presented for all plot data

Table 5.14 Summary of regression analysis of per-tree cyclic work time consumption. All time consumption values in centiminutes

Work phase model	Dependent variable	R^2	F-test	Term		Constant / Coefficient		t-test	
						Estimate	Std. Error	t-value	p
Total (all plots)	T_{tree}^{total}	0.411	[F(2,1204)=420.510, p=.000]	Constant		206.489	23.156	8.917	0.000
				d	x	-10.892	1.521	-7.162	0.000
				d	x^2	0.272	0.024	11.140	0.000
Total (thinning)		0.407	[F(2,866)=296.957, p=.000]	Constant		241.455	29.200	8.269	0.000
				d	x	-13.776	1.999	-6.893	0.000
				d	x^2	0.334	29.200	8.269	0.000
Total (clearfell)		0.533	[F(2,335)=191.258, p=.000]	Constant		214.395	43.124	4.972	0.000
				d	x	-11.547	2.608	-4.427	0.000
				d	x^2	0.270	0.039	6.998	0.000
Total less movement (all plots)	$T_{tree}^{-A\&G}$	0.479	[F(2,1204)=553.299, p=.000]	Constant		193.557	19.704	9.823	0.000
				d	x	-10.869	1.294	-8.399	0.000
				d	x^2	0.269	0.021	12.954	0.000
Total less movement (thinning)		0.463	[F(2,866)=373.274, p=.000]	Constant		237.341	24.895	9.534	0.000
				d	x	-14.364	1.704	-8.430	0.000
				d	x^2	0.338	0.028	11.880	0.000
Total less movement (clearfell)		0.574	[F(2,335)=225.346, p=.000]	Constant		180.366	38.088	4.735	0.000
				d	x	-9.749	2.304	-4.232	0.000
				d	x^2	0.240	0.034	7.045	0.000
Process (all plots)	$T_{tree}^{process}$	0.427	[F(2,1204)=448.729, p=.000]	Constant		154.661	17.138	9.025	0.000
				d	x	-9.283	1.126	-8.247	0.000
				d	x^2	0.223	0.018	12.315	0.000
Process (thinning)		0.417	[F(2,866)=309.348, p=.000]	Constant		189.426	21.756	8.707	0.000
				d	x	-12.214	1.489	-8.202	0.000
				d	x^2	0.282	0.025	11.314	0.000
Process (clearfell)		0.502	[F(2,335)=168.525, p=.000]	Constant		178.945	32.987	5.425	0.000
				d	x	-10.046	1.995	-5.035	0.000
				d	x^2				
Fell (all plots)	T_{tree}^{fell}	0.266	[F(2,1204)=218.546, p=.000]	Constant		38.896	6.826	5.698	0.000
				d	x	-1.586	0.448	-3.538	0.000
				d	x^2	0.047	0.007	6.473	0.000
Fell (thinning)		0.240	[F(2,866)=136.898, p=.000]	Constant		47.915	8.444	5.674	0.000
				d	x	-2.150	0.578	-3.720	0.000
				d	x^2	0.057	0.010	5.874	0.000
Fell (clearfell)		0.406	[F(2,335)=114.572, p=.000]	Constant		1.420	13.875	0.102	0.919
				d	x	0.297	0.839	0.353	0.724
				d	x^2	0.021	0.012	1.725	0.086

5.5.8.2 Comparison of Clearfell to Thinning

Whilst significant differences were found between treatments for many of the elements in section 5.5.7, no consistent pattern was discernable in terms of treatment time-consumption for the four work elements in 5.5.8; the relative position of treatment changing between work elements and along the diameter distribution. Many studies (e.g. Nurminen *et al.*, 2006; Hånell *et al.,* 2000; Eliasson *et al.*, 1999) separate clearfell data from thinning data in analysis and this approach was investigated to see if differences warranted separation in this study.

To test if the curves representing thinning and clearfelling were the same, the intercept and slope parameters of the quadratic curves were statistically compared. Treatment was recoded as either thinning or clearfell and used as the independent variable and diameter and diameter squared were used as covariates. The slopes (d and d^2) of all four curves were found to be significantly different whilst the intercepts were found to be significantly different for *total less movement* (less A & G) and for *fell.* The F-values and respective significance are presented in Table 5.15.

Table 5.15 Summary of work element time-consumption ANCOVA between clearfelling and thinning

Work Phase	Group	Mean	Std. Dev.	N	F-test	Intercept F	Intercept Sig.	d F	d Sig.	d^2 F	d^2 Sig.
Total	Thinned	135.9125	63.91456	869	[F(1,1201)=48.943, p=.000]	0.236	0.627	33.438	0.000	73.512	0.000
	Clearfell	132.8876	62.25471	338							
	Total	135.0655	63.44297	1207							
AG	Thinned	118.4453	57.26809	869	[F(1,1201)=19.700, p=.000]	1.417	0.000	45.200	0.000	95.753	0.000
	Clearfell	124.4704	57.53823	338							
	Total	120.1326	57.38385	1207							
Process	Thinned	82.94131	48.0221	869	[F(1,1201)=6.613, p=.010]	0.063	0.802	46.369	0.000	91.018	0.000
	Clearfell	90.72189	46.08796	338							
	Total	85.12013	47.59792	1207							
Fell	Thinned	35.50403	16.33073	869	[F(1,1201)=40.637, p=.000]	7.913	0.005	7.119	0.001	19.016	0.000
	Clearfell	33.74852	17.76099	338							
	Total	35.01243	16.75466	1207							

5.5.8.3 Regression Analysis of Rate of Work

Regressions of work-phase rate in centiminutes per cubic metre were performed against tree diameter with power curves ($y = a \cdot x^b$) selected as the optimal balance of best fit and curve simplicity defined through Akaike scoring (Burnham & Anderson, 2002; Akaike, 1981). The calculated curves are presented in Figure 5.25 and the details of parameters in Table 5.16. The curves for all-plot data are presented together in Figure 4.26 to enable easier comparison.

In all regressions clearfell rate is highest and thinning lowest with all-plot data between them.

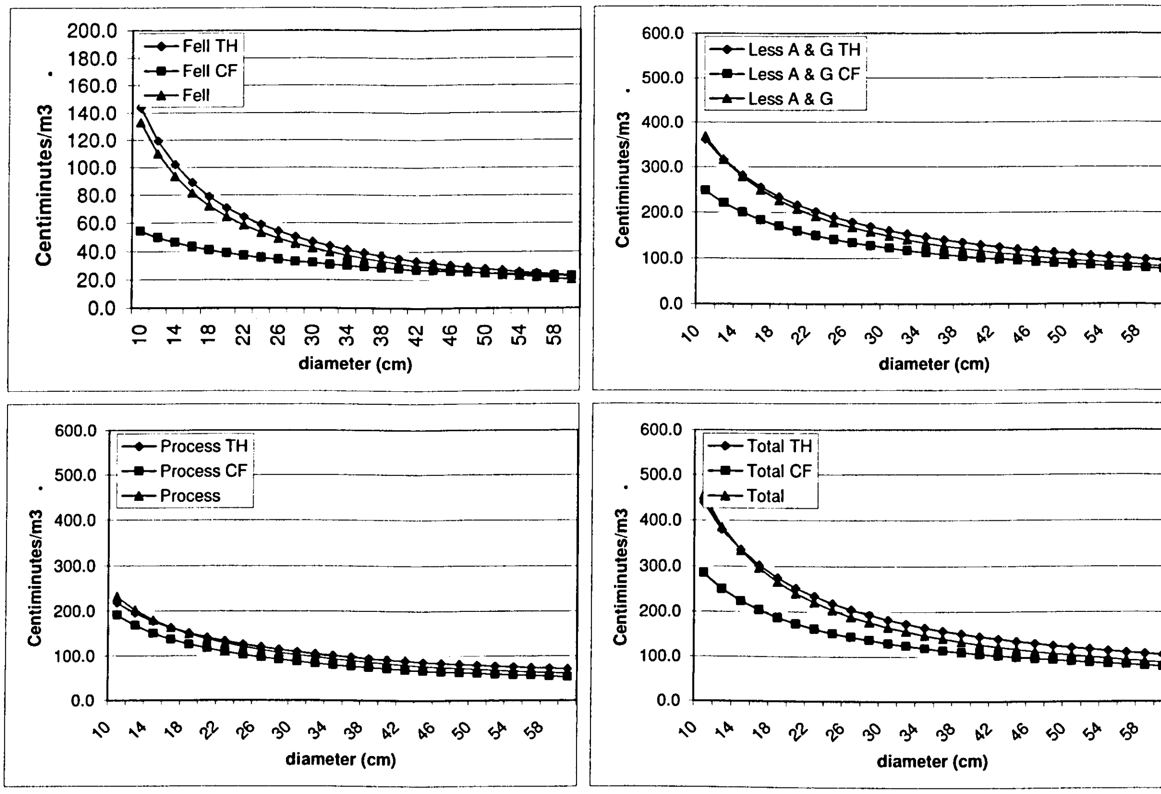


Figure 5.25 Fitted curves for work rate in relation to tree diameter for work elements; Fell, Total less movement (A & G), Process and Total

Curves are presented for all plot data, for thinned plots (TH) and the clearfell (CF).

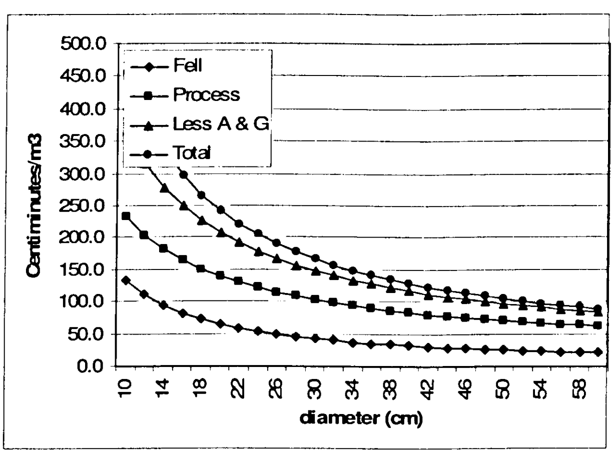


Figure 5.26 Work rate in relation to tree diameter for work elements; Fell, Total less movement (A & G), Process and Total

Curves are presented for all plot data.

Table 5.16 Summary of regression analysis of per-tree cyclic work rate

All rate values in centiminutes per cubic metre.

Work phase model	Dependent variable	R^2	F-test	Term		Constant / Coefficient Estimate	Std. Error	t-test t-value	p
Total (all plots)	R_{tree}^{total}	0.306	[F(2,1204)=266.049, p=.000]	Constant		736.150	31.271	23.541	0.000
				d	x_1	-31.617	2.054	-15.394	0.000
				d	x^2	0.421	0.033	12.755	0.000
Total (thinning)			[F(2,866)=296.957, p=.000]	Constant		241.455	29.200	8.269	0.000
				d	x_1	-13.776	1.999	-6.893	0.000
				d	x^2	0.334	29.200	8.269	0.000
Total (clearfell)			[F(2,335)=191.258, p=.000]	Constant		214.395	43.124	4.972	0.000
				d	x_1	-11.547	2.608	-4.427	0.000
				d	x^2	0.270	0.039	6.998	0.000
Total less movement (all plots)	$R_{tree}^{-A\&G}$	0.326	[F(2,1204)=291.828, p=.000]	Constant		643.367	24.713	26.034	0.000
				d	x_1	-28.077	1.623	-17.298	0.000
				d	x^2	0.383	0.026	14.685	0.000
Total less movement (thinning)			[F(2,866)=373.274, p=.000]	Constant		237.341	24.895	9.534	0.000
				d	x_1	-14.364	1.704	-8.430	0.000
				d	x^2	0.338	0.028	11.880	0.000
Total less movement (clearfell)			[F(2,335)=225.346, p=.000]	Constant		180.366	38.088	4.735	0.000
				d	x_1	-9.749	2.304	-4.232	0.000
				d	x^2	0.240	0.034	7.045	0.000
Process (all plots)	$R_{tree}^{process}$	0.216	[F(2,1204)=165.514, p=.000]	Constant		419.369	20.063	20.903	0.000
				d	x_1	-18.096	1.318	-13.733	0.000
				d	x^2	0.251	0.021	11.868	0.000
Process (thinning)			[F(2,866)=309.348, p=.000]	Constant		189.426	21.756	8.707	0.000
				d	x_1	-12.214	1.489	-8.202	0.000
				d	x^2	0.282	0.025	11.314	0.000
Process (clearfell)			[F(2,335)=168.525, p=.000]	Constant		178.945	32.987	5.425	0.000
				d	x_1	-10.046	1.995	-5.035	0.000
				d	x^2				
Fell (all plots)	R_{tree}^{fell}	0.303	[F(2,1204)=261.091, p=.000]	Constant		223.998	10.220	21.917	0.000
					x_1	-9.981	0.671	-14.869	0.000
					x^2	0.132	0.011	12.210	0.000
Fell (thinning)			[F(2,866)=136.898, p=.000]	Constant		47.915	8.444	5.674	0.000
				d	x_1	-2.150	0.578	-3.720	0.000
				d	x^2	0.057	0.010	5.874	0.000
Fell (clearfell)			[F(2,335)=114.572, p=.000]	Constant		1.420	13.875	0.102	0.919
				d	x_1	0.297	0.839	0.353	0.724
				d	x^2	0.021	0.012	1.725	0.086

5.5.8.4 Discussion of Cyclic Per-tree Analysis

5.5.8.4.1 Regression Analysis of Time Consumption

The series of regressions shows that the overall shape of the diameter:time-consumption relationship was not linear, although the diameter range of 25 to 36 cm (the diameter range covered by sections 5.5.6 and 5.5.7) can be seen to be describable through a linear expression.

When compared with other studies a number of things become apparent. The majority of shortwood harvester studies have been undertaken in Scandinavia and the mean tree size of studied trees is smaller than that at Trallwm. Figure 5.27 compares per-tree time-consumption curves from published studies (where regression parameters were provided) against the derived curve for all trees felled at Trallwm. Most published study data cover diameter ranges from around 10 to 30 cm (Johansson, 1996 and Lageson, 1996). The study by Nurminen *et al.* (2006) covers a wider range owing to including study of final fellings, rising to around 38 cm. In comparison, the smallest felled tree at Trallwm had a diameter of 13.4 cm and only 23 trees were below 18 cm.

The published curves, whilst all quadratic, are far more linear in form than that for Trallwm and there is reasonable consensus between curves up to their intersection with the Trallwm curve at around 22 cm. The curve of Nurminen *et al.* (2006) shows much higher time-consumption in diameters larger than 20 cm which is surprising as the machines studied include Timberjack 1270B & 1270C, Ponsse Ergo and Valmet 911.1, machines comparable in power and specification to the Sleipner used at Trallwm. The curve by Lageson (1996) shows lower time-consumption and the curve by Johansson (1996) follows the form of the Trallwm curve from 24 cm to its end.

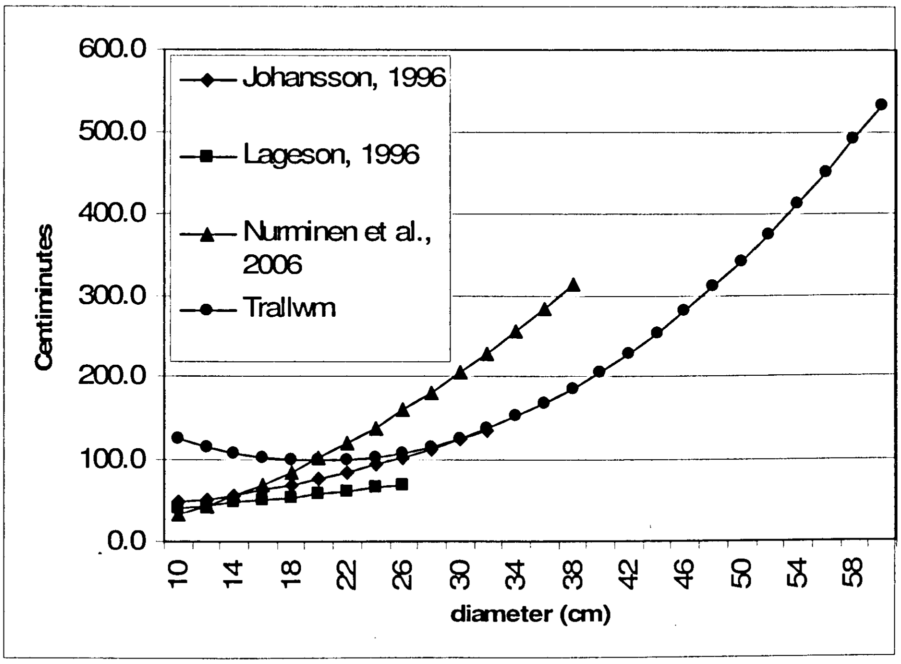


Figure 5.27 Comparison of published per-tree time-consumption curves with that derived for Trallwm

The curves presented by Kärhä *et al.* (2004) show regressions for a Timberjack 770 and a Nokka Profi. No parameters were given so the curves cannot be re-plotted, but with visual comparison they appear to take a very similar line to that of Johansson (1996): linear to around 34 cm and rising more steeply after 40 cm.

Due to the diameter ranges studied at Trallwm it is likely that the regressions performed are statistically biased towards mid-size diameters; 60% of felled trees had diameters between 24.2 and 35.5 cm and 90% between 20.0 and 40.7 cm. The choice of a quadratic curve as the optimal model solution is still retained however, even when the data set is constrained to points between 20 and 40 cm.

The relationship provides higher values than published studies in diameters smaller than 20 cm. It is unlikely that per-tree time consumption will start to rise in smaller trees, the only likely argument for this being that smaller trees are more liable to hang-up during felling and can prove difficult to push through neighbouring crowns. More likely is that the fall in work rate in smaller diameters is an artefact of the data-point distribution in the quadratic regression. If this is the case, the relationship is likely to be more akin to the published studies previously mentioned, the "true" curve a combination of Trallwm and that of Johansson (1996). The curve presented for felling in the clearfell may in fact show the more correct relationship than that for thinning or all trees. With regard to the constraints of the Trallwm data-set, Figure 5.28 is presented to show the Trallwm curve constrained to the diameter range achieved by removing the 5% smallest and 5% largest diameter trees.

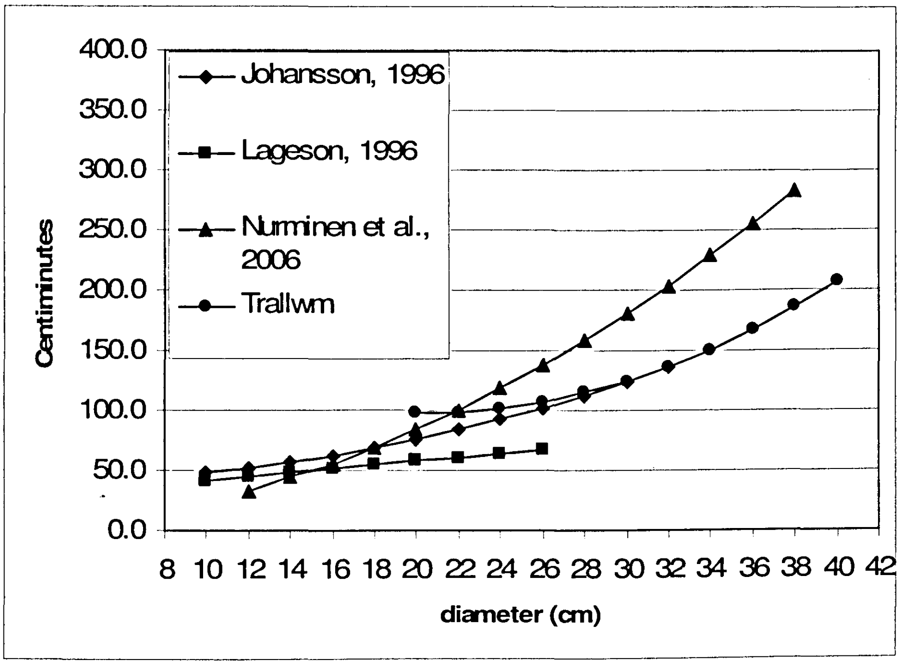


Figure 5.28 Comparison of published per-tree time-consumption curves with that derived for Trallwm constrained to 90% of sample diameter range

5.5.8.4.2 Comparison of Clearfell to Thinning

As all four comparisons of element curves (total, total less A&G, Process and Fell) showed significantly different slopes and the intercepts for total less movement and fell were also significantly different it seems that the approach taken by studies such as Nurminen *et al.*, (2006), Hånell *et al.,* (2000) and Eliasson *et al.* (1999) in separating clearfell work from thinning seems justified.

As significant differences were found in this test, homogeneity of slope could not be proved and there is a suggestion that treatment interacts with the covariates. As the covariates in this instance were diameter this is unsurprising.

5.5.8.4.3 Regression Analysis of Work Rate

Analysis of work rate indicated that it increases with tree diameter, the time per cubic metre handled reducing as tree diameter rises.

The decrease in time taken per unit volume with increasing tree diameter is caused by time consumption increasing almost linearly with diameter whilst volume increases at a rate closer to the square, leading to an inverse relationship. This agrees with published work e.g. Nurminen *et al.* (2006), Kärhä *et al.* (2004) and Kellogg & Bettinger (1994).

A comparison is made in Figure 5.29 of the change in work rate with diameter in the Scandinavian studies as presented in Figure 5.28. The time taken per unit volume to fell and process can be seen to decrease in all studies. The relationship described by Nurminen *et al.* (2006) has a shallower form than the other Scandinavian studies suggesting a work rate that changes little over the studied diameter range in contrast to the much higher changes in rate described by Johansson (1996) and Lageson (1996). The slope of the relationship is more similar to that of the Trallwm study but shows markedly lower work rates. As stated in 5.5.8.4.1, the machines studied by Nurminen *et al.* (2006) were similar in capability to the Silvatec used at Trallwm and so it is strange that productivity rates should differ so markedly. As discussed in 5.5.8.4.1, the forms of the relationships published by Johansson (1996) and Lageson (1996) show general agreement with that of the Trallwm study and a generalised relationship could be created by the combination of curves at around 22 cm.

Work rates were converted to productivity values of m^3/PMH and are presented for Trallwm clearfell, thinning and all-plot data in Figure 5.30. The clearfell productivity curve shows around 40% higher productivity across the range of diameters than that of the combined thinning curve. The interpretation of this must consider the effect of the higher site index found in the clearfell (GYC 26) compared with those of the thinning plots (GYC 16-24). A tree of a given diameter will have a greater volume on higher index sites, so increasing productivity. Given equal site indices the difference between thinning and clearfell will be less. The difference in productivities is also due to the thinning intensity of 20% reduction of basal area. A greater reduction of basal area would increase productivity of thinning and reduce the difference between the two curves further. Analysis and discussion of this subject is pursued further in Chapter 7.

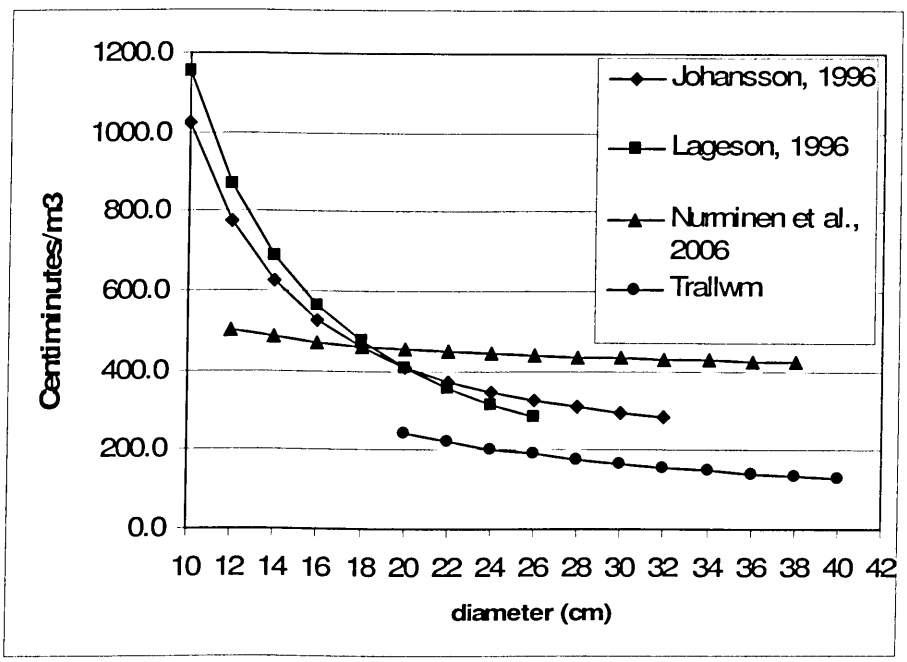


Figure 5.29 Comparison of published time-consumption per unit volume curves with that derived for Trallwm constrained to 90% of sample diameter range

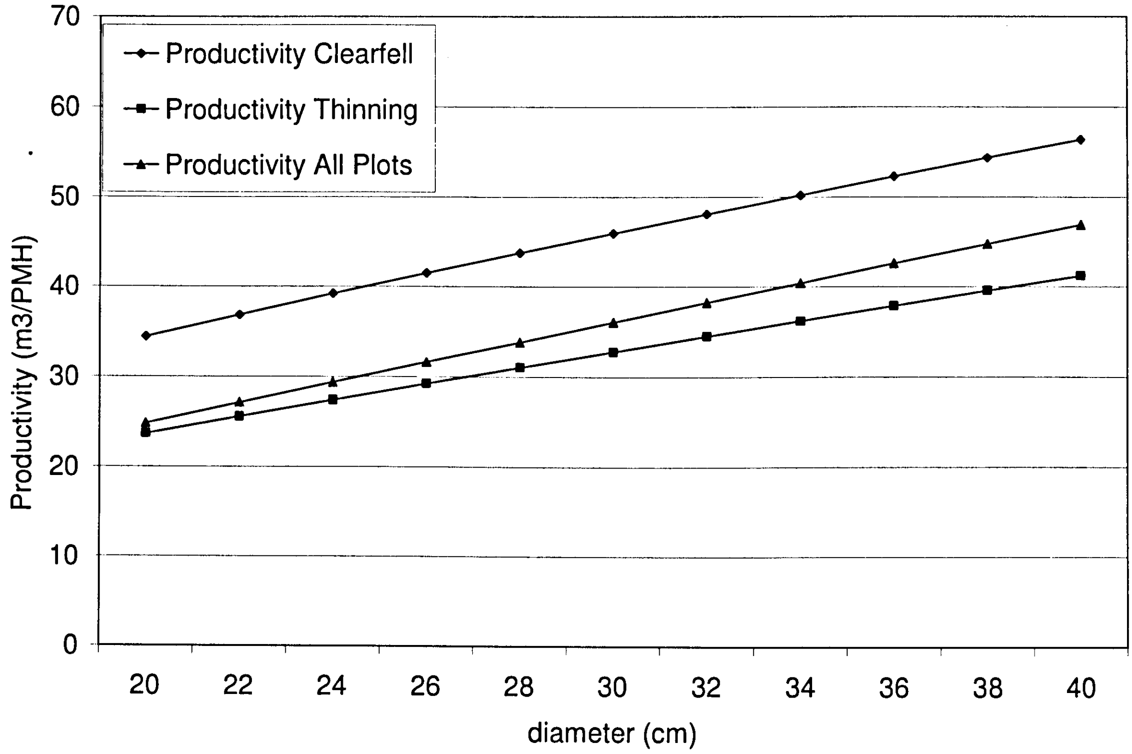


Figure 5.30 Comparison of delay-free productivities derived from work rate regressions for Trallwm constrained to 90% of sample diameter range

5.6 CONCLUSIONS

5.6.1 Work Elements

5.6.1.1 Non-cyclic Work

Non-cyclic work was found to be, in general, strongly influenced by terrain conditions and the regularity of racking and so generally influenced by the effect of treatment on felled tree diameter range.

Time consumption for inspect and consider was most influenced by the regularity of the racking network, an additional 10 m of track leading to an approximate increase of 0.53 cmin per tree and 50 m rack leading to approximately 1.18 cmin per tree.

Move between rack time-consumption (C3) also shows that a more regular racking system leads to lower total time-consumption. Time-consumption for this element decreases with increasing rack and track use, a decrease of 600 cmin corresponding to an increase of 1300 cmin or more for movement (A0) and manoeuvre (A9) time. A more regular rack layout will therefore lead to lower movement time and lower overall time-consumption.

Time spent manoeuvring was also found to be attributable to the regularity of the rack network, poorer networks requiring a greater length of track which in turn requires the harvester to manoeuvre more to pass through the stand.

Route preparation was found to be more closely associated with the difficulty of the terrain, steeper slopes and soft soils requiring more work and so higher time-consumption per used metre.

Of the commonly used non-cyclic elements, the exception was log stacking as time consumption was linked with felling time consumption. Time-consumption rose with felling time-consumption (C0) and mean duration rose with the complexity of product assortment mix.

Some of the less frequently used work elements also provide an insight into the causes of increased time-consumption. The minor component choice of harvester head measuring wheel was identified as responsible for a 6 cmin per tree rise in time-consumption.

5.6.1.2 Cyclic Work

In comparison with non-cyclic elements, cyclic work was found to be far more correlated with tree spacing, size and morphology. Spacing of felled trees can be seen as describing the concentration of working whilst tree size and morphology describe the difficulty of working. For a given stand, different treatments will cause the mean felled tree size and morphology to alter as well as their relative spacing. Cyclic work can therefore be seen to be greatly controlled by treatment.

Movement time per tree was found to be best described by a combination of felled tree spacing and length of rack which together described the concentration of working along the rack network. Decreasing tree spacing reduces time-consumption by concentrating working; whilst increasing rack length, as in non-cyclic work, increases time taken and decreases concentration of working. The protocol used (Technical Development, undated (a)) did not include any provision for calculating speed so it is impossible to compare activity with the forwarder and investigate if treatments had similar effects on both vehicles.

Felling time, due to being a less specific element than in other studies (e.g. Eliasson, 1998; Kellogg & Bettinger, 1994) was found to be influenced by both felled tree spacing and tree size and morphology. Increases in felled tree spacing increased time consumption associated with moving of the boom. Increasing tree size increased felling time as the tree required more effort to fell. The surprising finding was that increasing c/h ratio aided in felling, presumably by increasing crown weight and hence reducing the likelihood of hanging up. Although c/h tends to be positively correlated with tree diameter, there is enough variation that different thinning prescriptions could remove larger crowned (crown thinning) or smaller crowned (low thinning) in a diameter class. The effect is certainly not inconsiderable, a tree of 30 cm diameter felled at a relative felling spacing of 9 m will require 5% less felling time (around 2 cmin) with an increase in c/h of 0.05.

In retrospect, study of this element is likely to have yielded more if it had been split into components such as boom-out, attach head, cut and fell. As such it is certainly worth considering reviewing the used protocol for future studies.

Processing time was found to be dictated by c/h ratio, time consumption rising very quickly with increasing branchiness. Rises in time consumption outweigh any savings made in felling, an increase from 15.3 to 46.8 cmin/tree occurring with the rise of c/h from 0.5 to 0.7, equivalent to an increase of 7.88 cmin/tree for a rise of 0.05 in c/h and its saving of 2 cmin/tree.

Time consumption involved with processing was found to be best described overall by product volume percentage, which itself is directly affected by tree diameter. Time consumption showed many parallels with the relationships between assortment volumes and tree diameter, logs being the most correlated to tree size due to their position in the stem and primary products such as 495 cm logs and 375 cm bars showing less variation than secondary products (315 cm log and 254 cm bar).

Density of working, measured through felled tree spacing, was also found to be predominantly responsible for aside-top time-consumption as boom movement time increased with spacing.

Trimming of logs and tree butts was found to be strongly related to tree volume. Although time consumption rises quickly with volume, a likely rise of 4.8 to 8.1 cmin/tree occurring with a volume increase of 0.55 m^3 to 0.95 m^3, total time consumption is not particularly different between plots or treatments because per-tree increases are balanced by an overall reduction in number of felled trees.

5.6.1.3 Cyclic Work Per-tree

Derived per-tree diameter:time-consumption relationships showed a quadratic form, increasing with diameter. Work rate also increased with diameter, the time taken per cubic metre decreasing with increasing tree diameter, indicating greater productivity in larger tree sizes.

As one of the greatest effects of treatment is to alter the mean felled tree diameter in comparison to the stand mean, the treatment type can be seen to greatly influence pre-tree time consumption and work rate, low thinning requiring less time per tree than crown thinning but taking longer per cubic metre processed.

The diameters sampled in the study were larger than those generally found in Scandinavian studies, covering the "mid" diameter ranges of around 20 to 40 cm compared with "small" diameters of 10 to 25-30 cm. The Trallwm sampled diameter range and distribution causes the derived relationships to be doubtful for diameter values below 20 cm and above 40 cm, however there appears to be general agreement with other studies on the form of the relationship passing from small to mid diameter range.

Future work is needed on the "large" diameter classes of 35-40 cm and above, investigating harvester working at its upper limit. This is of particular importance as there is likely to be a future increase of larger trees and crown thinning if CCF management is pursued.

All curves describing diameter:time-consumption were found to be significantly different between thinning and clearfell, suggesting that, like in other studies, they should be treated separately.

5.6.2 Harvesting Head Calibration and Measurement Check

The checks carried out on harvester head calibration and accuracy suggest that the head was measuring within acceptable limits during the study. A mean volume error of 0.89% (range 0.14% to 1.22%) was calculated for all plots which is equivalent to an error of between 0.1 and 0.8 m^3/ha and comparable to other studies published.

Some outliers may have been caused by product form or problems associated with peeling bark, however most were unattributable.

5.6.3 Products Cut and Assortments

Shortwood harvesting carries out primary processing at stump and like secondary and tertiary processing, cubic recovery percentage (CR%) was found to rise with diameter, levelling out at around 30 cm. The form of the diameter:CR% relationship is uncertain after tree diameter exceeds 50 cm however, as limited data were available in larger diameter classes and it is uncertain how much the 60 cm maximum butt diameter limit will decrease values as trimming becomes necessary for oversize butts.

Thinning type affects product assortment proportions by altering mean felled tree diameter in relation to initial mean diameter. Crown thinning will fell larger trees relative to the stand mean and low thinning smaller.

Diameter was found to be a good predictor for assortment percentage, better regressions being achieved overall if log and bar types were amalgamated (495+315 & 375+254).

Log percentage was found to rise with diameter, levelling off at around 90%, whilst bars, stake and pulp percentage declined. The more random nature of pulp and secondary products such as 315 cm logs and 254 cm bars causes a less defined relationship with diameter and is the reason why combining product types improves overall description.

Mean piece volume was also found to increase with tree diameter, 495 cm logs showing the highest rate of rise and strongest correlation due to their position in the stem and also due to their inability to be cut into a larger class as product size increases, but must simply get larger.

5.6.4 Rack Usage

Study showed that similar proportional area coverage was achieved in all plots, although the rack length needed for this was different between plots.

Plot topography and ground conditions within the stand were found to influence initial rack density although adaptation to topography could lead to higher density as in plot 3 or lower density as in plot 5.

The study caused rack usage to be to some extent an artefact of working within the plots. Small pockets of plot were not covered and portions of rack network were not travelled in deviation from normal working as it could be seen that no work was needed in that area.

Treatment was found to influence used rack length, crown thinning requiring more than low thinning, a change in SG from 0.74 to 1.38 accounting for a reduction in 128m of rack.

Brash lay-down was not found to be treatment specific and was not well correlated with the number of trees removed.

CHAPTER 6: FORWARDER STUDY

6.1 INTRODUCTION

The forwarder is half of the shortwood harvesting system, collecting produce cut by the harvester from rack-side and transporting it to stacking areas where it is piled for collection and transport to mill by lorry.

The forwarder studied was a Timberjack 810b, a small thinnings forwarder weighing around 11,000kg and with a 13.0-17.4 m^3 bunk space. The Timberjack 810b has now been superseded by the John Deere 810d, although there is a great deal of commonality between the two machines (John Deere, 2006). The 810b was chosen by the experienced contracting team over larger capacity machines as the majority of work to be undertaken at Trallwm was thinning, the seven thinning plots and the stands surrounding them, with only the one patch of clearfelling (plot 7). Forwarder working was organised as multiple pass, the operator normally loading only two products from the drift. A large product was loaded parallel to the bunk and the second, smaller product was loaded behind it, laid parallel or perpendicular to the bunk depending on product lengths.

6.1.1 Aims

- Identify differences in forwarder working between treatments
- Identify, if possible, the causes of any treatment differences
- Relate forwarder working as far as possible to harvester working and stand parameters

6.2 LITERATURE REVIEW

As forwarder working within the shortwood system is inherently tied to harvester working, the Chapter 4 literature review covers both machines and as such covers the literature pertinent to this chapter.

Forwarder studies are not as abundant as those of harvesters. Nurminen *et al.* (2006) speculate that the disparity may be due to research perception: forwarders are "perhaps considered to be a mature technology that needs no extra research". Variation in approach is also noted, North American studies being more likely than European to consider harvester and forwarder together.

The most significant published work is that by Nurminen *et al.* (2006) who covered shortwood harvesting in Finland in detail and gave the forwarder study equal weight to that of the harvester. This is the most modern work on forwarders, studying both modern machines and working techniques and can be considered an update to previous Scandinavian studies.

Other studies of note are those by Lanford & Stokes (1996) and Kellogg & Bettinger (1994). Both are North American and consider the shortwood system as a whole.

6.3 METHOD

6.3.1 Forwarder Time Study Method

As with the harvester time study, the forwarder study aims to ascertain differences in working due to intervention type. As such, much of what is said about the harvester study in 5.5.1 can be applied here to identifying work elements affected by treatment in the forwarder study.

6.3.1.1 Time Study

The time study was carried out using the protocol set out in HM5 (Technical Development, undated b) which is included in full in Appendix 2.13. The time study was recorded on a Husky FS-2 data-collector using Forestry Commission Technical Development software.

The field data collection was conducted by Duncan Ireland of Technical Development, Forest Research, Forestry Commission. Data editing and analysis was carried out by the author.

6.3.1.2 Changes in Protocol

The protocol was used as presented with no alteration to the application of codes. Travel codes were assigned to aid in separation of movement within the plots from that outside. Movement by the forwarder was broken down and classified as:

- In and out Road (A & H) covered travel on the metalled forest road
- In and out Ride (B & F) covered travel within the stand on racks between the road and the plot boundary
- In and out Rack (C & F) covered travel on racks within the plot boundary
- In and out Wood (D & E) covered travel off racks within the plot boundaries

All movements were allotted a distance travelled, calculated using pre-measured markers along the route.

6.3.1.3 Product Specifications

Product types forwarded were the ones cut by the harvester. Product codes used in the forwarder study varied slightly from those in the harvester and are presented in Table 6.1. Prices presented are the revenue returned to the forest owner for the standing sale.

Table 6.1 Product codes and dimension specifications for forwarder time study

Product	Vehicle-log product code	Time study product code	Length (cm)	maximum base diameter (cm)	minimum top diameter (cm)	Sale value to owner (£/tonne)
Log	111	1	495	60	18	£16.90
Small Log	112	2	315	60	18	£14.00
Bar	113	3	375	-	14	£8.65
Small Bar	114	4	254	-	14	£6.70
Stake	115	5	172	13	7.5	£8.00
Pulp	127	6	300	-	8	£0.25

6.3.1.4 Defining Working in Plots

As described in 2.3.1.4 and 5.5.1.3, plot boundaries were marked on the ground by spraying paint dashes along the ground. Movement within the plots was recorded in accordance with HM5 (Technical Development, undated (b)), starting when the rearmost axle of the forwarder moved over the boundary line and finishing in the same manner.

6.3.2 Forwarder Time Study Data Processing

6.3.2.1 Forwarder Data Files

The forwarder study produced only one data file; a delimited text file downloaded from the Husky and imported into EXCEL.

6.3.2.2 Forwarder Time Study Data Log

The forwarder data-log took the same form as that produced for the harvester (see 5.5.3.3), a text file consisting of an activity code and time stamp delimited by an = sign for each activity observation.

A full cyclic sequence would include both travel into and out of the plot and loading and unloading of the forwarder and as such is too long to present in the text. Sample output is included in Figure 6.1, taken from study FW0103 (plot 3).

The forwarder moves in road towards the plot (A) and covers 5 metres on the road (measurement J1, value 5). The forwarder moves into the wood outside of the plot boundary (move in ride B) and travels for 30 metres (measurement J2, value 30). The forwarder then moves into the plot (travel in rack C) and travels 5 metres (measurement J3, value 5). The forwarder then starts to load pulp (L6), five pieces followed by a manoeuvre (K) and then another five pieces, followed by an adjustment of the loaded produce (A8). Produce by the rack-side is sorted to aid future loading (D2) after which two small bars are loaded (L4). The forwarder next continues to move along the rack (C) for 15 metres (J315). The last two lines show the forwarder to have stopped and loaded two pieces of pulp which are subsequently adjusted in the bunk.

```
03I1A=132685
03J15=132693
01A=132700
01B=132736
04J230=132756
01C=132780
03J35=132796
01C=132798
03L65=132831
01K=132836
03L65=132875
02A8=132893
02D2=132918
03L42=132953
01C=132956
04J315=132978
01C=132986
03L62=133006
02A8=133018
```

Figure 6.1 Sample of Husky log text file for forwarder

6.3.2.3 Forwarder Data Log Handling, Checking and Editing

The forwarder data log was imported into the same EXCEL base file used for the harvester and described in 5.5.3. The time stamp for each activity was broken down into hours, minutes and centiminutes and used to calculate code duration. Memos, load cycle and movement measurement codes were removed from the sequence (but kept for reference) so that time stamps ran sequentially and code duration could be calculated. Loading cycles were identified and alternately coloured to aid in visual interpretation.

Manual editing identified and corrected erroneous codes, allocated movement distance to each move time and calculated speed, allocated number of pieces and type of product to each load or unload time and calculated grapple volume based on plot mean piece volume.

6.3.2.4 Use and description of elements

Tables 6.2 and 6.3 present the elements studied, their use and their breakpoints. Time consumption associated with the elements is presented in section 6.4. The full time-study protocol (Technical Development, undated (b)) is presented in Appendix 2.13.

Table 6.2 Movement and loading elements used in the forwarder time study

Operation	Code	Element	Breakpoint	
			Start	Stop
Move in road	A	Move on forest road to plot	All wheels start to move on road	Rear wheels exit from road or next element starts
Move in ride	B	Move off-road to plot	All wheels start to move off-road	Rear wheels enter plot or next element starts
Move in rack	C	Move on racks in plot	All wheels start to move in plot	Rear wheels exit from plot or next element starts
Move out rack	F	Move on racks moving out of plot	All wheels start to move out plot	Rear wheels exit from plot or next element starts
Move out ride	G	Move off-road away fro plot	All wheels start to move out of plot	Rear wheels move onto road or next element starts
Move out road	H	Move on forest road away from plot	All wheels start to move on road	Rear wheels exit from road or next element starts
Move to unload	A2	Movement between timber stacks	Wheels start to move	Wheels stop moving
Load	Lxn	Load n pieces of product x	Boom starts to move	Boom stops moving or next element
Unload	Uxn	Unload n pieces of product x	Boom starts to move	Boom stops moving or next element

Table 6.3 Other elements used in the forwarder time study

Operation	Code	Element	Breakpoint	
			Start	Stop
Manoeuvre in wood	K	Manoeuvring in stand	Starts manoeuvring	Stops manoeuvring
Manoeuvre on road	A3	Manoeuvre to move from or on to road	Starts manoeuvring	Stops manoeuvring
Stack	A5	Butting-up of produce unloaded onto stacks	Booms starts to move or end of last element	Boom stops moving or next element
Stow / unstow grapple	A6	Boom movement associated with stowing and unstowing boom at the start and end of long movements	Boom starts to move or end of last element / Grapple starts to open	Grapple secured & boom stops / Boom starts to move from stowed position
Adjust load	A8	Boom movement associated with adjusting produce in bunk	Boom start to move	Start of next element
General preparation	B2	Includes getting & replacing tools	End last element	Start next element
Avoidable delay	B7	Unnecessary work	End last element	Start next element
Unavoidable delay	B8	Includes receiving instructions and answering radio/phones	End last element	Start next element
Rest & personal	B9	Does not include IPE	End last element	Start next element
Wait or talk to work study	C1	Any delay caused by study staff	End last element	Start next element
Inspect & consider	C2	Pause to plan work	End last element	Start next element
Aside brash	C4	Does not include route preparation	End last element	Start next element
Start machine	C5	Includes warm up	End last element	Start next element
Maintenance	C6	Routine maintenance e.g. lubrication of bushings	End last element	Start next element
Refuel	C7	All time associated with refuelling	End last element	Start next element
Fit / remove tracks or chains	C8	All time associated with traction aids	End last element	Start next element
Debog machine	C9	Includes all time spent getting assistance and debogging	End last element	Start next element
Aside produce to travel	D1	Movement of produce to facilitate vehicle movement	End last element	Start next element
Aside produce to load	D2	Movement of produce to facilitate future loading	End last element	Start next element
Move headboard / bolster pins	D3	All time associated with changing bunk configuration	End last element	Start next element
Prepare stacking area	D4	All time associated with improving stacking area	End last element	Start next element
Prepare route	D5	Includes movement of brash loads	End last element	Start next element

6.4 RESULTS

6.4.1 Total Time Usage

Total time usage is summarised for all plots in Appendix 24. Total observed time was compared against the sum of all element times and no difference was found, indicating all time is accounted for in the study.

Total forwarder time consumption per plot and per-hectare equivalent values are presented in Figure 6.2.

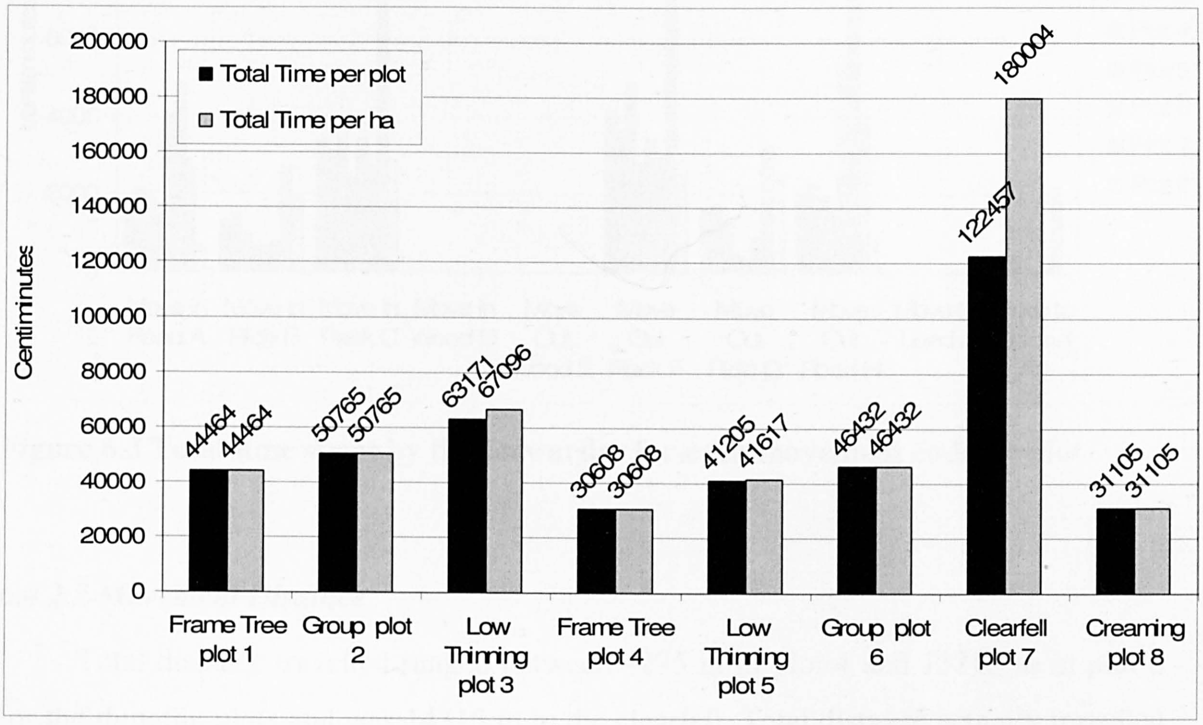


Figure 6.2 Total forwarder time consumption per plot and per hectare

6.4.2 Forwarder Movement

Forwarder movement time is summarised and presented with all other activity summary data in Appendix 24. Total time spent for each of the ten movement types is presented in Figure 6.3. Distance moved is summarised in Appendix 25 and total distance presented in Figure 6.4 for each of the movement types. Forwarder speed is summarised in Appendix 26 and mean speed in Figure 6.5 for each of the movement types.

6.4.2.1 Movement Time

Total time spent moving ranges between 9517 cmin in plot 4 and 19898 cmin in plot 6 for the thinning plots and was 36949 cmin in the clearfell. Time spent moving on racks within the plot ranged from between 5158 cmin in plot 4 to 8580 in plot 3 for the thinning plots and was 21871 cmin in the clearfell.

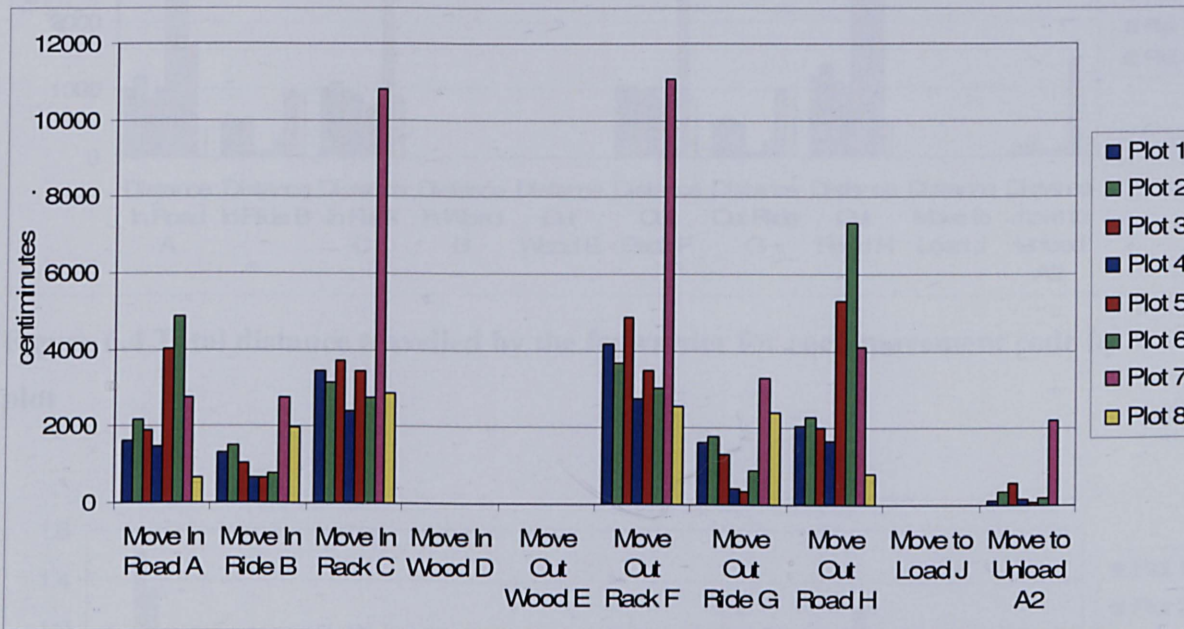


Figure 6.3 Total time spent by the forwarder for each movement code by plot

6.4.2.2 Movement Distance

Total distance travelled ranged between 4275 m in plot 4 and 13219 m in plot 6 for the thinning plots and was 14315 m in the clearfell. Total distance actually travelled on racks within the plots (move in rack and move out rack) ranged between 1568 m for plot 5 and 2130 m for plot 2 in the thinning plots and 6162 m for the clearfell.

6.4.2.3 Movement Speed

Mean speed for combined movement ranged from 0.49 m/s in plot 5 to 0.68 m/s in plot 4 for the thinning plots (0.57 m/s mean all plots, 0.35 m/s st.dev.) and was 0.57 m/s (0.36 m/s st.dev) for the clearfell. Mean speeds for travelling within the plots ranged from 0.38 m/s in plot 3 to 0.62 m/s in plot 4 (0.46 m/s mean all plots, 0.24 m/s st.dev.) and was 0.42 m/s (0.23 m/s st.dev.) in the clearfell.

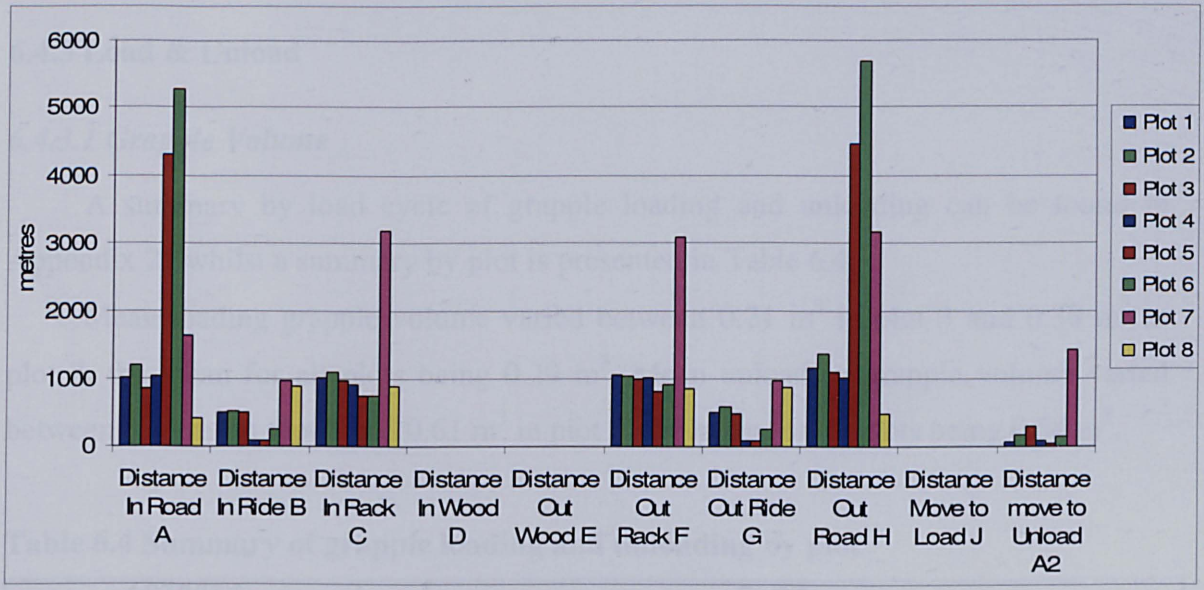


Figure 6.4 Total distance travelled by the forwarder for each movement code by plot

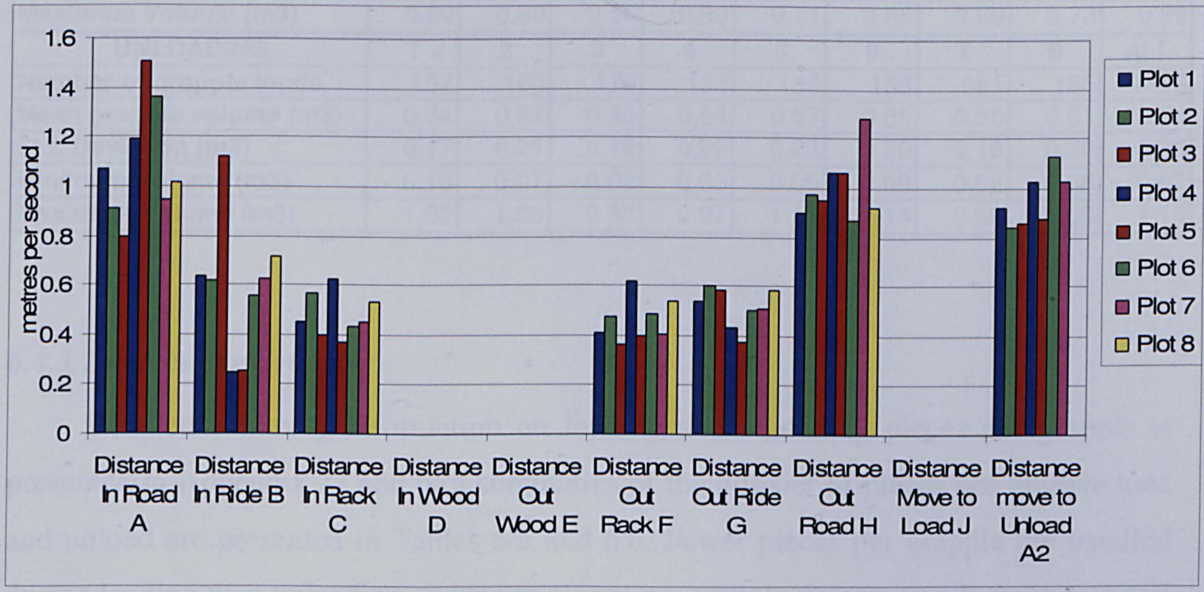


Figure 6.5 Mean forwarder speed for each movement code by plot

6.4.3 Load & Unload

6.4.3.1 Grapple Volume

A summary by load cycle of grapple loading and unloading can be found in Appendix 27 whilst a summary by plot is presented in Table 6.4.

Mean loading grapple volume varied between 0.21 m^3 in plot 3 and 0.38 m^3 in plot 8, the mean for all plots being 0.29 m^3. Mean unloading grapple volume varied between 0.45 m^3 in plot 3 and 0.61 m^3 in plot 8, the mean for all plots being 0.54 m^3.

Table 6.4 Summary of grapple loading and unloading by plot

ACTIVITY	PLOT								
LOADING	1	2	3	4	5	6	7	8	ALL
Number of grapple loads	298	308	375	234	297	288	947	168	2915
Mean grapple volume (m3)	0.29	0.27	0.21	0.30	0.26	0.31	0.32	0.38	0.29
Std. Deviation (m3)	0.19	0.16	0.12	0.21	0.17	0.20	0.16	0.22	0.18
Minimum Volume (m3)	0.02	0.02	0.02	0.03	0.02	0.02	0.02	0.07	0.02
Maximum Volume (m3)	0.89	0.60	0.50	0.80	0.71	0.85	0.89	0.73	0.89
UNLOADING	1	2	3	4	5	6	7	8	ALL
Number of grapple loads	157	160	170	132	135	159	551	105	1569
Mean grapple volume (m3)	0.54	0.52	0.45	0.54	0.57	0.55	0.55	0.61	0.54
Std. Deviation (m3)	0.17	0.21	0.18	0.22	0.23	0.20	0.18	0.20	0.20
Minimum Volume (m3)	0.10	0.07	0.02	0.03	0.05	0.09	0.02	0.08	0.02
Maximum Volume (m3)	1.00	1.08	0.86	0.97	1.12	1.14	0.99	1.06	1.14

6.4.3.2 Pieces per Grapple

Detailed summary information on loading and unloading pieces per grapple is presented in Appendix 27 and plot summaries of the number of pieces per grapple load and unload are presented in Tables 6.5 and 6.6. Fewer pieces per grapple are handled during loading than unloading and mean pieces per grapple decrease with mean tree and product size.

Table 6.5 Pieces per grapple load by plot and product

PLOT		log 495cm	log 315cm	bar 375cm	bar 254cm	pulp 300cm	stake 172cm
Frame plot 1	Mean pieces per grapple load	1.5	2.0	2.4	2	2.1	3
	Standard Deviation [range]	0.52 [1-3]	0.73 [1-4]	1.39 [1-5]	0.8 [1-4]	1.2 [1-6]	1.74 [1-9]
Group plot 2	Mean pieces per grapple load	1.6	2.0	2.3	2	3.2	5
	Standard Deviation [range]	0.5 [1-2]	0.83 [1-4]	1.11 [1-5]	1.14 [1-5]	1.87 [1-7]	2.7 [1-10]
Low plot 3	Mean pieces per grapple load	1.3	1.8	2.4	1.8	2.9	4.9
	Standard Deviation [range]	0.48 [1-2]	0.83 [1-4]	1.1 [1-5]	1.25 [1-8]	1.45 [1-6]	2.89 [1-12]
Frame plot 4	Mean pieces per grapple load	1.5	1.9	1.3	1.1	2.4	1.6
	Standard Deviation [range]	0.5 [1-2]	1.18 [1-5]	0.83 [1-4]	0.33 [1-2]	1.34 [1-5]	1.27 [1-6]
Low plot 5	Mean pieces per grapple load	1.5	2.1	3.1	1.7	2.8	3.3
	Standard Deviation [range]	0.5 [1-2]	0.84 [1-4]	1.96 [1-7]	0.96 [1-5]	1.54 [1-7]	2.03 [1-9]
Group plot 6	Mean pieces per grapple load	1.6	2.4	2.8	1.8	2.9	2.8
	Standard Deviation [range]	0.51 [1-3]	1.08 [1-5]	2.01 [1-7]	1.21 [1-6]	1.65 [1-8]	1.62 [1-7]
Clearfell plot 7	Mean pieces per grapple load	1.3	2.1	2.5	2.2	3.1	5.8
	Standard Deviation [range]	0.44 [1-2]	0.84 [1-6]	1.16 [1-6]	1.22 [1-5]	1.76 [1-8]	2.86 [1-14]
Creaming plot 8	Mean pieces per grapple load	1.5	1.9	3.7	4.6	2.2	5.0
	Standard Deviation [range]	0.5 [1-2]	0.89 [1-4]	2.31 [1-5]	2.51 [1-7]	1.35 [1-6]	2.83 [3-7]
All Plots	Mean pieces per grapple load	1.4	2.0	2.4	1.9	2.7	4.3
	Standard Deviation [range]	0.5 [1-3]	0.9 [1-6]	1.3 [1-7]	1.2 [1-8]	1.6 [1-8]	2.8 [1-14]

6.4.3.3 Loading Rate

Details of time consumption for loading and unloading can be found in Appendix 27. A summary of mean loading and unloading times is presented in Table 6.7. Mean unloading times are lower than loading in all plots and have a lower variance, the mean unload time for all plots being 28.4 cmin (st.dev. 8.3 cmin) compared with 33.0 cmin (st.dev. 12.6 cmin) for loading.

6.4.4 Other Cyclic Work elements

Table 6.8 summarises cyclic elements for all plots whilst fuller details can be found in Appendix 24.

6.4.5 Non-cyclic Work Elements

Table 6.9 indicates whether non-cyclic elements were used in at least one plot during the study. Used element details can be found in Appendix 24.

Table 6.6 Pieces per grapple unload by plot and product

PLOT		log 495cm	log 315cm	bar 375cm	bar 254cm	pulp 300cm	stake 172cm
Frame plot 1	Mean pieces per grapple unload	2.0	3.4	4.4	5.6	5.0	13.1
	Standard Deviation [range]	0.46 [1-3]	0.99 [2-6]	3.15 [1-9]	1.84 [3-8]	1.56 [1-8]	2.93 [9-18]
Group plot 2	Mean pieces per grapple unload	2.3	3.8	5.3	5.8	6.0	13.2
	Standard Deviation [range]	0.68 [1-4]	1.25 [1-6]	2.79 [1-11]	2.56 [1-9]	2.79 [1-10]	4.65 [5-18]
Low plot 3	Mean pieces per grapple unload	2.0	3.9	5.0	7.8	6.0	13.4
	Standard Deviation [range]	0.54 [1-3]	1.69 [1-7]	2.2 [1-9]	2.27 [3-11]	2.6 [2-10]	5.46 [1-20]
Frame plot 4	Mean pieces per grapple unload	1.9	3.8	3.0	4.8	5.6	4.7
	Standard Deviation [range]	0.48 [1-3]	1.48 [1-6]	1.9 [1-6]	1.33 [4-7]	2.95 [1-10]	3.83 [1-12]
Low plot 5	Mean pieces per grapple unload	2.1	4.8	5.0	6.1	6.8	12.7
	Standard Deviation [range]	0.68 [1-4]	1.55 [2-7]	2.94 [1-10]	3.2 [1-10]	2.06 [3-11]	4.36 [2-16]
Group plot 6	Mean pieces per grapple unload	2.1	4.0	5.0	5.9	6.6	11.7
	Standard Deviation [range]	0.69 [1-4]	1.19 [1-7]	2.96 [2-9]	1.68 [3-9]	1.83 [3-10]	4.74 [4-16]
Clearfell plot 7	Mean pieces per grapple unload	1.9	3.6	6.1	6.4	5.2	13.0
	Standard Deviation [range]	0.46 [1-3]	1.25 [1-6]	1.97 [2-10]	1.9 [1-10]	1.83 [1-8]	5.53 [1-22]
Creaming plot 8	Mean pieces per grapple unload	1.9	2.7	3.7	5.8	6.6	10.0
	Standard Deviation [range]	0.48 [1-3]	1.03 [1-4]	2.31 [1-5]	1.89 [3-7]	2.32 [1-11]	0 [10-10]
All Plots	Mean pieces per grapple unload	2.0	3.8	5.2	6.2	6.0	12.6
	Standard Deviation [range]	0.5 [1-4]	1.4 [1-7]	2.5 [1-11]	2.2 [1-11]	2.3 [1-11]	5.3 [1-22]

Table 6.7 Plot mean loading and unloading times All values in centiminutes per grapple.

Activity	Code	Frame plot 1	Group plot2	Low plot 3	Frame plot 4	Low plot 5	Group plot 6	Clearfell plot 7	Creaming plot 8	All Plots Mean	All Plots St.Dev
Load 495cm log	L1	34.5	38.3	40.7	36.9	35.1	36.3	30.5	33.7	33.8	12.0
Load 315cm log	L2	34.4	34.5	36.1	29.9	31.9	33.7	31.5	27.5	32.8	12.0
Load 375cm bar	L3	25.9	31.9	34.7	25.3	26.8	27.8	31.9	35.0	31.5	12.3
Load 254cm bar	L4	27.4	31.2	32.3	23.0	26.5	26.3	29.2	38.0	28.7	11.0
Load 172cm stake	L5	38.2	37.8	39.5	32.5	29.2	33.1	28.6	30.4	33.1	14.1
Load 300cm pulp	L6	33.8	40.5	44.0	24.7	30.7	30.2	34.5	20.5	35.6	13.9
All Products	-	33.7	36.2	38.1	32.0	30.8	32.8	30.9	31.9	33.0	12.6
Unload 495cmLog	U1	28.8	28.9	29.2	29.1	29.7	28.8	28.0	27.7	28.5	7.3
Unload 315cm log	U2	28.8	30.7	27.3	27.2	32.5	28.9	26.1	32.4	28.6	9.1
Unload 375cm bar	U3	33.9	28.4	29.4	23.7	30.7	33.2	30.5	26.7	29.9	11.5
Unload 254cm bar	U4	29.6	26.3	24.5	29.3	27.2	32.3	24.2	22.5	26.7	8.0
Unload 172cm stake	U5	31.6	30.1	31.3	27.7	27.5	27.7	26.6	26.2	28.5	8.3
Unload 300cm pulp	U6	24.4	30.6	26.2	27.3	31.8	29.8	27.0	26.0	27.7	8.7
All Products	-	29.2	29.2	28.4	28.3	29.8	29.3	27.6	27.9	28.4	8.3

Table 6.8 Use and duration of cyclic work elements All values in centiminutes.

ELEMENT DESCRIPTION	MANOEUVRE IN WOOD	MOVE TO UNLOAD	MANOEUVRE ON ROAD	STACK	STOW / UNSTOW GRAPPLE	ADJUST LOAD	GRADE LOGS AT UNLOADING
CODE	K	A2	A3	A5	A6	A8	A9
MEAN	19.7	8.1	17.0	16.6	15.7	16.0	NOT USED
STD. DEV	17.3	7.5	1.4	12.1	10.0	14.7	
MIN	2	1	16	1	3	1	
MAX	88	48	18	90	65	122	

Table 6.9 Use of non-cyclic work elements

ELEMENT DESCRIPTION	CODE	USED ?
CLOCK READING	B1	No
GENERAL PREPARATION	B2	Yes
ON / OFF PROTECTIVE CLOTHING	B3	No
TO / FROM CAMP	B4	No
FETCH TOOLS	B6	No
AVOIDABLE DELAY	B7	Yes
UNAVOIDABLE DELAY	B8	Yes
REST AND PERSONAL	B9	Yes
WAIT OR TALK WORK STUDY	C1	Yes
INSPECT	C2	Yes
COUNT / CHECK	C3	No
ASIDE BRASH	C4	Yes
START MACHINE	C5	Yes
MAINTENANCE	C6	Yes
REFUEL	C7	Yes
FIT / REMOVE CHAINS AND TRACKS	C8	Yes
DEBOG	C9	Yes
ASIDE PRODUCE TO TRAVEL	D1	Yes
ASIDE PRODUCE TO LOAD	D2	Yes
MOVE HEADBOARD / BOLSTERS	D3	Yes
PREPARE STACKING AREA	D4	Yes
PREPARE ROUTE	D5	Yes
TRAVEL BETWEEN WORKSITES	D6	No
TRAVEL TO / FROM WORKSITE	D7	No
WET TIME	D8	No
UNPAID MEALBREAKS	D9	No
PERIOD NOT STUDIED (PNS)	F9	No

6.5 ANALYSIS

Whilst initial results for the forwarder are presented in 6.4, and as stated for the harvester study, little about treatment effects can be concluded from these. Analysis of forwarder movement, loading and unloading, and other work elements, investigates whether increased time consumption is caused by variables that can be attributed to treatment effect or if it is due to an unaffected stand or working parameter.

Analysis of work elements first assesses differences in element duration between plots, comparing the mean length of individual element observations.

In addition, time consumption for each element can be compared against tree, plot or treatment parameters and other element values.

Avenues of investigation were identified using a correlation matrix as well as logical deduction from studying machine working methods.

The analysis aims to more fully understand cyclic and non-cyclic time consumption and how it changes with intervention and stand parameters.

6.5.1 Forwarder Movement

6.5.1.1 Vehicle Speed in Relation to Treatment Type

Of the movement codes used, only C and F, the movement on racks within the plots, are specific to the treatment type. Codes A and H describe movement along the forest road and so only reflect the position of the plot in relation to the timber stacking area. Likewise, codes B and G reflect the distance of the plot from the forest road.

To assess effect of treatment on forwarder speed, an analysis of variance test was conducted for both C and F. Significant differences were found between treatments for both C and F; respectively [$F(4,884)=11.276$, $p=0.000$] and [$F(4,924)=15.099$, $p=0.000$].

Speed for element *moving in rack* (C) in low thinning (0.38 m/s) was found to be significantly less than in all other treatments (group 0.48 m/s, frame 0.53 m/s, creaming 0.53 m/s) with the exception of clearfelling (0.44 m/s). Speed for *moving in rack* for clearfelling was also found to be significantly less than that for frame tree.

Speeds for element *moving out rack* (F) in low thinning (0.38 m/s) and clearfelling (0.40 m/s) were both found to be significantly lower than all other treatment types (frame 0.51 m/s, group 0.48 m/s, creaming 0.54 m/s).

Mean treatment values for *moving within the plots* (C+F) were 0.52 m/s for frame-tree, 0.48 m/s for group, 0.38 m/s for low thinning, 0.42 m/s for clearfelling and 0.53 m/s for creaming.

Mean *speed in rack* ($\overline{F}^{C\&F}_{speed}$), both for *move in* (C) and *move out* (F) was found to be significantly [$F(8)=59.170$, $p=0.000$] linked to the mean *distance travelled in rack* ($\overline{F}^{C\&F}_{move}$) ($\overline{F}^{C\&F}_{speed} = 0.023\overline{F}^{C\&F}_{move} + 0.212$, R^2=.881), speed increasing with the distance moved, the regression summarised in Table 6.10.

6.5.1.2 Vehicle Speed in Relation to Load

Independent samples t-tests were used to compare unloaded speed of element *move in road* (A) with loaded speed of element *move out road* (H) and unloaded / loading speed *moving in rack* (C) with loaded speed *moving out rack* (F). Data for all plots were pooled for the analysis. Moving unloaded on the road (A) (M=1.08, SD=.483) was not found to be significantly different from moving loaded on road (H) (M=1.01, SD=.362) (t(246)=1.433,p=0.153). Moving unloaded in the rack (C) (M=.456, SD=.245) was also not found to significantly different from moving loaded in rack (F) (M=.447, SD=.229) (t(1816)=.846,p=0.398).

When all plot movements were pooled, moving when loaded was only found to be significantly slower (M=1.25, SD=.233) than moving unloaded (M=1.38, SD=.417) (t(95)=2.375,p=0.020) for distances greater than 60 m.

Forwarder speed whilst unloaded, loaded and moving to load in relation to movement distance is presented in Figure 6.6.

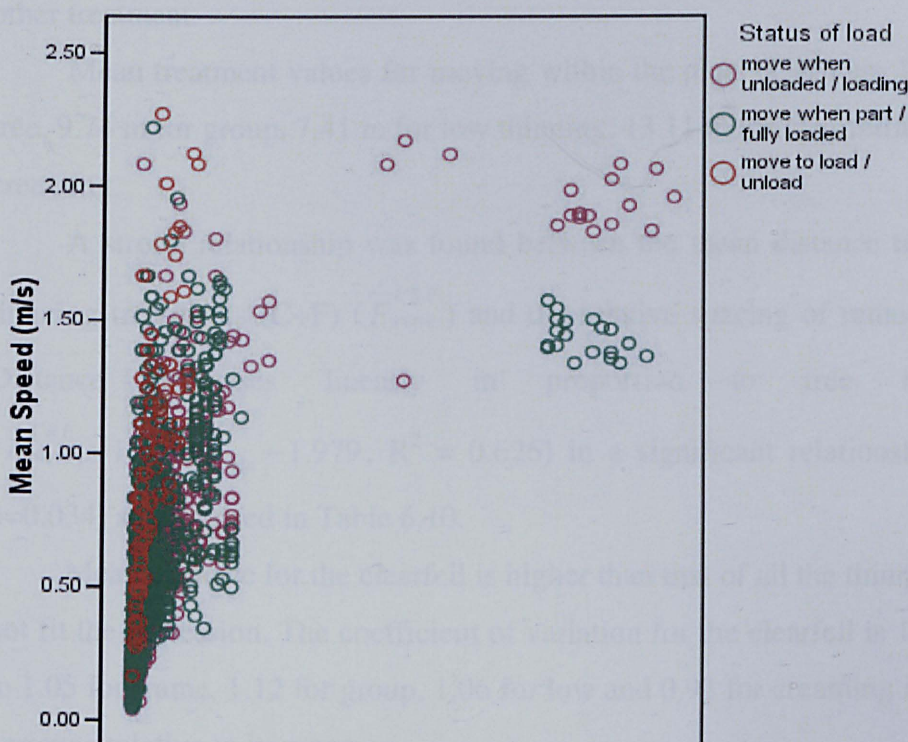


Figure 6.6 Forwarder mean speed in relation to travel distance for all plots when loading, loaded and moving to load and unload

Move when unloaded contains elements A, B and C, move when loaded contains elements F, G and H and move to load / unload contains elements J and A2.

6.5.1.3 Distance per Move in Relation to Treatment Type

To assess the effect of treatment on the distances moved by the forwarder between loading or other work, an analysis of variance test was conducted for movement distances for both C and F. Significant differences were found between treatments for both C and F; respectively [F(4,884)=8.143, p=0.000] and [F(4,924)=6.621, p=0.000]. Figure 6.7 presents treatment mean movement distance and ranges for in-plot movement, the combined elements C and F.

Mean distance moved travelling in rack (C) in low thinning (7.2m) was found to be significantly less than in all other treatments (frame 12.3 m, clearfell 12.7 m, creaming 14.8 m) with the exception of the group treatment (9.8 m).

Mean distance moved out rack (F) in low thinning (7.6 m) was found to be significantly lower than in frame (11.4 m) and clearfelling treatment types (13.5 m). Distances for clearfelling were found to be significantly higher than in low thinning and group treatments (9.7 m). Creaming (11.1 m) was not significantly different from any other treatment.

Mean treatment values for moving within the plots (C+F) are 11.82 m for frame-tree, 9.74 m for group, 7.41 m for low thinning, 13.11 m for clearfelling and 12.77 m for creaming.

A strong relationship was found between the mean distance travelled in rack in thinning treatments (C+F) ($\overline{F}^{C\&F}_{move}$) and the relative spacing of removed trees (RS_{thin}). Distance decreases linearly in proportion to tree removal density ($\overline{F}^{C\&F}_{move} = 1.314RS_{thin} - 1.979$, $R^2 = 0.626$) in a significant relationship [F(1,5)=8.358, p=0.034] summarised in Table 6.10.

Mean distance for the clearfell is higher than that of all the thinning plots and does not fit the regression. The coefficient of variation for the clearfell is 1.39 in comparison to 1.05 for frame, 1.12 for group, 1.06 for low and 0.93 for creaming indicating a higher variance relative to its mean.

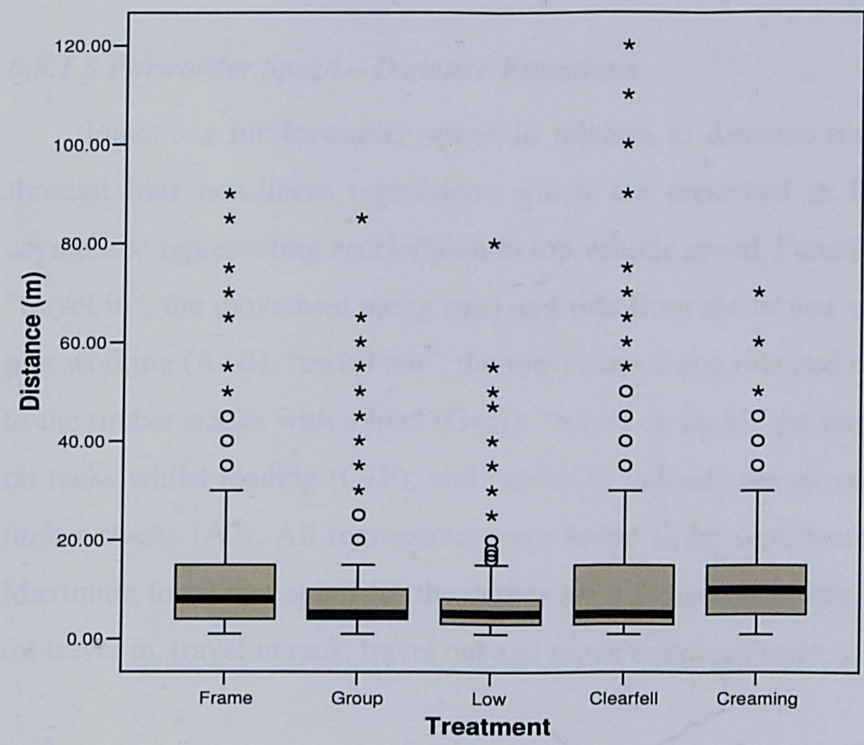


Figure 6.7 Treatment distributions of forwarder within-plot movement distance (C+F)

Heavy black lines represent plot medians, box represents 50% of population. Outliers are classified as points lying greater than 1.5 box-lengths from the edge of the box. Circles represent outliers lying 1.5 to 3.0 box lengths from the edge of the box, asterisks represent outliers lying more than 3.0 boxes away. Whiskers define maximum and minimum values not including outliers.

6.5.1.4 Total Movement Distance

The *total distance travelled* by the forwarder within the plots (C+F) ($F_{total}^{C\&F}$) was investigated. *Number of loading cycles* was found to be the single most important variable influencing total distance travelled. ($F_{total}^{C\&F} = 154.59l^{n} + 131.03$, R^2 = 0.969, [F(6)=189.05, p=0.000]) and *distance travelled in the rack by the harvester* (L_{used}^{rack}) the second most important ($F_{total}^{C\&F} = 64.009L_{used}^{rack} + 1144.8$, R^2 = 0.651 [F(5)=9.33, p=0.028]).

A linear regression using the product of *number of loads* and *harvester distance in rack* was found to offer a better description of *total forwarder distance in rack* instead of using them as separate covariates ($F_{total}^{C\&F} = 0.196(L_{used}^{rack} \cdot l^{n}) + 464.569$, R^2 = 0.995, [F(6)=1233.53, p=0.000]). The regression is summarised in Table 6.10.

6.5.1.5 Forwarder Speed – Distance Functions

Functions for forwarder speed in relation to distance travelled were calculated through four non-linear regressions which are presented in Figure 6.8. Curves are asymptotic representing acceleration to top vehicle speed. Functions were calculated for "travel in", the movement along road and ride from the timber stacks to the start of the plot working (A+B); "travel out", the movement along ride and road away from the plot to the timber stacks with a load (G+H); "travel on rack", the movement within the plot on racks whilst loading (C+F); and "move to unload" the movement on road between timber stacks (A2). All regressions were found to be significant at the $p<0.005$ level. Maximum forwarder speed for the curves are 1.89 m/s, 0.71 m/s, 1.34 m/s and 1.58 m/s for travel in, travel in rack, travel out and move to unload respectively.

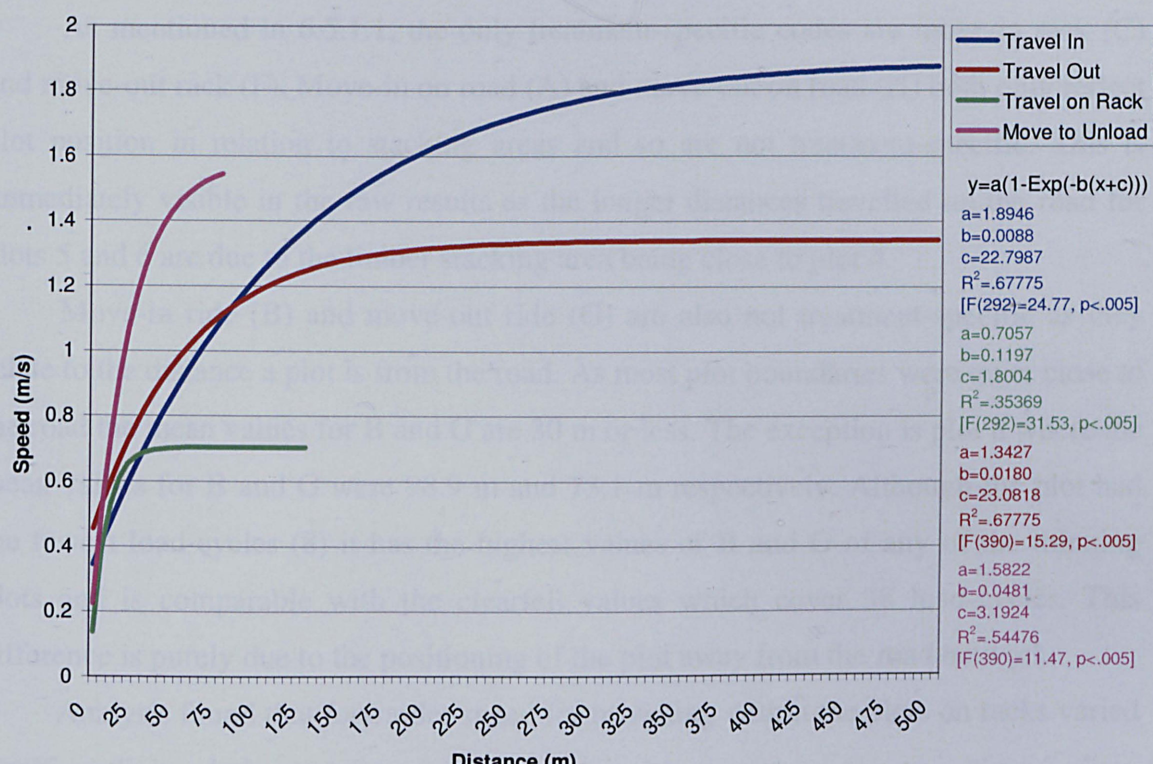


Figure 6.8 Forwarder speed-distance curves for travel-in, travel-out, travel on rack and move to unload

Table 6.10 Summary of forwarder movement regressions

Work phase model	Dependent variable	R^2	F-test	Term		Constant / Coefficient		t-test	
						Estimate	Std. Error	t-value	p
Speed move in/out rack (all plots)	$\overline{F}^{C\&F}_{speed}$	0.881	[F(1,8)=59.167, p=.000]	Constant		0.212	0.034	6.232	0.000
				$\overline{F}^{C\&F}_{move}$	x_1	0.023	0.003	7.692	0.000
Mean move in/out distance (thinning)	$\overline{F}^{C\&F}_{move}$	0.626	[F(1,5)=8.358, p=.034]	Constant		-1.979	4.218	-0.469	0.659
				RS_{thin}	x_1	1.314	0.455	2.891	0.034
Total C+F distance (all plots)	$F^{C\&F}_{total}$	0.995	[F(1,6)=1233.53, p=.000]	Constant		464.569	68.733	6.759	0.001
				$L^{rack}_{used}\cdot l^{n}$	x_1	0.196	0.006	35.122	0.000

6.5.1.6 Discussion of Forwarder Movement

The raw results presented in 6.4.2 show the greater plot time consumption and distance travelled involved with the clearfell due to the greater number of loading cycles required to deal with the higher volume cut in the plot.

As mentioned in 6.5.1.1, the only treatment-specific codes are move-in rack (C) and move-out rack (F). Move-in on road (A) and move-out on road (H) both only reflect plot position in relation to stacking areas and so are not treatment-specific. This is immediately visible in the raw results as the longer distances travelled on the road for plots 5 and 6 are due to the timber stacking area being close to plot 4.

Move-in ride (B) and move-out ride (G) are also not treatment-specific as they relate to the distance a plot is from the road. As most plot boundaries were quite close to the road the mean values for B and G are 30 m or less. The exception is plot 8 where the mean values for B and G were 98.9 m and 73.1 m respectively. Although the plot had the fewest load-cycles (8) it has the highest values of B and G of any of the thinning plots and is comparable with the clearfell values which cover 38 load-cycles. This difference is purely due to the positioning of the plot away from the road network.

Analysis found that forwarder speed for travelling within the plots on racks varied significantly in relation to treatment type.

Mean speed for C in low thinning was 0.38 m/s, compared with 0.53 m/s in the frame-tree treatment and the creaming treatment, representing a 39% increase in speed for crown thinning in comparison to low thinning. Mean speed for F in low thinning was again 0.38 m/s compared to 0.51 m/s for frame-tree and 0.54 m/s for creaming, representing 34% and 42% increases respectively. These speeds compare with the value of 0.45 m/s given by Nurminen *et al.* (2006) for movement in racks whilst loading.

If mean treatment values for moving within the plot are used and low thinning taken as a comparison, moving within the clearfell was 10.5% faster, group shelterwood 26.3% faster, frame-tree 36.8% faster and creaming 39.5% faster.

The differences in speed were found to be positively and significantly linked to the distances the forwarder travelled between stops. Longer distances between stops allow acceleration to a higher speed before stopping and may also allow travel at the accelerated-to maximum speed, the mean speed increasing with distance travelled as can be seen in Figure 6.6.

The analysis of movement distance indicates that the distances between stops when moving within the plots were significantly different between treatments. Distances for the thinning plots were found to be dictated by the number of trees removed per hectare. In low thinning a greater number of trees per hectare were removed and the piles of logs along the rack were consequently closer together. Conversely, in crown thinning (frame-tree and creaming) fewer trees per hectare were removed and forwarder loading stops were further apart. The higher coefficient of variation calculated for the group treatment indicates that whilst the mean distance travelled is mid-way between frame and low treatments, the variation of distances travelled is proportionally higher. This is most likely to be due to the effect of small movements around the groups and longer movements in the differentially thinned matrix. This also seems to be confirmed by the box-plot in Figure 6.7 as the group has the lowest median value of all treatments but with a comparatively wide spread of values in the upper half of the distribution. Clearfelling has a similar distribution to the group treatment. The clearfell has the highest mean distance value and also the highest coefficient of variation whilst having the second-lowest median value and the widest spread of values in the upper half of the distribution. This seems to confirm that movement consisted of a mix of very small and large distances. Interpretation of this is that the forwarder moved small distances between piles as there was a high density of produce in the clearfell, however this was mixed with longer travelled distances. Longer distances would occur when the bunk was filled towards the end of a rack so necessitating a long move-out (F) and a subsequent long move-in (C) to return to the point.

Total movement distance was found to be positively related to the number of loading cycles in a plot and the length of rack used by the harvester. As cut produce would only have been left at the side of racks used by the harvester, the forwarder had to travel the same racks to load, generally ignoring unused racks. The number of load cycles is the more significant variable though, as it describes the number of "loops" the forwarder travelled through the plot. The combination of the two variables in the regression can therefore be seen as a description of a number (loading-cycles) of an average loop travelled through the plot.

The study by Nurminen *et al.* (2006) had a mean rack density of 769 m/ha in the clearfell and 500 m/ha in thinnings compared to 1118 m/ha in the clearfell and 640 m/ha in thinning plots at Trallwm. Total distance was calculated using number of loading cycles derived from product density along racks and bunk load volume.

A reduction in loaded forwarder speed has been reported in some studies (e.g. Nurminen *et al.*, 2006; Johansson, 1996) but not in others (e.g. Lanford and Stokes, 1996). Analysis found no significant difference between loaded and unloaded speeds when all movement distances were compared together. Inspection of Figure 6.6 shows two distinct groupings for longer distances when loaded and unloaded, suggesting slower loaded speeds. Further analysis found that loaded speed was significantly lower than unloaded when considering distances of over 60 m. The reduction in mean speed for distances over 60 m represents a 9% drop compared to the 21% reported by Nurminen *et al.* (2006) and 34-45% reported by Johansson (1996). A more marked reduction in speed can be seen in Figure 6.6 for distances of over 150 m which represents a 25% reduction (M=1.92, SD=0.188: M=1.44, SD=0.069). This reduction corresponds better with published figures but only corresponds to longer travel distances on forest roads, distance travelled on racks never exceeding 110 m. Published studies tend not to distinguish between movement within stands or on roads, generally classifying speeds for a total travel distance, for example Nurminen *et al.* (2006) specify productivities for 200 m and 400 m haulage distances. It is therefore difficult to fully compare the effect of load on speed.

A possible reason for the smaller difference between loaded and unloaded speed when compared to published studies may be due to the development of machinery over time as noted by Nurminen *et al.* (2006); newer machines in more recent studies being more capable and efficient than those in studies of a decade ago.

Forwarder speed is generally presented as an average calculated for all movement types (e.g. Nurminen *et al.*, 2006; Lanford & Stokes, 1996; Kellogg & Bettinger,1994) and from which time consumption can be calculated for a selected distance. The shape of functions presented in Figure 6.8 suggests that if the calculation of mean speed is based on a study with short haulage distances, predictions of time consumption for longer distances could be overestimated. The functions present a maximum reduction in loaded forwarding speed of 29% at distances close to 500 m.

6.5.2 Load and Unload

6.5.2.1 Treatment on Grapple Volume

To investigate the effect of treatment on grapple load and unload volumes an analysis of variance was conducted. Both load and unload volumes showed significant differences between treatments, respectively [$F(4,2910)=39.339$, $p=0.000$] and [$F(4,1564)=6.594$, $p=0.000$].

Post-hoc Tukey analysis indicates that when loading, grapple volumes were significantly smaller in low thinning (0.228 m^3) than in all other treatments, significantly higher in creaming (0.383 m^3) than in all other treatments and those in group (0.289 m^3) were significantly smaller than in clearfelling (0.318 m^3). The mean volume for the frame treatment was 0.295 m^3.

Grapple volumes during unloading were found to be significantly higher in creaming (0.613 m^3) than in all other treatments and those in low thinning (0.503 m^3) were significantly lower than in clearfelling (0.546 m^3). Group had a mean value of 0.539 m^3 and frame 0.542 m^3.

Mean grapple volume is to a large part explained by mean product volume which is a derivative of mean felled tree diameter. Significant correlations were found between *mean plot felled tree diameter* ($\overline{d}_{thin}$) and both *plot mean loading grapple volume* ($\overline{GL}_v = 0.012\overline{d}_{thin} - 0.072$, R^2=0.872) [$F(6)=37.94$, $p=0.001$] and *plot mean unloading grapple volume* ($\overline{GU}_v = 0.009\overline{d}_{thin} + 0.274$, R^2=0.622) [$F(6)=9.89$, $p=0.020$], both summarised in Table 6.12.

6.5.2.2 Product on Grapple Volume

In order to investigate the relationship of the separate products with grapple volumes, mean grapple volume for each product within each plot was plotted against mean plot felled tree diameter. Figure 6.9 presents the results for loading and Figure 6.10 for unloading.

During loading there is a significant positive relationship between diameter and grapple volume for both 495 cm and 315 cm logs. All other products show no significant relationship with diameter. During unloading a significant positive relationship was found for 495 cm logs only, all other products again showing no significant relationship.

For both loading and unloading mean grapple volume is positively correlated with mean product volume as can be seen by the product distribution across the Y axis of both figure 6.9 and 6.10, products ordered from 495 cm logs at the top to 172 cm stakes at the bottom.

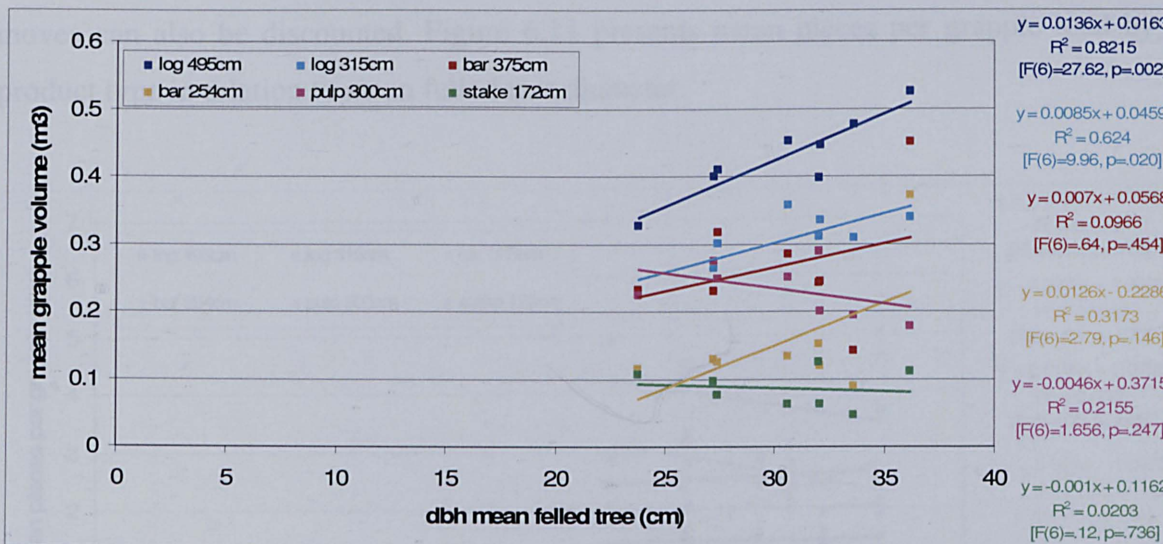


Figure 6.9 Relationship between mean felled tree diameter and mean loading grapple volume by product type

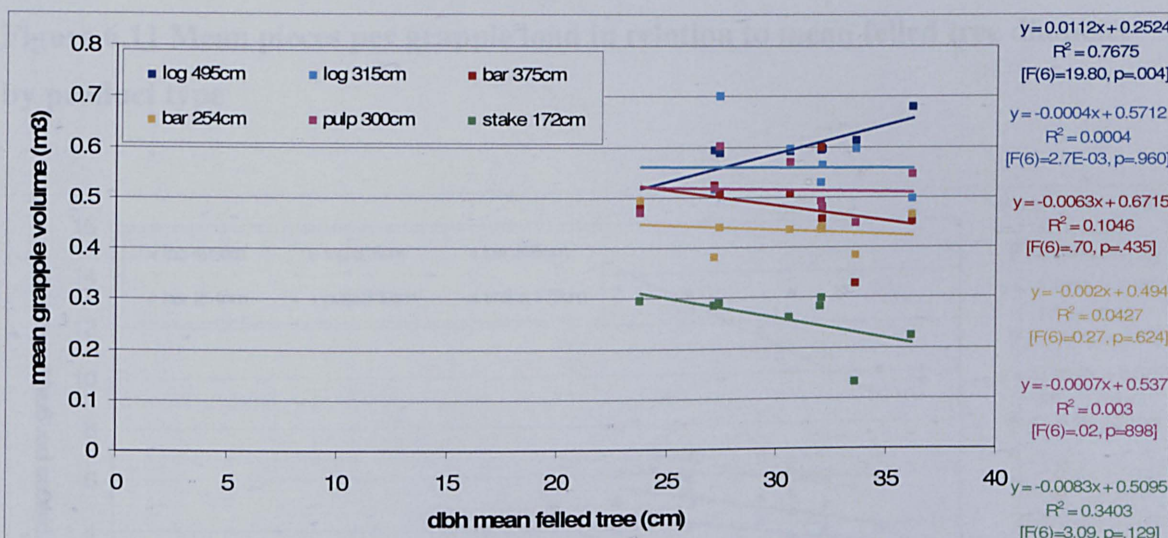


Figure 6.10 Relationship between mean felled tree diameter and mean unloading grapple volume by product type

6.5.2.3 Treatment on Pieces per Load

Significant differences were found between the mean number of pieces picked-up per grapple load for every product between both plots and treatments. There is, however, no pattern to the differences. No correlation was found between mean pieces per grapple load and mean felled tree diameter or volume, product percentage of assortment by volume or by pieces cut, or by mean pieces of product per tree. As clearfelling did not always have the highest value, number of trees processed between moves can also be discounted. Figure 6.11 presents mean pieces per grapple load by product type in relation to mean felled tree diameter.

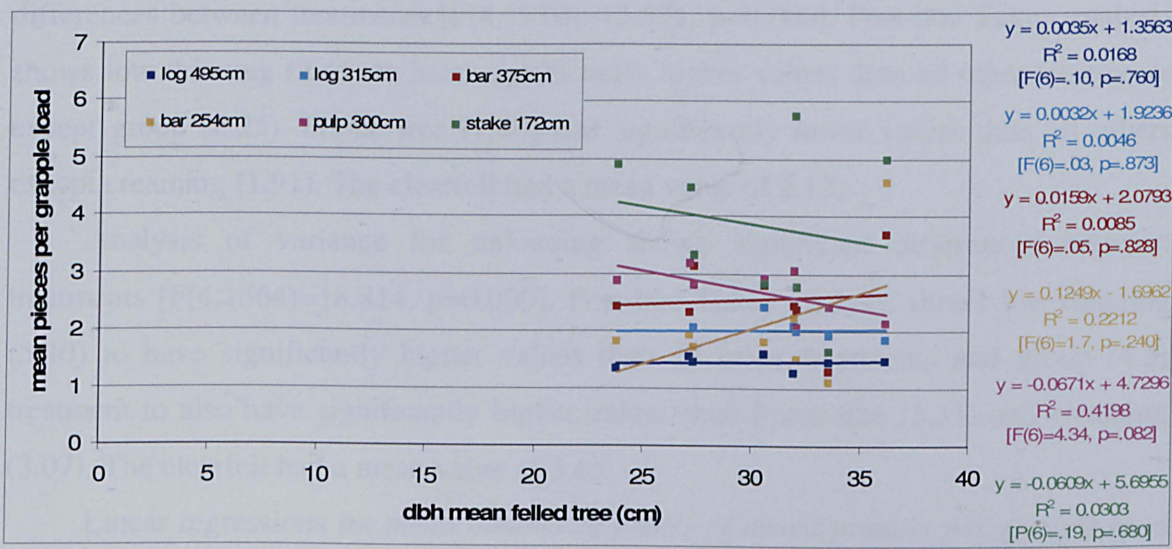


Figure 6.11 Mean pieces per grapple load in relation to mean felled tree diameter by product type

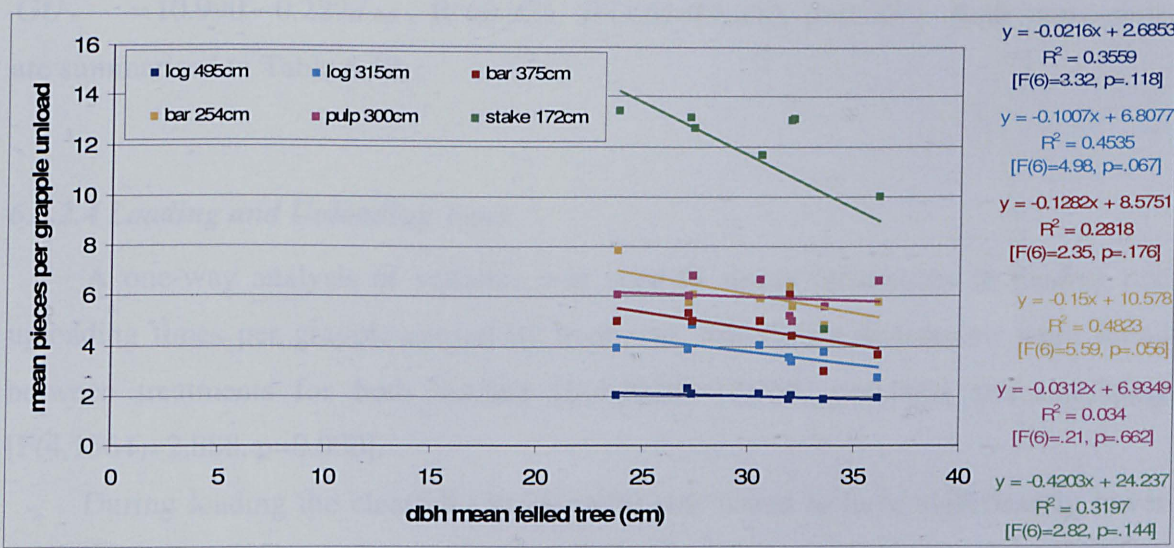


Figure 6.12 Mean pieces per grapple unload in relation to mean felled tree diameter by product type

The mean number of pieces per grapple load whilst unloading was also found to have significant differences between both plots and treatments. A very weak inverse trend with mean felled tree dbh was identified although it was not significant for any product as can be seen in Figure 6.12.

When all products were combined and the mean number of pieces per grapple were compared between treatments, significant treatment differences were found as well as a strong correlation to mean felled tree diameter.

Analysis of variance of pieces of all product types per load shows significant differences between treatments [F(4,2910)=13.571, p=0.000]. Post-hoc Tukey analysis shows low thinning (2.45) to have significantly higher values than all other treatments except group (2.25). Frame tree (1.80) had significantly lower values than all others except creaming (1.91). The clearfell had a mean value of 2.12.

Analysis of variance for unloading shows significant differences between treatments [F(4,1564)=18.814, p=0.000]. Post-hoc Tukey analysis shows low thinning (5.40) to have significantly higher values than all other treatments and group (4.2) treatment to also have significantly higher values than frame tree (3.31) and creaming (3.07). The clearfell had a mean value of 3.65.

Linear regressions for *mean number of pieces of mixed product per grapple load* ($\overline{GL_n}^{mixed}$) in relation to *mean felled tree diameter* ($\overline{d}_{thin}$) can be presented for loading as $\overline{GL_n}^{mixed} = 4.042 - 0.063\overline{d}_{thin}$, R^2=0.796, [F(1,6)=23.465, p=0.003] and for unloading as $\overline{GU_n}^{mixed} = 10.990 - 0.229\overline{d}_{thin}$, R^2=0.928, [F(1,6)=77.640, p=0.000]. Both regressions are summarised in Table 6.12.

6.5.2.4 Loading and Unloading Time

A one-way analysis of variance was used to assess differences in loading and unloading times per grapple caused by treatment. Significant differences were found between treatments for both loading [F(4,2910)=12.755, p=0.000] and unloading [F(4,1564)=2.888, p=0.000].

During loading the clearfell (30.95 cmin) was found to have significantly lower values than all other plots except the creaming plot (31.87 cmin). Frame, group and low treatments had mean values of 32.96 cmin, 34.57 cmin and 34.84 cmin respectively.

During unloading the clearfell (27.56 cmin) was found to have significantly lower values than only the group treatment (29.24cmin). Frame, low and creaming mean values were 28.78 cmin, 28.99 cmin and 27.87 cmin respectively.

The relationships for all products between felled tree diameter and mean loading time are presented in 6.13 and for mean unloading time in 6.14.

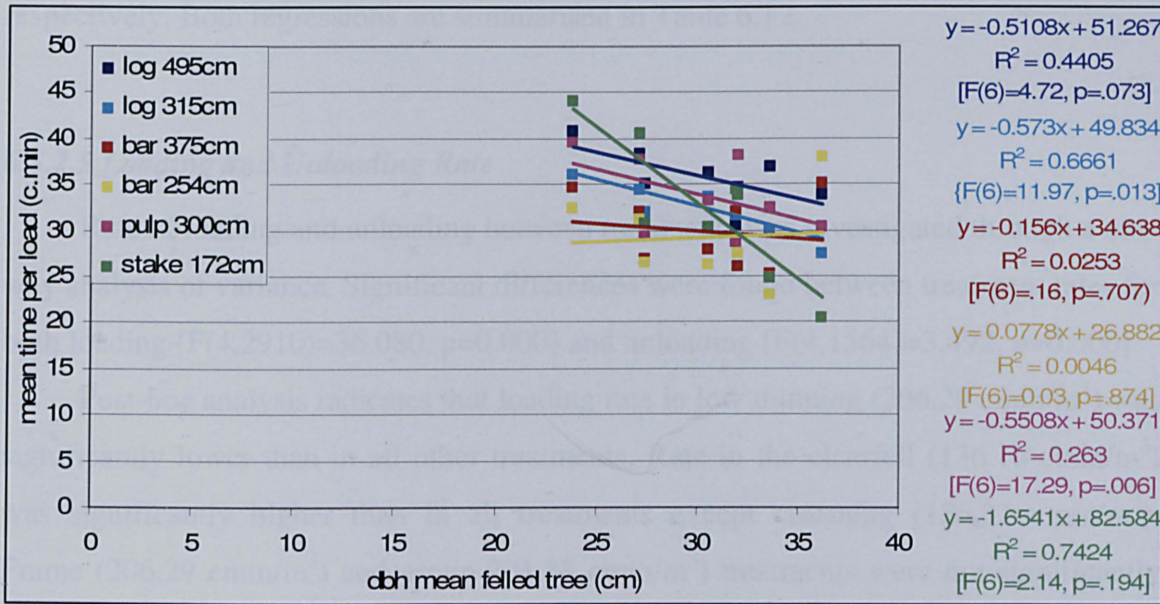


Figure 6.13 Mean time per load in relation to mean felled tree diameter by product type

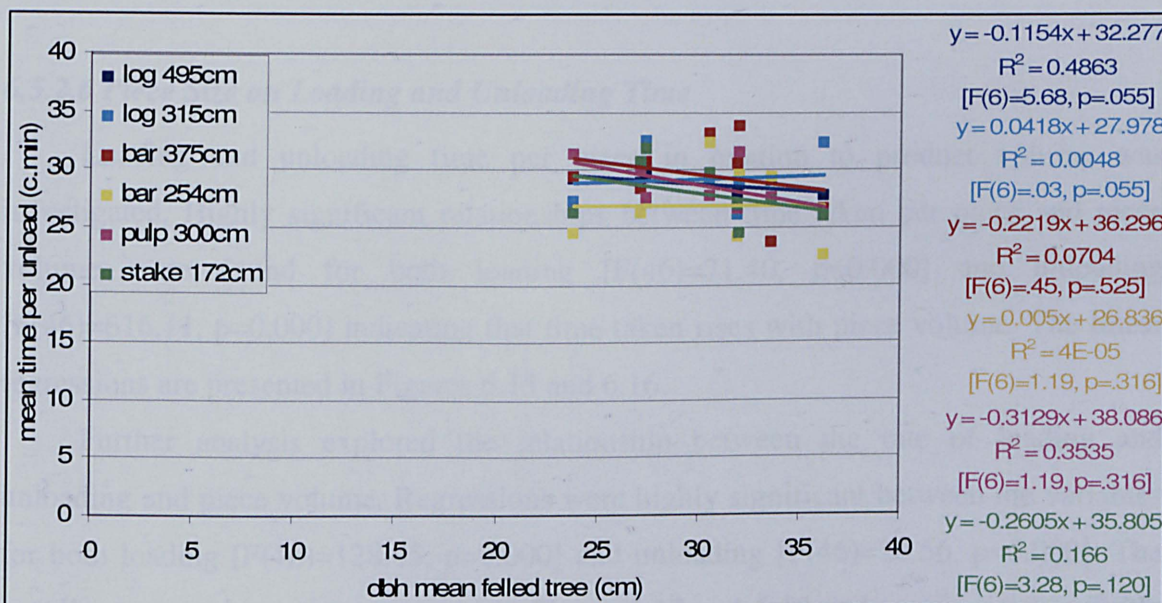


Figure 6.14 Mean time per unload in relation to mean felled tree diameter by product type

Mean felled tree diameter ($\overline{d}_{thin}$) is the best single predictor of *mean time to load* ($\overline{GL_T}^{mixed}$) and *unload* ($\overline{GU_T}^{mixed}$), showing an inverse relationship of $\overline{GL_T}^{mixed} = 46.5308 - 0.4358\overline{d}_{thin}$ ($R^2 = 0.449$) for loading and $\overline{GU_T}^{mixed}$ $31.2743 - 00.0851\overline{d}_{thin}$ ($R^2 = .194$) for unloading although neither is statistically significant at the p<.05 level; [F(6)=4.89, p=0.069] and [F(6)=1.45, p=0.274] respectively. Both regressions are summarised in Table 6.12.

6.5.2.5 Loading and Unloading Rate

Rate of loading and unloading between treatments was investigated through a one-way analysis of variance. Significant differences were found between treatment rates for both loading [F(4,2910)=36.080, p=0.000] and unloading [F(4,1564)=3.492, p=0.000].

Post-hoc analysis indicates that loading rate in low thinning (206.29 cmin/m^3) was significantly lower than in all other treatments. Rate in the clearfell (136.16 cmin/m^3) was significantly higher than in all treatments except creaming (126.37 cmin/m^3). Frame (206.29 cmin/m^3) and group 201.38 cmin/m^3) treatments were not significantly different from each other. Unloading rates were significantly lower for low thinning (81.55 cmin/m^3) than for clearfelling (64.25 cmin/m^3) and creaming (54.93 cmin/m^3) although not for frame (68.86 cmin/m^3) or group (65.99 cmin/m^3).

6.5.2.6 Piece Size on Loading and Unloading Time

Loading and unloading time per piece in relation to product volume was investigated. Highly significant relationships between time taken per piece and piece volume were found for both loading [F(46)=71.40, p=0.000] and unloading [F(46)=616.11, p=0.000] indicating that time taken rises with piece volume. The linear regressions are presented in Figures 6.15 and 6.16.

Further analysis explored the relationship between the rate of loading and unloading and piece volume. Regressions were highly significant between the variables for both loading [F(46)=128.45, p=0.000] and unloading [F(46)=20.56, p=0.000]. The non-linear regressions are presented in Figure 6.17 and 6.18 and summarised in Table 6.12.

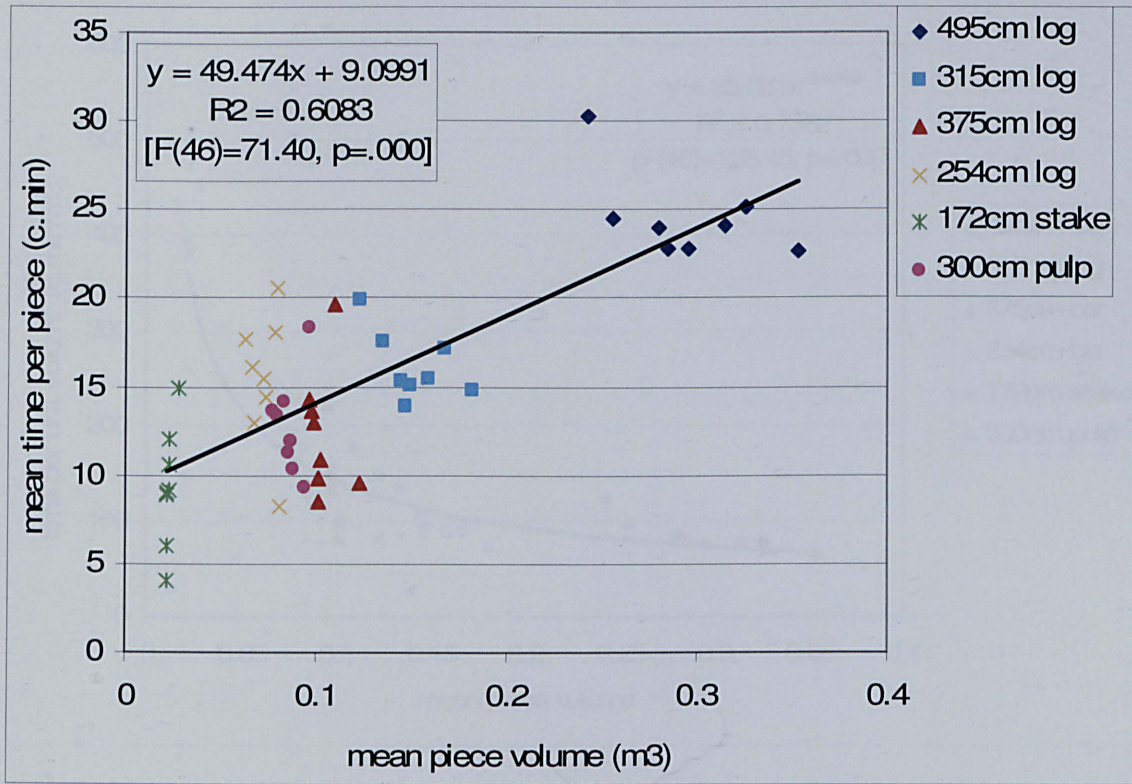


Figure 6.15 Time taken for loading in relation to piece volume

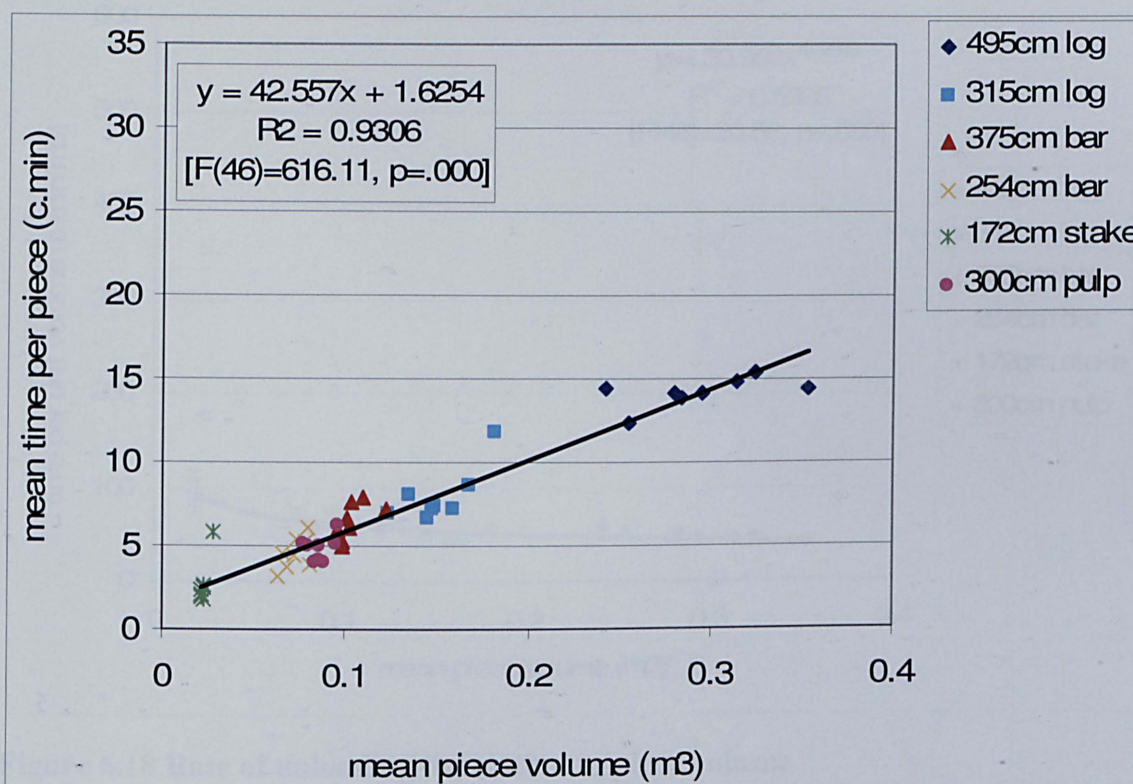


Figure 6.16 Time taken for unloading in relation to piece volume

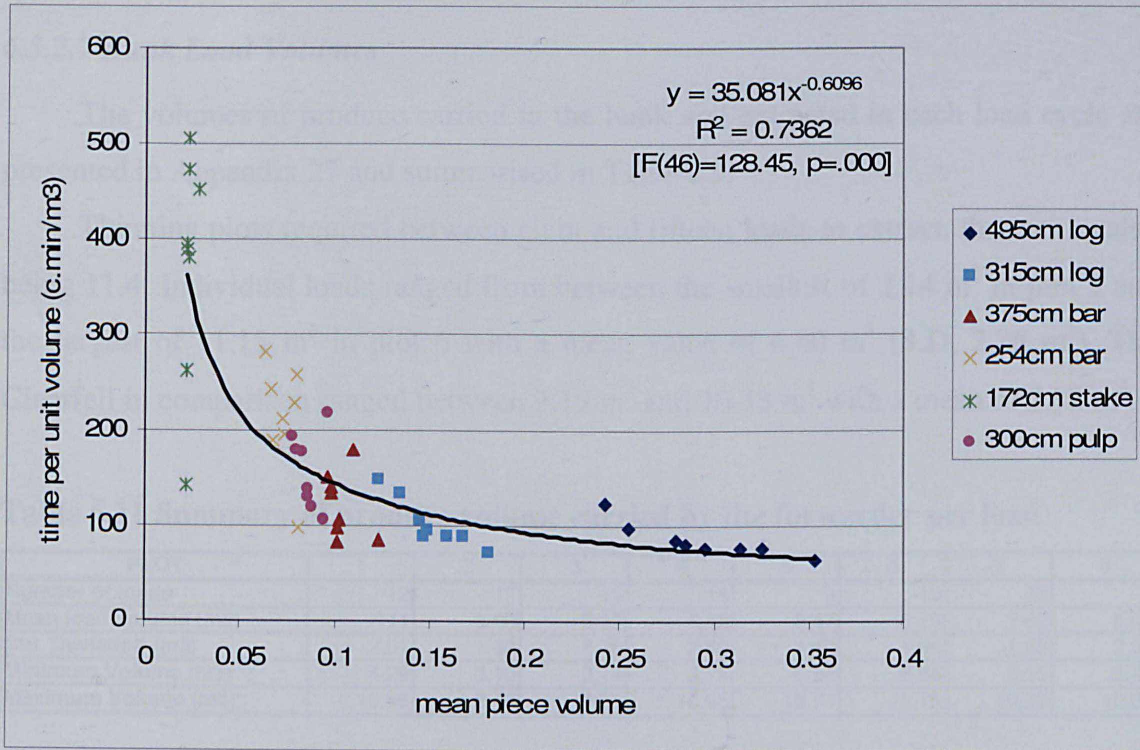


Figure 6.17 Rate of loading in relation to piece volume

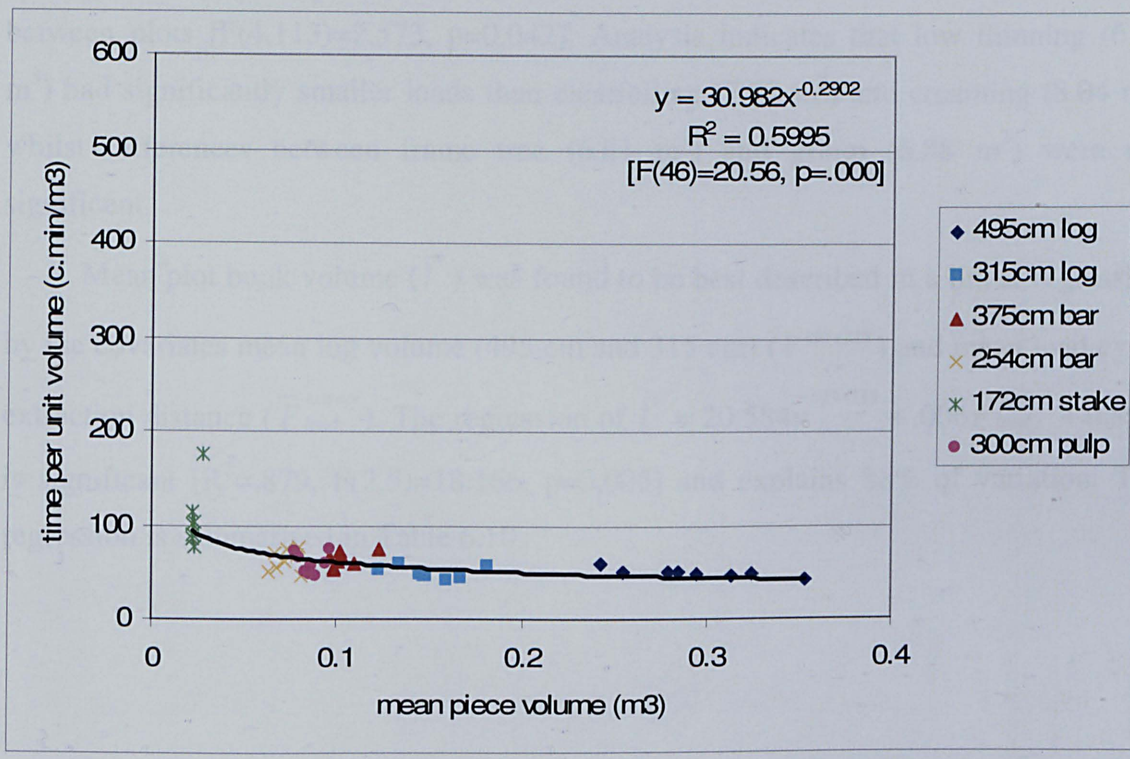


Figure 6.18 Rate of unloading in relation to piece volume

6.5.2.7 Bunk Load Volumes

The volumes of produce carried in the bunk and extracted in each load cycle are presented in Appendix 27 and summarised in Table 6.9.

Thinning plots required between eight and fifteen loads to extract, the mean value being 11.4. Individual loads ranged from between the smallest of 2.14 m^3 in plot 3 and the largest of 11.15 m^3 in plot 6 with a mean value of 6.80 m^3 (S.D. 2.38 m^3). The Clearfell in comparison ranged between 3.15 m^3 and 10.33 m^3 with a mean of 7.92 m^3.

Table 6.11 Summary of produce volume carried by the forwarder per load

PLOT	1	2	3	4	5	6	7	8
Number of loads	12	15	15	11	9	10	38	8
Mean load volume (m3)	7.11	5.60	5.13	6.48	8.47	8.79	7.92	8.04
Std. Deviation (m3)	2.01	1.88	1.75	2.80	1.46	1.96	1.55	2.37
Minimum Volume (m3)	4.29	3.10	2.14	3.13	5.54	6.36	3.15	3.43
Maximum Volume (m3)	10.86	8.48	8.51	10.55	10.71	11.15	10.33	10.87

A one-way between-groups analysis of variance was used to investigate differences in treatment load volumes. A statistically significant difference was found between plots [$F(4,113)=2.573$, $p=0.042$]. Analysis indicates that low thinning (6.38 m^3) had significantly smaller loads than clearfelling (7.92 m^3) and creaming (8.04 m^3) whilst differences between frame tree (6.81 m^3) and group (6.88 m^3) were not significant.

Mean plot bunk volume ($\bar{l}^{v}$) was found to be best described in a linear regression by the covariates mean log volume (495 cm and 315 cm) ($\bar{v}^{495+315}$) and mean load cycle extraction distance ($\overline{F}_{load}^{extract}$). The regression of $\bar{l}^{v} = 20.584\bar{v}^{495+315} + .006\overline{F}_{load}^{extract} + 0.898$ is significant [R^2=.879, $F(2,5)=18.166$, $p=0.005$] and explains 88% of variation. The regression is summarised in Table 6.10.

Table 6.12 Summary of forwarder load and unload regressions

Work phase model	Dependent variable	R^2	F-test	Term		Constant / Coefficient Estimate	Std. Error	t-test t-value	p
Mean grapple loading volume (all plots)	$\overline{GL}_v$	0.872	[F(1,6)=40.708, p=.001]	Constant		-0.072	0.057	-1.253	0.257
				$\bar{d}_{thin}$	x_1	0.012	0.002	6.380	0.001
Mean grapple unloading volume (all plots)	$\overline{GU}_v$	0.622	[F(1,6)=9.887, p=.020]	Constant		0.274	0.086	3.185	0.019
				$\bar{d}_{thin}$	x_1	0.009	0.003	3.144	0.020
Mean pieces per grapple load (all plots)	$\overline{GL}_n^{mixed}$	0.796	[F(1,6)=23.465, p=.003]	Constant		4.042	0.399	10.121	0.000
				$\bar{d}_{thin}$	x_1	-0.063	0.013	-4.844	0.003
Mean pieces per grapple unload (all plots)	$\overline{GU}_n^{mixed}$	0.928	[F(1,6)=77.640, p=.000]	Constant		10.990	0.793	13.851	0.000
				$\bar{d}_{thin}$	x_1	-0.229	0.026	-8.811	0.000
Mean time per grapple load (all plots)	$\overline{GL}_T^{mixed}$	0.449	[F(1,6)=4.888, p=.069]	Constant		46.531	6.030	7.717	0.000
				$\bar{d}_{thin}$	x_1	-0.436	0.197	-2.211	0.069
Mean time per grapple unload (all plots)	$\overline{GU}_T^{mixed}$	0.194	[F(1,6)=1.448, p=.274]	Constant		31.274	2.164	14.451	0.000
				$\bar{d}_{thin}$	x_1	-0.085	0.071	-1.203	0.274
Mean time per piece load (all plots)	T_{piece}^L	0.608	[F(1,46)=71.397, p=.000]	Constant		9.100	0.877	10.374	0.000
				$\bar{v}^x$	x_1	49.469	5.855	8.450	0.000
Mean time per piece unload (all plots)	T_{piece}^U	0.931	[F(1,46)=616.11, p=.000]	Constant		1.625	0.257	6.326	0.000
				$\bar{v}^x$	x_1	42.557	1.715	24.822	0.000
Mean time per piece load (all plots)	T_{m3}^L	0.736	[F(1,46)=128.35, p=.000]	Constant		35.081	4.718	7.436	0.000
				$\bar{v}^x$	x^a	-0.610	0.054	-11.329	0.000
Mean time per piece unload (all plots)	T_{m3}^U	0.600	[F(1,46)=68.870, p=.000]	Constant		30.982	2.708	11.441	0.000
				$\bar{v}^x$	x^a	-0.290	0.035	-8.299	0.000
Bunk mean load volume (all plots)	$\bar{l}^v$	0.879	[F(2,5)=18.166, p=.005]	Constant		0.898	1.325	0.678	0.528
				$\bar{v}^{495+315}$	x_1	20.584	5.089	4.045	0.010
				$\overline{F}_{load}^{extract}$	x_2	0.006	0.001	5.324	0.003

6.5.2.8 Discussion of Grapple Volume and Pieces

Analysis shows that mean grapple volume and mean pieces per grapple load are significantly different between treatments. The differences can be traced to the differing treatment mean felled tree diameters. Tree diameter has a strong relationship with mean piece volume (See d : MPV curves Appendix 20), mean piece volumes increasing with diameter. The effect of the treatments is not only that the mean piece sizes produced are different but also product proportion differs, in terms of both volume and count (See d : product % curves 5.3.2.3). Low thinning cut smaller diameter trees and hence produced products of smaller mean dimensions and proportionately less log material. In contrast, creaming cut trees of larger diameter, producing larger sized products and proportionately more log material.

As mean product size increased, mean grapple volume was also found to increase and the mean number of pieces per grapple load to decrease.

The relationship between grapple volume and mean felled tree diameter appears to be distinct between loading and unloading. During loading, volume of log grapples (495 cm and 315 cm) are significantly correlated with diameter, whilst bars (375 cm and 254 cm) show only a non-significant positive relationship and pulp and stakes are unrelated. This pattern is an effect of the relationship between diameter and piece volume. Log volume is the most related to diameter of any of the products cut and also as only 1.5 logs were picked up on an average load, any increase in diameter would have a very direct effect on piece and grapple volume. Conversely, pulp and stake volumes are little affected by tree diameter and so will show little relationship with increasing diameter. Bars form the median, due to their weaker relationship with diameter and hence only a non-significant positive relationship exists.

During unloading, 495 cm logs are the only product to show any relationship to diameter. This is likely to be due to the small number of logs that are carried by the grapple, the mean being around 2. As the grapple is likely to have spare capacity, any increase in log volume (highly correlated with tree diameter) will increase the grapple volume. The smaller diameters of the other products allow for a more complete utilisation of the grapple capacity and are also less related to diameter, so producing a trend-less relationship.

As logs make up the majority of the tree volume, they are the product that will influence mean values the most and so the significant relationships for log loading and unloading are likely to be largely responsible for the significant differences between treatments.

The regression of mean grapple volume against mean felled tree diameter suggests that at Trallwm there was a difference between crown thinning and low thinning due to mean felled tree size. The size of difference was around 0.1 m^3 per grapple load and unload.

Mean values for the number of pieces per grapple load ($\overline{GL_n}^{mixed}$) are 5 or less in all plots. This compares to mean values for unloading ($\overline{GU_n}^{mixed}$) which are higher in all plots, the difference varying with the average size of the product. This suggests that mean loading values are controlled more by the presentation of products in the drift than the forwarder grapple capability.

This seems to be further confirmed when pieces per grapple load are studied by product as there is no relationship (non-significant or significant correlation) between mean felled tree diameter and mean pieces per grapple load (see Figures 6.11 and 6.12). During unloading there is however a general non-significant relationship for all products except pulp, of fewer pieces per grapple with increasing diameter, suggesting more optimal use of the grapple capability during unloading which is affected by increasing mean piece size.

The analysis of treatment mean number of pieces per grapple load and unload does suggest that diameter has a significant effect overall on both loading and unloading grapple counts. The difference in mean tree diameter between crown and low thinning at Trallwm was responsible for a difference in grapple counts between low and crown thinning of around 0.5 pieces for loading and around 2.25 pieces for unloading.

It is interesting to note that the result of increasing diameter creates opposing trends. The volume of a log will increase as the square of the diameter increase due to the length remaining constant. The mean number of pieces in a grapple load will however decrease with increasing diameter as the cumulative diameter of the grapple load will exceed the capacity of the grapple more frequently, requiring a piece to be removed from the load and reducing the load volume. The gain in volume per mean grapple load from a rise in diameter must therefore be greater than the loss in volume caused by the following decrease in pieces per grapple load.

Mean grapple volumes of 0.29 m^3 [0.02-0.89] for loading, 0.54 m^3 [0.02-1.14] for unloading and 0.38 m^3 [0.02-1.14] for all grapple loads tally well with those published by Nurminen *et al.* (2006) for final felling of 0.47 m^3 [0.05-1.28].

The mean tree volume in the final fellings studied by Nurminen *et al.* was around half that of the Trallwm study mean, with the follow-on effect of mean log size being 0.188 m^3 compared with 0.300 m^3. The figures presented by Nurminen *et al.* suggest a mean of 2.5 logs picked up in each grapple load compared with 1.4 for loading and for 2.0 unloading in this study. The mean grapple volume achieved during unloading at Trallwm of 0.54 m^3 should logically be close to the capacity value for the machine as the operator will be able to completely fill the grapple from the bunk on most unloads. Assuming that grapple size and capacity is equal between studies, the mean grapple volume of 0.47 m^3 found by Nurminen *et al.* suggests close to capacity grapple usage in both loading and unloading. The higher mean value of logs per grapple is therefore due to the smaller mean log volume and its corresponding smaller mean log diameter; the log volume of 0.188 m^3 is equivalent to 22 cm mid diameter whereas 0.300 m^3 is equivalent to around 28cm. The mean grapple loading volume at Trallwm of 0.29 m^3 again suggests that the grapple was being used at less than capacity during loading in all plots including the clearfell. Nurminen *et al.* note that mean pile volume in their clearfell study was only slightly in excess of the capacity of the grapple, so generally enabling a one-grab removal and hence close to optimal efficiency. In contrast, thinning plots were noted as having lower produce density, so decreasing mean grapple volume and efficiency. This suggests that the sub-capacity grapple usage found is most likely to be due to poor product presentation and small pile size, although operator working cannot be ruled out as a factor.

Although the findings cannot lend weight to the assertion that grapple size is more important than mean tree size for productivity (Väätäinen, 2005; Tufts, 1997; Gullberg, 1997), it certainly seems true that grapple size *in relation to* tree size and pile size is a factor in productivity and that concentration of produce is also very important.

Time consumption by the forwarder during loading and unloading is poorly defined as it involves competing trends which vary between both product and activity. An increase in mean felled tree diameter leads to an increase in mean piece volume and mean grapple volume and is also linked to an inverse trend in number of pieces per grapple. Time consumption tends to rise with grapple volume (fewer and larger pieces) but also with number of pieces per grapple (smaller and more pieces).

The significant differences for time to load between plots can be partially explained by diameter, accounting for 45% of variance. The inverse trend can be seen in Figure 6.13, suggesting a decrease in handling time with increasing piece and grapple volume and decreasing pieces per grapple.

The distribution of treatment mean element duration values for unloading is similar to that for loading, although all values are lower and the spread less. Diameter was found to account for only around 19% of variance and, on inspection, the curves in Figure 6.14 can be seen to confirm this as they have no particular trend. Unloading can be seen as being less sensitive to piece size, presumably because the grapple was being used to fuller capacity.

Time per piece for loading and unloading can be seen to increase with mean piece volume in Figure 6.15. The increase in moved volume outweighs the increased time consumption however and loading rate can be seen to increase with mean piece volume in Figure 6.16 for both loading and unloading. The significant differences in rate between treatments can therefore be seen to be a product of increasing mean piece volume due to increasing felled tree diameter causing an increase in loading and unloading productivity.

This relationship agrees with previously published studies such as Nurminen *et al.* (2006), Johansson (1996), Kellogg & Bettinger (1994) and Kahala & Kuitto (1986).

Nurminen *et al.* (2006) used timber volume at the loading stop to predict loading rate rather than piece volumes used in Figure 6.15 and Figure 6.16. The use of pile volume necessitates the specification of both product mix and intervention type (thin or clearfell) to select a specific curve. The selection of the correct curve would appear to approximate product mean piece volume which is then used to predict the number of loads required for the pile.

6.5.2.9 Discussion of Bunk Volumes

The mean bunk volumes of 6.8 m^3 for thinning plots and 7.9 m^3 for the clearfell are lower than the values presented by Nurminen *et al.* (2006) of 11.0 m^3 and 14.0 m^3 for thinning and clearfells respectively, although the models of forwarders used in the study were not stated and it can be assumed that capacity was larger. Likewise, Johansson (1996) details mean sawlog load volume of 9.2 m^3 and 8.5 m^3 for pulp, representing a summary of several machines. Kellogg & Bettinger (1994) present a mean load volume of 8.69 m^3 [2.2-15.1] for a FMG 910 which is more similar to the figure found at Trallwm although still higher and with a higher maximum. The volumes compares best to McLaren's (1994) calculated maximum load for the 810B of 8.27 m^3 for a pure load of 495 m logs and 7.9 m^3 for 2 m pulp. No mean felled tree diameter is given for McLaren's calculation so it is not possible to fully compare the bunk usage in the study and it must also be taken into account that six products were cut as opposed to log and pulp in all other studies.

The analysis of load volume indicates that plot mean felled tree diameter is again the major determinant of load volume, although it is better described through the derivative of mean log volume. This agrees with published literature, both Andersson & Eliasson (2004) and Kellogg & Bettinger (1994) noting that load efficiency increases with piece volume. The inclusion of plot mean extraction distance as a significant covariate suggests that the forwarder operator was influenced in his working by the distance of the plot to the stacking area and actively altered bunk load volumes in response to extraction distance. Total forwarder movement distance was reduced by increasing bunk load size and so reducing the number of load cycles required to clear the plots of cut produce. The high time consumption associated with long extractions was therefore minimised by reducing the number of times the forwarder travelled the route.

The loads carried in the clearfell do not appear to be different from those in the thinning plots, although due to the volume cut 38 loads (55.8/ha) were completed compared to a mean of 11.4 for thinning. The mean load volume for clearfelling was lower than that of creaming and was only 0.47 standard deviations from the thinning mean value.

6.5.3 Other Cyclic Work Elements

6.5.3.1 K – Manoeuvre in Wood

A one-way analysis of variance was used to investigate differences in manoeuvre duration between treatments. No statistically significant differences were found between treatments [F(4,121)=2.131, p=0.081]. Mean treatment element durations were 20.42 cmin for frame tree, 15.15 cmin for group, 15.50 cmin for low, 24.82 cmin for clearfelling and 11.00 cmin for creaming.

Total time consumption for manoeuvre within the wood (T_{total}^{K}) was found to be most related to the distance travelled within the plot ($F_{total}^{C\&F}$) by the forwarder. The linear regression of $T_{total}^{K} = 0.1869F_{total}^{C\&F} - 141.23$ was found to explain 56.9% of variance and was also found to be significant [F(6)=7.93, p=0.031].

Plot 1 (frame tree) was seen as an outlier due to the very irregular plot racking, and when removed from analysis a second regression of $T_{total}^{K} = 0.2003F_{total}^{C\&F} - 259.28$ was found to explain 96.6% of variance and to be highly significant [F(5)=140.7, p=0.000]. The regression is summarised in Table 6.13.

As number of loading cycles (l^{n}) is very well correlated with plot distance travelled ($F_{total}^{C\&F}$), all regressions are very similar when it is substituted as a variable.

6.5.3.2 A2 – Move to Unload

Total time consumption for moving to unload (T_{total}^{A2}) was found to correlate with the volume removed from the plot ($v_{total}^{allproducts}$). A highly significant linear regression of $T_{total}^{A2} = 8.8388v_{total}^{allproducts} - 479.3$ was found to explain 94.7% of variance [F(6)=107.67, p=0.000] and is summarised in Table 6.13. Log percentage by volume was not found to be either a significant variable or covariate.

6.5.3.3 A3 – Manoeuvre on Road

This code only occurred twice, both times in plot 7.

6.5.3.4 A5 - Stack

A one-way analysis of variance was used to investigate differences in the duration of stacking activity between treatments. No statistically significant differences were found between treatments [F(4,346)=.562, p=0.690]. Mean treatment element durations were 17.76cmin for frame tree, 14.88cmin for group, 16.70cmin for low, 17.26cmin for clearfelling and 17.07cmin for creaming.

Time consumption for stacking per cubic metre of produce (T_{m3}^{A5}) was found to correlate with the percentage by volume of log material produced by the plot ($P_v^{495+315}$). A highly significant linear regression of $T_{m3}^{A5} = 19.8426 - 17.879 P_v^{495+315}$ was found to explain 79.3% of variance [F(6)=23.05, p=0.003] and is summarised in Table 6.13.

6.5.3.5 A6 - Stow / Un-stow Grapple

Total time consumption for stowing and un-stowing the grapple (T_{total}^{A6}) was found to correlate with the number of loading cycles undertaken (l'') by the forwarder. A highly significant linear regression of $T_{total}^{A6} = 32.4646 l'' + 89.7724$ was found to explain 92.9% of variance [F(6)=78.5, p=0.000] and is summarised in Table 6.13.

6.5.3.6 A8 – Adjust Load

A one-way analysis of variance was used to investigate differences in the duration of load adjustments between treatments. Statistically significant differences were found between treatments [F(4,520)=4.505, p=0.001]. Element duration in low thinning (18.48cmin) was significantly higher than in frame (11.78cmin) and clearfell (13.80cmin). Group duration (18.39cmin) was also found to be significantly higher than frame. The creaming mean value was 17.64cmin.

Time consumption per cubic metre of forwarded produce (T_{m3}^{A8}) was found to be inversely related to mean felled tree volume ($\bar{v}_{thin}$). A regression of $T_{m3}^{A8} = 31.7149 - 25.129\bar{v}_{thin}$ was found to explain 55% of variance and was significant [F(6)=7.34, p=0.035], the regression summarised in Table 6.13.

Mean element duration (T_{mean}^{A8}) was found was be inversely proportional to mean felled tree volume ($T_{mean}^{A8} = 1.2111 - 0.0244\bar{v}_{thin}$, R^2=.224) although the relationship is not significant [F(6)=1.73, p=0.236].

The number of occurrences of the element per cubic metre forwarded (N_{m3}^{A8}) is also inversely proportional to mean felled tree volume ($N_{m3}^{A8} = 1.2649 - 0.6639\bar{v}_{thin}$, R^2=.643) and is significant [F(6)=10.78, p=0.017].

6.5.3.7 A9 – Grade Logs

This code was not used.

Table 6.13 Summary of forwarder cyclic work element regressions

Work phase model	Dependent variable	R^2	F-test	Term		Constant / Coefficient		t-test	
						Estimate	Std. Error	t-value	p
Total manoeuvre time (all plots)	T_{total}^{K}	0.966	[F(1,5)=140.696, p=.000]	Constant		-259.275	0.017	11.862	0.000
				$F_{total}^{C\&F}$	x_1	0.200	48.814	-5.312	0.003
Total move to unload time (all plots)	T_{total}^{A2}	0.947	[F(1,6)=107.673, p=.000]	Constant		-479.295	0.852	10.377	0.000
				$v_{total}^{allproducts}$	x_1	8.839	110.583	-4.334	0.005
Stacking time (all plots)	T_{m3}^{A5}	0.793	[F(1,6)=23.048, p=.003]	Constant		19.843	3.724	-4.801	0.003
				$P_{v}^{495+315}$	x_1	-17.879	2.684	7.394	0.000
Stow grapple (all plots)	T_{total}^{A6}	0.929	[F(1,6)=78.498, p=.000]	Constant		89.772	3.664	8.860	0.000
				l^{n}	x_1	32.465	63.519	1.413	0.207
Adjust load (all plots)	T_{m3}^{A8}	0.550	[F(1,6)=7.338, p=.035]	Constant		31.715	9.277	-2.709	0.035
				$\bar{v}_{thin}$	x_1	-25.129	7.909	4.010	0.007

6.5.3.8 Discussion of Other Cyclic Work Elements

6.5.3.8.1 K – Manoeuvre in Wood

Manoeuvring describes the forwarder moving between racks after finishing a rack instead of reversing back out.

It is intuitive to expect manoeuvring to be related to rack layout and usage and the produce density at rack-side in a similar way to other plot movement. The regression calculated in 6.5.3.1 appears to uphold this expectation, in terms of both rack layout and rack use.

The classification of plot 1 as an outlier is unsurprising as both the harvester and racking study found the rack system to be very irregular. Whilst the plot 1 rack layout was appropriate to maintain working, it is sub-optimal in comparison to the parallel rack network of a flat and well drained plot e.g. plot 4. The convoluted layout and tendency to rut excessively due to poor drainage constrained forwarder movement leading to an increased likelihood of needing to manoeuvre. Poor rack layout can therefore be seen to increase manoeuvre time over what might otherwise be expected.

The regression uses the total forwarder distance within the plot ($F_{total}^{C\&F}$) as the variable. As described in 6.5.1.4, total forwarder movement distance was found to correlate well with number of bunk loads. Treatment is therefore likely to have some effect on time spent manoeuvring. Although no difference in manoeuvring element duration was found between treatments, for a given volume and a common rack layout, fewer bunk loads will be extracted in crown thinning which in turn leads to a lower total movement and hence less total manoeuvring.

6.5.3.8.2 A2 – Move to Unload

The relationship identified between volume extracted and moving to unload is likely to be due to the lengthening of timber stacks with increasing stacked volume requiring the forwarder to move greater distances when changing between and moving around stacks. As log percentage by volume ($P_v^{495+315}$) was found to not influence move to unload, the assortment make-up of the stacks and hence the effect of treatment appears to not be a factor. The time consumption during working in plot 3 appears to be disproportionately high. An explanation for this could be that a common stacking area was used for plots 1, 2 and 3 and as working in plot 3 was undertaken last the timber stack lengths and positions will have been an artefact of working in plots 1 and 2.

6.5.3.8.3 A5 – Stack

The relationship defined between log percentage by volume ($P_v^{495+315}$) and total time consumption (T_{total}^{A5}) is due to different occurrence ratios of stacking to unloading for the six products and not a difference in element duration as no significant difference was found in the analysis of variance in 6.5.3.4. Stacking was less frequent after unloading logs than other product types. The mean occurrence ratio of stacking to unloading logs was 1:10.16 compared to 1:2.44 for stakes and 1:2.02 for pulp. Treatment can therefore be seen to affect stacking time as crown thinning a stand will produce a greater percentage of log relative to low thinning and so decrease the incidence of stacking.

6.5.3.8.4 A6 - Stow / Un-stow Grapple

The form and nature of the relationship seems intuitive as the grapple is stowed before travelling from the stacking area into the wood and again when leaving the wood to travel to stack, a working method common to all loading cycles likely to result in a linear rise in time consumption with number of loading cycles. The regression suggests that between 43.7 and 34.8 centiminutes was spent per loading cycle stowing and un-stowing the grapple. Summary figures (Appendix 24) show that plot mean values range between 13.1 and 19.3 centiminutes for each occurrence and that the mean number of occurrences are generally over two per load cycle. Incidences of more than two occurrences per load cycle are likely to be due to moving-out of the wood being interrupted by opportunistic loading or aside of produce (D2) requiring an extra stow and un-stow. Plots 3 and 4 are notable in that the number of occurrences per load cycle was below 2 for both; 1.9 and 1.4 respectively. This is thought to be due to the proximity of the timber piles to the plot boundary for both these plots. As the move out distance was very low in some instances the operator is likely to have considered stowing the grapple to have been unnecessary.

6.5.3.8.5 A8 – Adjust Load

The identified inverse relationship between mean felled tree volume and time consumption for adjusting load suggests that handling smaller volume products due to smaller tree volume leads to an increase in total time spent. The increase in total time consumption with decreasing tree volume is due to an increase in element duration as shown by the analysis of variance performed, as well as an increase in element frequency relative to loaded volume. The inverse relationship between time consumption and mean felled tree size is likely to be due to the higher proportion of small roundwood produced from smaller trees which will require longer than log material to arrange in the bunk.

6.5.4 Non-cyclic Work Elements

6.5.4.1 C2 – Inspect and Consider

Time consumption for inspect and consider was found to be strongly associated with movement, manoeuvre and produce movement elements: loading, adjusting load and aside produce.

There is considerable correlation between movement time within the plot (T_{total}^{C+F}) and loading (T_{total}^{L}) and unloading (T_{total}^{U}) time, manoeuvre (T_{total}^{K}) and adjust load (T_{total}^{A8}).

Moving in plot when regressed against loading and unloading provides R^2 values of 0.9597 and 0.976 respectively and is significant at the p=0.000 level.

There is also strong positive correlation significant at $p<0.05$ with manoeuvre ($T_{total}^{C+F} = 0.0521T_{total}^{K} - 134.98$), adjust load ($T_{total}^{C+F} = 0.0898T_{total}^{A8} + 284.48$) and aside to load ($T_{total}^{C+F} = 0.1772T_{total}^{D2} + 1502.02$).

The strongest correlation found between inspect and consider and the listed activities was for combined loading time (T_{total}^{L}), the regression of $T_{total}^{C2} = 30.5675T_{total}^{L} + 3338.31$ providing an R^2 value of 0.8069 and proving highly significant [$F(6)=25.08$, $p=0.002$], the regression being summarised in Table 6.14.

6.5.4.2 C4 – Aside Brash

Aside brash was used to describe the activity of moving brash to uncover produce to load. Time consumption per cubic metre (T_{total}^{C4}) was found to decrease with increasing log proportion by number ($P_n^{495+315}$) and increase with rising combined pulp and stake proportion by number ($P_n^{300+172}$). The inverse relationship with log proportion of $T^{C4}_{total} = 2.7196 - 4.2355P_n^{495+315}$ has an R^2 of 0.423 but is not significant at the p=0.05 level [F(6)=4.40, p=0.081]. The regression is summarised in Table 6.14.

6.5.4.3 C8 – Fit / Remove Chains and Tracks

This code was used but is independent of treatment. Details can be found in Appendix 24. Tracks were fitted during working in plot 3 after the forwarder lost traction and became stuck on the steep slope.

6.5.4.4 C9 – Debog

This code was used but is independent of treatment. Details can be found in Appendix 24. The forwarder was towed out by the harvester after losing traction and this was classed as de-bogging.

6.5.4.5 D1 – Aside Produce to Travel

Aside produce to travel was used when produce had been left by the harvester in the path of the forwarder. The clearfell was found to have the highest time consumption for this activity but when time consumption is calculated per cubic metre any difference between the clearfell and the thinning plots is lost. Time consumption is not correlated to any plot parameter and so it is likely that this activity is caused by variable product presentation by the harvester.

6.5.4.6 D2 – Aside Produce to Load

Aside produce to load was used to sort and re-pile produce not being forwarded in the current bunk load to facilitate its faster loading into a subsequent bunk-load. Total time consumption (T^{D2}_{total}) was found to be proportional to total plot volume forwarded ($v^{allproducts}_{total}$), $T^{D2}_{total} = 2.1341 v^{allproducts}_{total} + 1722.8$ explaining 72.4% of variance and significant at the p<.05 level [F(6)=15.78, p=0.007]. The regression is summarised in Table 6.14.

6.5.4.7 D3 – Move Headboard & Bolsters

Moving of the headboard and bolsters occurred once each in plots 4, 5 and 8. Four occurrences were recorded in plot 3 totalling 426 cmin. The high use of this activity in plot 3 is likely to be due to the steep slopes encountered in the plot. Extracting on steep slopes is likely to require the headboard to be raised so that produce does not slide off the bunk toward the cab.

6.5.4.8 D4 – Prepare Stacking Area

Preparation of the stacking area did not occur in all plots. The highest time consumption was in plot 1 with no subsequent occurrence in the adjacent and sequentially forwarded plots 2 or 3. Time consumption was also high for plot 6 but low for plots 4, 7 and 8. It is likely that this code corresponds with the establishment of new stacking areas, as in plot 1, or their upkeep and expansion such as for plot 7 or 8. The activity is related to both stacking area location and capacity in relation to stand location and as such is not due to treatment.

6.5.4.9 D5 - Prepare Route

Route preparation is related to plot topography and ground conditions rather than treatment. The highest time consumption was seen in the clearfell and plot 1, both in absolute terms and relative to the number of load cycles. During each load cycle a mean of 171 cmin and 198 cmin were spent on route preparation in plots 1 and 7 respectively comparing to between 14 cmin and 76 cmin in other plots. The clearfell was situated on a soft peaty soil and parts of plot 1 were poorly drained and the racking system liable to severe rutting. The poor ground conditions are therefore likely to be the cause of the high time consumption, necessitating brash movement to bolster weak points in the brash mat.

Table 6.14 Summary of forwarder non-cyclic work element regressions

Work phase model	Dependent variable	R^2	F-test	Term		Constant / Coefficient		t-test	
						Estimate	Std. Error	t-value	p
Inspect & consider (all plots)	T^{C2}_{total}	0.807	[F(1,6)=25.076, p=.002]	Constant		-33.244	0.005	5.008	0.002
				T^{L}_{total}	x_1	0.026	73.276	-0.454	0.666
Aside brash (all plots)	T^{C4}_{m3}	0.423	[F(1,6)=4.400, p=.081]	Constant		2.720	2.019	-2.098	0.081
				T^{L}_{total}	x_1	-4.235	0.864	3.149	0.020
Aside produce to load (all plots)	T^{D2}_{total}	0.724	[F(1,6)=15.777, p=.007]	Constant		1722.796	3.055	3.972	0.007
				$v^{allproducts}_{total}$	x_1	12.134	396.568	4.344	0.005

6.5.4.10 Discussion of Non-cyclic Work Elements

6.5.4.10.1 C2 – Inspect and Consider

The analysis suggests that the activities associated with gathering and transporting a load within the stand are highly interdependent, time consumption rising proportionately in all activities.

Inspect and consider can be seen to be connected with choosing a route (movement and manoeuvre) and gathering loads (load, adjust load and aside produce), time consumption being to rise with that of the associated activities.

6.5.4.10.2 C4 – Aside Brash

The identified trend of aside brash time consumption decreasing with increasing log percentage is likely to be due to the relative sizes of the products. As logs were the largest product they were less likely to be obscured by brash. Stakes and pulp were conversely more likely to be obscured by brash. As log percentage increases, pulp and stake percentage decreases and so the time consumption for this activity is likely to decrease.

6.5.4.10.3 C8 – Fit / Remove Chains and Tracks and C9 - Debog

Time consumption associated with these codes is directly attributable to the steepness of the plot 3 topography. Debogging took 1821cmin, although this can be viewed as being a smaller figure than might otherwise have been the case due to the harvester being fortuitously close and able to help pull the forwarder up the slope. The incident confirms the statement by Kellogg & Bettinger (1994) that wheeled vehicle traction on steep slopes can ultimately be lost. As extraction continued successfully after the fitting of band tracks to the rear bogie and chains to the front, the benefits of traction aids (Ireland, 2006) for working on otherwise marginal ground are clear.

6.5.4.10.4 D1 – Aside Produce to Travel and D2 – Aside Produce to Load

The two aside produce elements are both related to the working pattern of the harvester and its presentation of produce at rack-side.

Aside produce to travel appears to have no association with treatment or stand parameters, the occurrence of produce in the path of the forwarder likely to be due to poor product placement by the harvester operator.

Aside to load is related to total volume forwarded as the forwarder operator re-piled produce to aid further loading. Loads were typically mixed, consisting of two or three product types, however these were stacked separately in the bunk to aid in unloading. Aside produce to load was used to sort the product types not loaded into piles to be loaded on the next pass. Time consumption can therefore be seen to be related to the volume loaded as this has been re-sorted and piled. Variance in the relationship will be added by differences in product density and distribution over the plot and the drift / pile presentation by the harvester.

6.5.4.10.5 D3 – Move Headboard & Bolsters, D4 – Prepare Stacking Area and D5 – Prepare Route

All three elements were found to be influenced by topography and site layout rather than treatment. Steep terrain is thought to have caused the increase in headboard movement in plot 3 and soft ground conditions the higher route preparation time consumption in plots 1 and 7. Stacking area preparation time consumption is thought to be a combination of layout, topographical restriction and working history. Increases in time consumption for these elements can therefore be seen to be due to combinations of site factors and not treatment.

6.6 CONCLUSIONS

6.6.1 Movement

Forwarder speed is dictated by terrain and the distance travelled between stopping points which in turn is dictated by felling pattern and intensity. Comparison of low thinning with the extreme crown thinning of creaming shows the number of thinned trees of 167 per hectare and 82 per hectare respectively to translate to mean movement distances of 7.41 m and 12.77 m and mean treatment speeds of 0.38 m/s and 0.51 m/s. Use of more irregular felling patterns such as in the group plots produced mean distance and speed values mid-way between low and crown thinning but with higher variance.

Movement within the clearfell was found to be different from that in thinnings, both mean distance and variance being higher due to a mixture of very small and long travels caused by the pile density and so higher intensity of working.

The relationship describing total distance moved within-plot was common to all treatments and is a product of the active rack network – that used by both harvester and forwarder – and the number of loading cycles undertaken by the forwarder. More regular racking layout and rack use by the harvester can therefore be seen to reduce total forwarder movement. Number of loading cycles is dictated by mean bunk volume in proportion to volume to be forwarded. Increasing log percentage of a given volume will increase mean bunk volume and therefore decrease total travel distance.

Effect of load on forwarder speed was found not to be significant for distances of less than 60 m although a 9% decrease in speed was found for distances above this between loaded and unloaded. Forwarder speed whilst within the plots was therefore generally unaffected by load as distances were generally less than 60 m. Speed on the road for distances of greater than 100 m when loaded was found to be 25% less than when unloaded.

6.6.2 Load & Unload

Treatment mean felled tree diameter was found to be the most important determinant in loading and unloading, changing both mean piece size and product proportions.

Both loading and unloading grapple volumes were found to be affected by the differences in treatment, rising with mean felled tree diameter, particularly by the strong log : diameter relationship. The effect on grapple volumes caused by the differences between treatment mean felled tree diameters at Trallwm were notable, about 0.1 m^3 per grapple load or unload between crown thinning and low thinning.

Number of pieces per grapple load and unload were found to be inversely linked to mean felled tree diameter, decreasing on average by around 0.5 pieces during loading and 2.25 pieces during unloading between low and crown thinning due to the increasing mean product volume.

Unloading compared with loading was found to utilise the grapple capacity more completely. Poor grapple utilisation during loading is most likely to be attributable to small pile size and poor presentation of products at rack-side.

Bunk volume is also dependent on mean felled tree diameter. Bunk volume increases due to more efficient space usage with an increase in mean piece volume and log proportion.

6.6.3 Other Cyclic Work Elements

Of the used cyclic work elements, treatment type and intensity can be seen as the main determinants of time consumption.

Manoeuvre time is related to total forwarding distance which itself is proportional to the number of loading cycles performed by the forwarder and the length of used rack. Intervention intensity will increase cut volume, so increasing the number of loading cycles, whilst thinning type will dictate the efficiency of bunk loads (through log percentage) and so regulate the increase of loading cycles in proportion to forwarded volume.

Move to unload time consumption is also affected by the volume extracted and stow / un-stow grapple time consumption by the number of loading cycles performed.

Intervention type also affects stacking time consumption by altering the percentage of sawlog material handled and load adjustment time which decreases with increasing mean tree volume.

6.6.4 Non-cyclic Work Elements

Non-cyclic work was less likely to be influenced by the intervention type or intensity.

Time consumption for inspect and consider was related to aspects of movement and loading, aside brash increased with increasing numbers of smaller products and aside to load was proportional to total forwarded volume.

Aside to travel was unrelated to intervention however and the elements of fit chains, debog, adjust bolsters, prepare route and prepare stacking area were all more related to site layout and topography and likely to increase with difficult working conditions.

CHAPTER 7: COMPARISON OF VEHICLE PRODUCTIVITY

7.1 INTRODUCTION

One of the central aims of the study at Trallwm was to assess if the transformation process was more costly than conventional working. Whilst Chapters 5 and 6 defined work-rate : stand-parameter relationships, the work rate of the harvester and forwarder need to be compared between plots to provide an answer.

7.1.1 Aims

- Present and discuss plot vehicle productivity
- Normalise plot diameter distributions to enable comparison
- Present and discuss normalised plot production and vehicle productivity
- Present and discuss future plot growth and implications due to diameter limits
- Discuss the general conclusions of the research and their implications

7.2 LITERATURE REVIEW

Vehicle productivity measures have already been covered in the Chapter 4 literature review section 4.3.

Measures of productivity are included in most published studies, although their utility is constrained by the need to take into account the machine, stand and intervention type and working method used.

The most commonly used value is P_e or delay-free productivity, measured in volume per productive machine hour (m^3/PMH) or volume per basic hour (m^3/BHR). P_{ge} or gross effective productivity is measured in volume per standard machine hour (m^3/SMH or m^3/SHR) and adds non-cyclic time consumption and some delays.

Conversion factors to estimate values of P_{ge} from P_e are sometimes given such as by Nurminen *et al.* (2006) or can be derived where both P_e and P_{ge} values are given e.g. Kellogg & Bettinger (1994). Conversion factors can also be expressed as "allowances" for other work and rest (Technical Development, undated (c)).

7.3 PLOT VEHICLE PRODUCTIVITY

Vehicle productivity was derived for the eight plots using the volume of cut produce. Delay-free productivity (P_e) or volume per productive machine hour (m^3/PMH) was calculated using cyclic time consumption. Gross-effective productivity (P_{ge}) or volume per standard machine hour (m^3/SMH) was calculated using cyclic and non-cyclic time consumption, disregarding delays of greater than 15 minutes.

Conversion factors were also calculated to convert P_e to P_{ge}.

7.3.1 Harvester Productivity

Harvester time consumption and productivity are presented in Table 7.1. P_e for all plots varied from a low of 20.85 m^3/PMH in plot 3 to a mean of 29.56 m^3/PMH (s.d.=5.58) and a high of 39.68 m^3/PMH in plot 7.

The mean P_e to P_{ge} conversion factor was 1.36.

Table 7.1 Harvester Productivity

HARVESTER	Frame plot 1	Group plot 2	Low plot 3	Frame plot 4	Low plot 5	Group plot 6	Clearfell plot 7	Creaming plot 8
Total Cyclic Time	17046	16660	22371	14338	18766	16168	45737	13609
Total Non-Cyclic Time	6088	4037	8607	3794	7551	7146	15687	6288
Volume Cut (m^3)	86.41	83.23	77.74	71.31	76.09	88.36	302.47	64.85
(P_e) Volume per Productive Machine Hour (m^3/PMH)	30.42	29.98	20.85	29.84	24.33	32.79	39.68	28.59
(P_{ge}) Volume per Standard Machine Hour (m^3/SMH)	22.41	24.13	15.06	23.60	17.35	22.74	29.55	19.56
P_e:P_{ge} Conversion Factor	1.36	1.24	1.38	1.26	1.40	1.44	1.34	1.46

7.3.2 Forwarder Productivity

7.3.2.1 Plot Productivity Values

Forwarder time consumption and productivity are presented in Table 7.2. P_e for all plots varied from a low of 12.21 m^3/PMH in plot 3 to a mean of 16.42 m^3/PMH (s.d.=2.94) and a high of 20.68 m^3/PMH in plot 7.

The mean P_e to P_{ge} conversion factor was 1.22.

Table 7.2 Forwarder Productivity

FORWARDER	Frame plot 1	Group plot 2	Low plot 3	Frame plot 4	Low plot 5	Group plot 6	Clearfell plot 7	Creaming plot 8
Total Cyclic Time	31419	33469	38214	21748	32199	35875	87768	21132
Total Non-Cyclic Time	7583	13690	8934	3207	5258	5228	19768	4859
Volume Cut (m^3)	86.41	83.23	77.74	71.31	76.09	88.36	302.47	64.85
(P_e) Volume per Productive Machine Hour (m^3/PMH)	16.50	14.92	12.21	19.67	14.18	14.78	20.68	18.41
(P_{ge}) Volume per Standard Machine Hour (m^3/SMH)	13.29	10.59	9.89	17.14	12.19	12.90	16.88	14.97
P_e:P_{ge} Conversion Factor	1.24	1.41	1.23	1.15	1.16	1.15	1.23	1.23

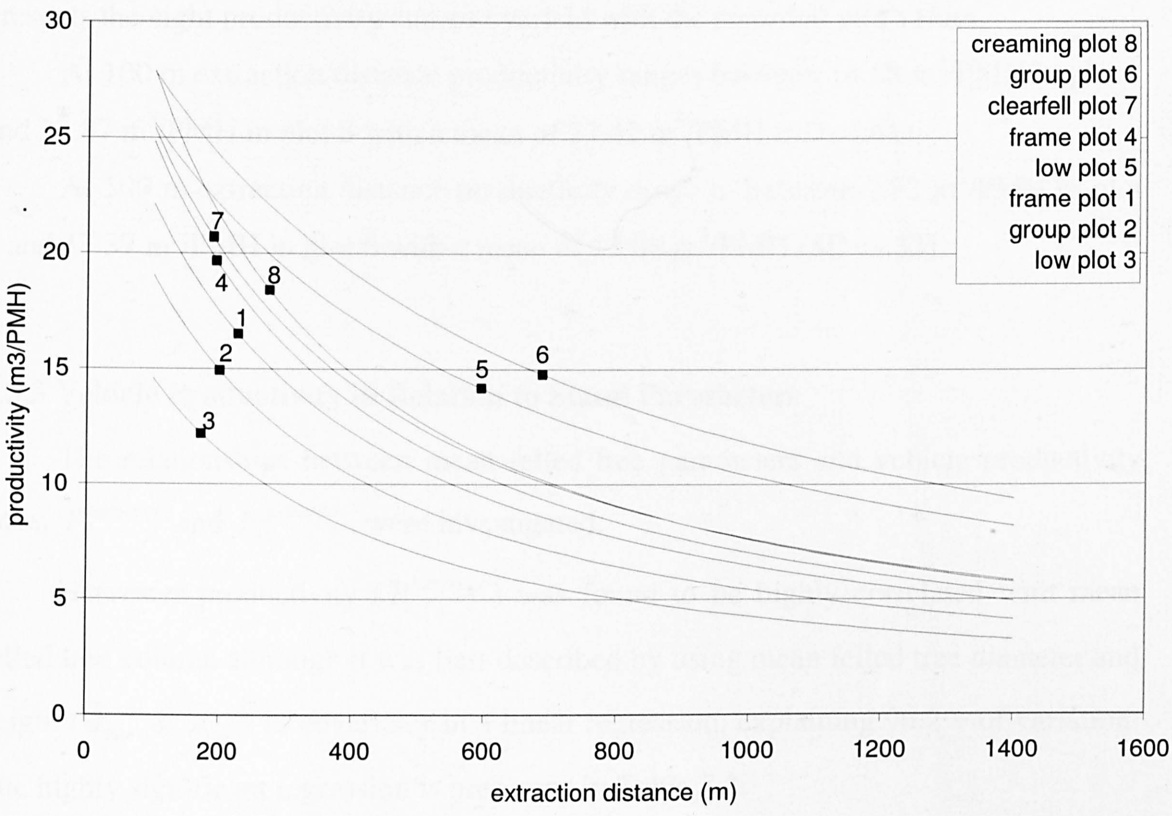


Figure 7.1 Forwarder extraction distance-productivity curves

Curves were calculated using plot means and assuming linear vehicle speed-distance relationship. Square points represent plot mean extraction distance.

7.3.2.2 Extrapolated Forwarder Productivity Rates

Forwarder productivity is often normalised between studies for a set extraction distance e.g. 100 m, by calculating average travel speed and loading & unloading rate (Technical Development, undated (b). The effect of altering extraction distance on forwarder productivity is often presented having used averaged vehicle speed and extrapolated over a range of distances (e.g. Kellogg & Bettinger, 1994; Nurminen *et al.*, 2006). As noted in 6.5.1, the relationship between forwarder speed and distance travelled is not linear. The use of a linear travel speed : distance relationship will provide questionable values for extraction distances dissimilar from those studied and this analysis aims to demonstrate this.

To compare forwarder plot productivity for equal extraction distance, productivity was calculated for extraction distances from 100 to 1400 metres using plot mean extraction speeds (time per cubic metre per 100 m extraction) and mean loading and unloading rates (time per cubic metre). Extraction distance is defined as the sum of move out rack (F), move out wood (G) and move out road (H) per load. Figure 7.1 presents the eight productivity curves overlaid with the recorded plot values.

At 100 m extraction distance productivity ranges between 14.58 m^3/PMH in plot 3 and 27.87 m^3/PMH in plot 8 with a mean of 23.42 m^3/PMH (SD=4.61).

At 500 m extraction distance productivity drops to between 7.02 m^3/PMH in plot 3 and 17.37 m^3/PMH in plot 6 with a mean of 12.08 m^3/PMH (SD=3.33).

7.3.3 Vehicle Productivity in Relation to Stand Parameters

The relationships between mean felled tree parameters and vehicle productivity rates, $P_e^{harvester}$ and $P_e^{forwarder}$, were investigated.

Harvester productivity ($P_e^{harvester}$) was found to be highly correlated with mean felled tree volume although it was best described by using mean felled tree diameter and height ($\bar{d}_{thin}$ & $\bar{h}_{thin}$) as covariates in a linear regression, explaining 96.2% of variation. The highly significant regression is presented in Table 7.3.

Forwarder productivity ($P_e^{forwarder}$) was found to be best described in a power regression using mean felled tree volume ($\bar{v}_{thin}$) as the variable. The highly significant regression explains 80.3% of variation and is presented in Table 7.3.

Table 7.3 Summary of regression analysis of Harvester & Forwarder delay-free productivity. All productivity values in m³/PMH

Dependent variable		R^2	F-test	Term		Constant / Coefficient Estimate	Std. Error	t-test t-value	p
Delay-Free Productivity Harvester	$P_t^{harvester}$	0.962	[F(2,5)=31.255, p=.001]	Constant		-41.409	8.999	-4.602	0.006
				$\bar{d}_{thin}$	x_1	0.793	0.170	4.671	0.005
				$\bar{h}_{thin}$	x_2	2.057	0.316	6.509	0.001
Delay-Free Productivity Forwarder	$P_t^{forwarder}$	0.803	[F(1,6)=24.382, p=.003]	Constant		0.572	0.116	4.938	0.003
				$\bar{v}_{thin}$	x	18.342	0.728	25.208	0.000

7.3.4 Discussion of Vehicle Productivity and Comparison to Other Studies

7.3.4.1 Discussion of Harvester Productivity

The regression chosen to describe harvester productivity, using diameter and height instead of volume, suggests that the relationship is sensitive to differences in stand form.

Harvester productivity was found to rise with the size of the mean felled tree as in other studies, as can be seen in Figure 7.2 which compares the productivities recorded at Trallwm with published figures.

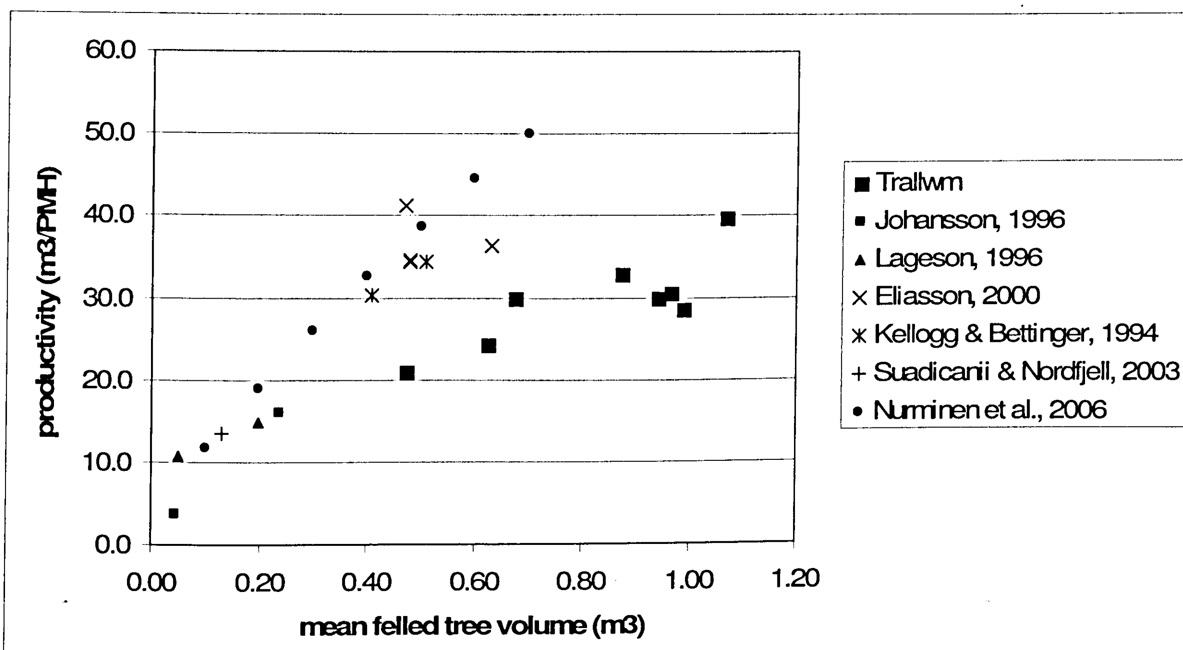


Figure 7.2 Comparison of harvester productivity at Trallwm to six other studies

Of note are the sets of points by Eliasson (2000) and Nurminen *et al.* (2006). The highest productivity value provided by Eliasson (2000) represents working in a clearfell, compared with thinning for the other three points. The points attributed to Nurminen *et al.* (2006) were calculated using the function presented for spruce final felling over the range of data collected in their study.

The per-tree time consumption curves published by Nurminen *et al.* (2006) show greater time consumption than this study (see 5.5.8.4.1), it is therefore surprising that their stated productivity rate for trees of 0.7 m^3 is higher than that found in the plot 7 clearfell ($\bar{v}=1.07m^3$), not lower as would be expected.

Different productivities for a given tree volume are likely to be attributable to several factors; machine type, intervention type and intensity, working method, ground and stand conditions etc. It is unsurprising then that there is a spread of productivity values for similar mean felled tree volumes.

It is unclear, however, if clearfell working is consistently more productive than thinning. For a given site and machine combination, clearfell should be more productive as harvester movement time will be less per tree than in thinning and felling and felling processing time may also decrease due to increased working space. These differences become proportionately smaller with increasing tree size as was shown in Chapter 5, so reducing the difference between thinning and clearfelling productivity values. The regression derived in section 7.3.3 for this study suggests that for mean tree volumes of a cubic metre or more, there may not be a great difference between thinning at 20% of G or clearfelling. Thinning at higher intensity is likely to reduce the difference further still.

Figure 7.3 is presented as a possible description of this relationship. The heavy line represents clearfelling and the lighter lines the removal of successively higher proportions of G. Thinning productivity rises and comes closer to that of clearfelling as mean felled tree diameter increases or thinning intensity rises.

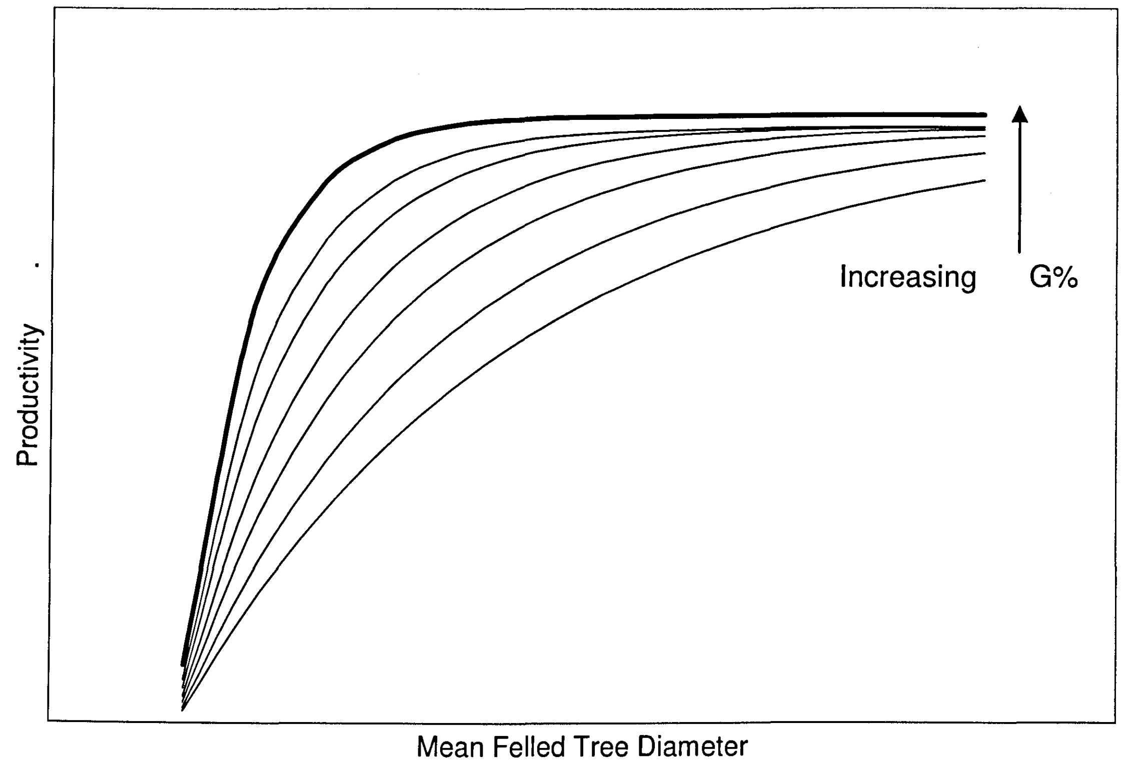


Figure 7.3 Conceptual illustration of the possible productivity increase in relation to felling intensity and mean felled tree diameter

7.3.4.2 Discussion of Forwarder Productivity

It was impossible to create a forwarder comparison in the same style as Figure 7.2 as the literature yielded too few studies from which suitable data could be gained.

Forwarder productivity is dependent on more variables than that of the harvester. As shown in Chapter 6, the intervention and stand parameters will dictate produce size and so loading and unloading rates. Forwarding distance, terrain, rack layout, working method and the size of the forwarder payload are however variables likely to have a great effect on productivity, altering the ratio of distance travelled to volume moved.

Tufts (1997), for example, found productivity rates of 33.79 m^3/PMH for log loads and 29.17 m^3/PMH for pulp loads over a 500 m extraction distance.

Kellogg & Bettinger (1994) found productivity rates for forwarding distances of between 230 m and 296 m of 14.3 m^3/PMH for sawlogs, 10.2 m^3/PMH for pulp, 13.0 m^3/PMH for mixed loads, 10.9 m^3/PMH for single passes (mixed loads) and averaging 12.2 m^3/PMH for all loads.

Favreau & Légère (1999) calculated forwarder productivity of 25.1 m^3/PMH for an extraction distance of 150 m in a mixed species stand in Canada.

Mean forwarding distances varied at Trallwm between 104 m and 577 m with a mean of 372 m. Loading cycles were generally mixed, although normally loading only two of the six products and maintaining separation for ease of unloading. Calculated productivity varied for the Trallwm plots between 14.19 m^3/PMH and 24.69 m^3/PMH from the mean of 19.47 m^3/PMH. The regression derived in section 7.3.3 does show that the vast majority (R^2=0.803) of forwarder productivity was related to tree volume. The remaining variation is likely to be due differences in forwarding distances and plot characteristics.

The extrapolation of forwarder productivity in relation to extraction distance carried out in 7.3.2.2 highlights the problem with using mean driving speeds as is common to most studies e.g. Kellogg & Bettinger (1994) and Nurminen *et al.* (2006). As shown in 6.5.1.5, the forwarder : distance relationship is not linear but instead shows an asymptotic form. Plots 5 and 6 had mean extraction distances of over 600 m compared with around 200 m for all other plots. As can be seen in Figure 7.1 the curves for these two plots have a different slope from those of the other six plots, showing higher productivities. The reason for this is that plot 5 and 6 mean speeds were higher than those of the other plots due to longer mean extractions much of which was on forest road.

The results of this analysis demonstrate that if this method is to be used then comparative studies should be conducted so that mean extraction distance is similar and the distance should also be stated to enable curve comparison with other studies.

7.3.4.3 Discussion of Conversion Factor

The P_e to P_{ge} conversion factors calculated for the harvester and forwarder are generally lower than those published. Table 7.4 presents conversion factors from published studies. Mean values for conversion factors are 1.461 for harvesters and 1.295 for forwarders, compared with 1.36 and 1.22 respectively for this study.

The studies at Trallwm were more concerned with plot working and as such paid less attention to work outside the plot. Work within individual plots was often started and finished within the workday, causing the studies to miss shift start and end maintenance work, the inclusion of which would increase factor value. The calculated factors may therefore be lower than for typical working, the "true" values being closer to published figures.

Table 7.4 Summary of published P_e to P_{ge} conversion factors for harvesters and forwarders

Study	Machine	Description	Factor
Nurminen *et al.*, 2006	harvester	general	1.529
Technical Development KD7	harvester	general	1.416
Kellogg & Bettinger, 1994	harvester	marked thinning	1.478
Kellogg & Bettinger, 1994	harvester	unmarked thinning	1.445
Kärhä *et al.*, 2004	harvester	general	1.393
Nurminen *et al.*, 2006	forwarder	general	1.327
Technical Development KD7	forwarder	general	1.346
Kellogg & Bettinger, 1994	forwarder	sawlog load	1.254
Kellogg & Bettinger, 1994	forwarder	pulp load	1.308
Kellogg & Bettinger, 1994	forwarder	mixed load	1.287
Kellogg & Bettinger, 1994	forwarder	single pass	1.298

7.3.4.4 Discussion of P_e Calculation

As stated in 7.3, P_e was calculated using the volume of produce cut or removed and the cyclic time required to do so.

In other studies, for example Eliasson (2000) and Kellogg & Bettinger (1994), P_e appears to have been calculated using the standing commercial volume of cut trees (UB in the case of Eliasson).

In section 5.3.2.1, cubic recovery percentage (CR%) in the primary processing carried out by the harvester is shown to increase with tree diameter. The effect of this relationship is that the volume of assortments cut, the actual product volume, will be less than the calculated standing volume, the proportionate difference decreasing with increasing tree size.

It is perhaps then arguable that productivity for both machines should be consistently derived not on the calculated volume of trees felled but on the actual volume of assortments produced. P_e values would be lower in all cases, the difference decreasing with increasing stem size.

7.4 CALCULATION OF NORMALISED PRODUCTIVITY

7.4.1 Limitations of Direct Comparison of Empiric Plot Data

Ideally, to enable a direct comparison of treatments, the eight plots would have been entirely homogeneous. However, there was a noticeable heterogeneity which precluded this. As discussed in Chapters 2 and 3, diameter distributions varied between plots in terms of both diameter range and distribution within that range. Stocking density also varied between plots. Plot site index also varied quite widely causing large differences between top heights and some form factor differences. A further problem was the differences found between plot racking networks, leading to differing movement times.

Because of this heterogeneity, even if a common treatment prescription had been applied to all plots, in terms of thinning type and percentage reduction of G, different outputs would have been achieved; different reduction in plot volumes, different plot values of $\bar{d}_{thin}$ and $\bar{v}_{thin}$ and different proportional assortment composition and mean piece volumes.

The plot heterogeneity could also accentuate the prescription applied, plot 3 being a good example, where starting with the lowest mean diameter of all the plots, the smallest trees were removed in a low thinning.

7.4.2 Synthetic Stand Creation

In order to provide treatment output values that can be compared directly, plot diameter distributions had to be normalised. The common base could then have plot intervention patterns applied to it to provide a comparison of interventions.

7.4.2.1 Synthetic Stand Method of Plot Diameter Distribution Normalisation

Diameter distributions for 1 cm diameter classes were calculated for each plot using the 2-parameter Weibull curves derived for pre and post thinning stocking densities in Chapters 2 & 3 (see also Appendices 5, 6 & 7). Thus for each plot a value of trees per hectare was calculated for the 54 diameter classes from 7 to 60 cm, for pre and post thinning.

The distributions were then constrained by rounding the trees per class to one decimal place and excluding classes with fewer than 1.0 trees within them. This was done to create a discrete diameter distribution range instead of the gradually diminishing values provided by the Weibull distribution.

For pre-intervention distributions, the number of trees in each class was then converted to a proportion of total rounded stocking.

The number of diameter classes used was then converted to proportions of the diameter range e.g. for 30 diameter classes (14-44 cm), each would represent 3.3333% of the diameter range, or for 28 classes (14-42 cm) each would represent 3.57% of the range.

For the residual stand distributions, the same pre-intervention diameter classes were used and class proportion was calculated as a proportion of the pre-thinning rounded stocking density.

Figure 7.4 demonstrates the proportional breakdown of stand stocking using plot 1 (frame tree) as an example.

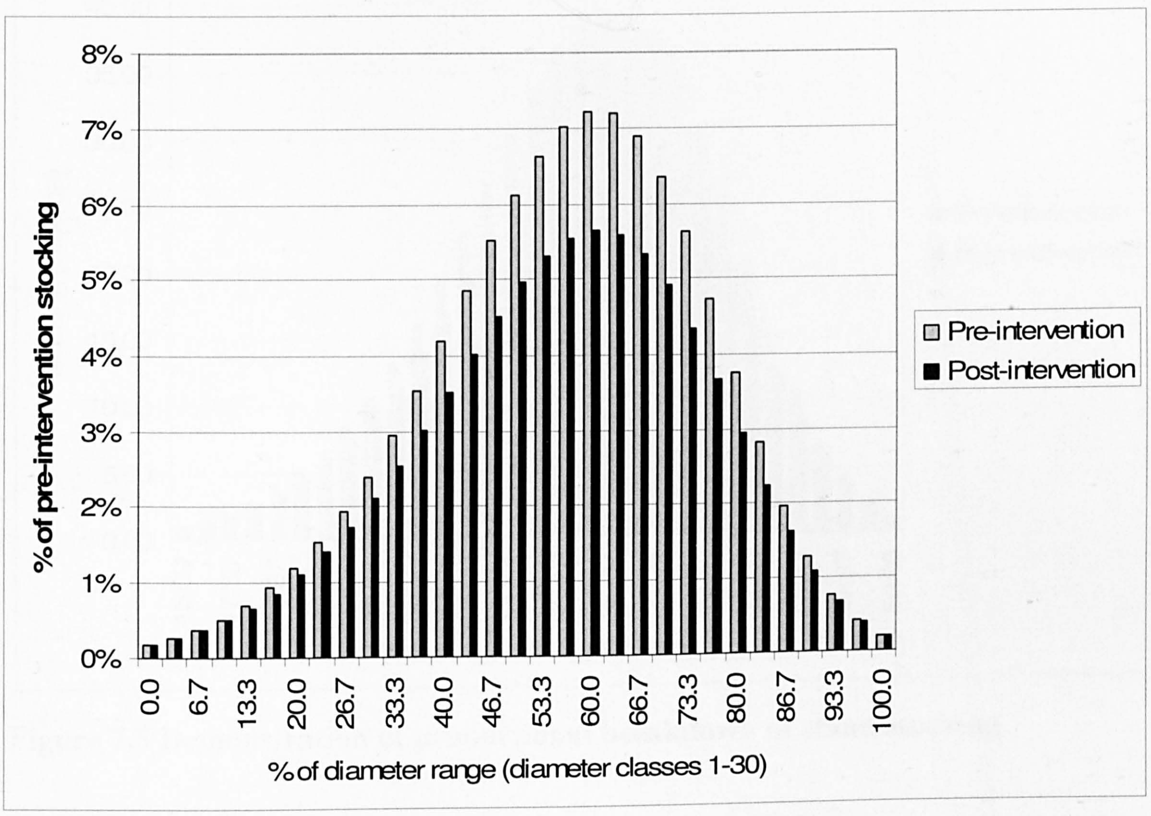


Figure 7.4 Demonstration of proportional breakdown of stand stocking

Parameters for the normalised diameter distribution were chosen as being representative of the eight plots, either as mean or common values.

Stand density of 548 trees per hectare was chosen as this was the mean of all plots pre-harvesting. A range of 15 cm to 50 cm was chosen as representative of the plot diameter distributions and a top height of 25 m with stand form height of 10.81 was taken as representative of the plots to calculate volume.

For each of the eight plots the number of diameter classes was used to split the normalised diameter range of 15-50 cm. For example, 30 classes would produce diameter classes 15.0, 16.17, 17.33……48.83, 50.0. The use of 28 classes would produce 15.0, 16.25, 17.5……48.75, 50.0.

The number of trees in each class was calculated from the classes' proportionate stocking and the stand density of 548 trees per ha. For example, if diameter class 30.17 cm has 4.82% of stocking then it will contain 26.54 trees.

Figure 7.5 demonstrates the results of proportional allocation of stocking on the synthetic stand using plot 1 (frame tree) as an example.

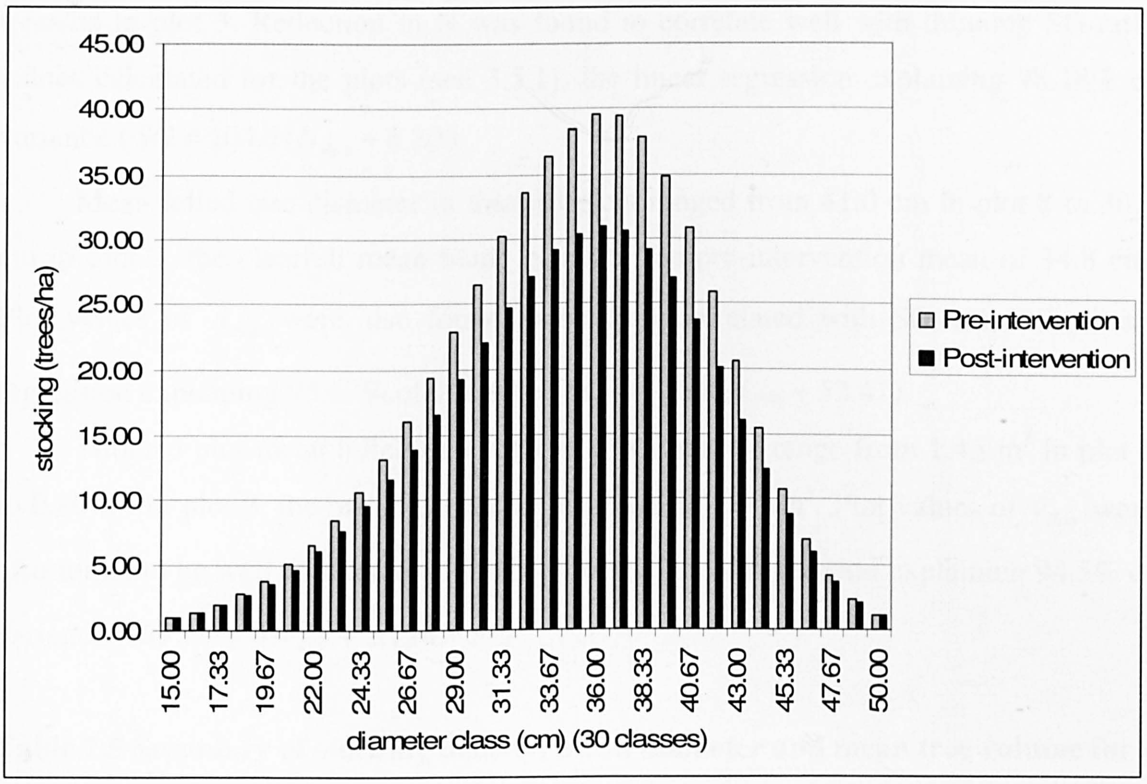


Figure 7.5 Demonstration of proportional breakdown of stand stocking

From the proportional allocation of stocking, pre, post and cut plot stocking, mean diameter and mean volume were calculated.

This gave a range of pre- intervention stocking density of 548 – 563.8, mean diameter 33.9 – 35.2 cm and mean tree volume 1.02 – 1.06 m^3.

Plot values were adjusted to pre-intervention values of 548 trees/ha, 34.8 cm mean diameter and 1.06 m^3 mean tree volume. Values were adjusted by dividing the unadjusted value by the ratio of unadjusted pre value to target value e.g. unadjusted pre-stocking (N) 553, unadjusted post-stocking (N) 397.8 would be adjusted to values of $\frac{553}{553/548}$ and $\frac{397.8}{553/548}$.

7.4.3 Effects of Diameter Distribution Normalisation on Plot Parameters

The results of plot normalisation are presented in Table 7.5 and figures 7.6 and 7.7. Values are presented for pre-felling (N_{pre}) and post-felling (N_{post}) stocking density and felled trees (N_{cut}) per hectare, and mean diameters ($\bar{d}_{pre}, \bar{d}_{post}, \bar{d}_{thin}$) and mean tree volumes ($\bar{v}_{pre}, \bar{v}_{post}, \bar{v}_{thin}$) for the modelled pre-felling and post-felling stands and cut trees.

Within the thinned plots, reduction in N ranged from 88 trees/ha in plot 8 to 154 trees/ha in plot 3. Reduction in N was found to correlate well with thinning SG-ratio values calculated for the plots (see 3.5.1), the linear regression explaining 98.18% of variance ($SG = 104.71N_{thin} + 6.20$).

Mean felled tree diameter in thinned plots ranged from 41.0 cm in plot 8 to 30.3 cm in plot 3, the clearfell mean being equal to the pre-intervention mean of 34.8 cm. Plot values of $\bar{d}_{thin}$ were also found to be well correlated with SG-ratio, the linear regression explaining 95.67% of variance ($SG = -16.81\bar{d}_{thin} + 52.41$).

Thinned plot mean felled tree volume was found to range from 1.45 m^3 in plot 8 to 0.80 m^3 in plot 3, the pre-intervention mean being 1.06 m^3. Plot values of $\bar{v}_{thin}$ were also found to be well correlated with SG-ratio, the linear regression explaining 94.5% of variance ($SG = -1.01\bar{v}_{thin} + 2.12$).

Table 7.5 Summary of stocking density, mean diameter and mean tree volume for plots before and after intervention and thinned portion

PLOT	N pre	N post	N cut	$\bar{d}_{pre}$	$\bar{d}_{post}$	$\bar{d}_{thin}$	$\bar{v}_{pre}$	$\bar{v}_{post}$	$\bar{v}_{thin}$
1 frame	548.0	444.6	103.4	34.80	34.54	35.91	1.06	1.05	1.12
2 group	548.0	416.5	131.5	34.80	35.78	31.68	1.06	1.12	0.88
3 low	548.0	394.2	153.8	34.80	36.55	30.30	1.06	1.17	0.80
4 frame	548.0	440.5	107.5	34.80	34.80	34.80	1.06	1.06	1.06
5 low	548.0	408.6	139.4	34.80	35.92	31.53	1.06	1.13	0.87
6 group	548.0	416.3	131.7	34.80	35.88	31.39	1.06	1.13	0.86
7 clearfell	548.0	0.0	548.0	34.80	0.00	34.80	1.06	0.00	1.06
8 creaming	548.0	460.3	87.7	34.80	33.61	41.04	1.06	0.99	1.45

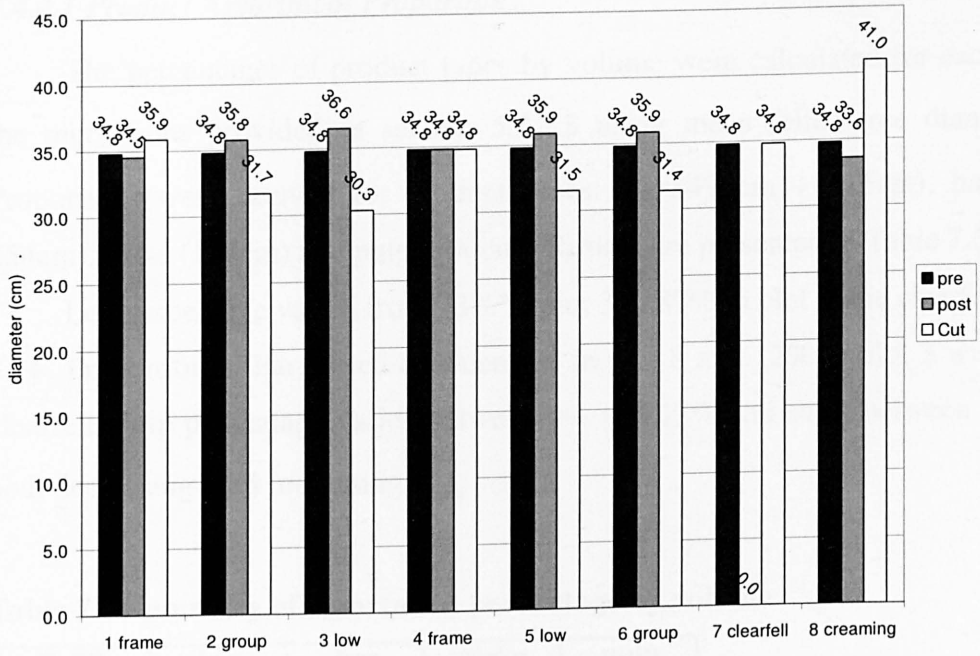


Figure 7.6 Comparison of plot pre and post thinning and cut tree mean diameter

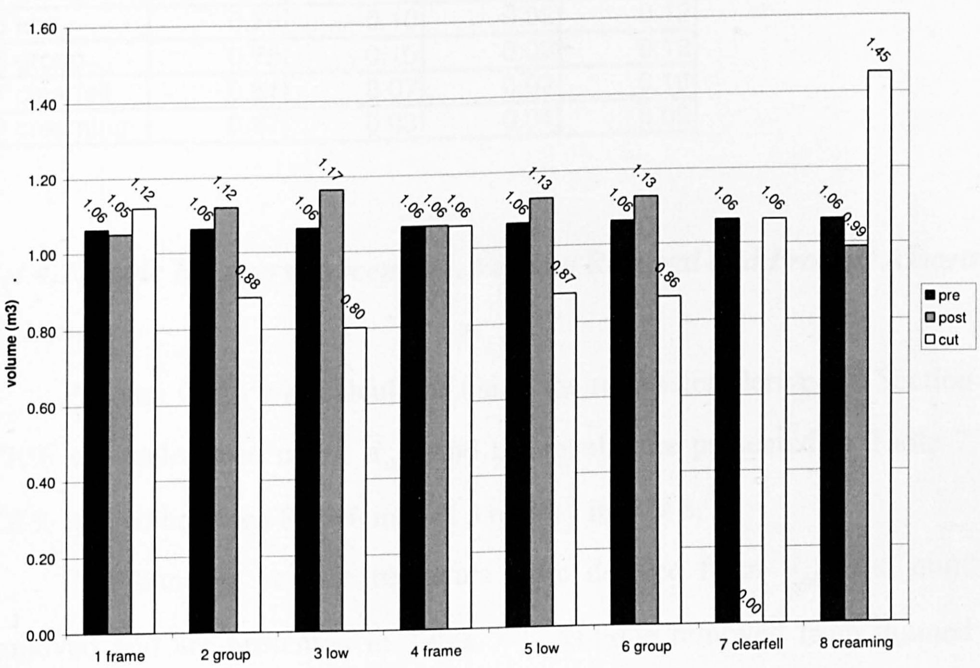


Figure 7.7 Comparison of plot pre and post thinning and cut tree mean volume

7.4.4 Effects of Normalisation on Product Assortments

Plot parameters calculated in 7.4.3 were used to derive product assortment proportions and volumes.

7.4.4.1 Product Assortment Proportions

The percentages of product types by volume were calculated for each plot using the regressions provided in section 5.3.2.3 using mean felled tree diameter ($\bar{d}_{thin}$). Proportions were derived for product types: log (495cm + 315cm), bar (375cm + 254cm), stake (172cm) and pulp (300cm). Results are presented in Table 7.6.

Log percentage varied from 73% in plot 3 to 87% in plot 8, the clearfell producing 81%. Proportion of bar varied between 3% in plot 8 and 12% in plot 3 with 7% in the clearfell. Pulp percentage varied between 9% and 12% and stake between 1% and 3%, both decreasing with increasing $\bar{d}_{thin}$.

Table 7.6 Summary of assortment percentage by volume

PLOT	log	bar	stake	pulp
1 frame	0.82	0.06	0.01	0.10
2 group	0.76	0.10	0.02	0.12
3 low	0.73	0.12	0.03	0.12
4 frame	0.81	0.07	0.02	0.10
5 low	0.76	0.10	0.02	0.12
6 group	0.75	0.10	0.02	0.12
7 clearfell	0.81	0.07	0.02	0.10
8 creaming	0.87	0.03	0.01	0.09

7.4.4.2 Cubic Recovery Percentage, Volume Removal and Product Assortment Volumes

Primary CR% was calculated using the regression derived in Section 5.3.2.1. Plot CR% was calculated using $\bar{d}_{thin}$ and the results are presented in Table 7.7. Values of CR% ranged between 87.0% in plot 3 to 87.4 in plot 8.

Plot standing volume removals were derived from $\bar{v}_{thin}$ and number of stems removed and are presented in Table 7.7. Volume removed from thinned plots varied from 113.5 m^3 in plot 6 to 127.2 m^3 in plot 8 whilst 582.6 m^3 was removed in the clearfell.

The volumes of assortments produced were derived from standing volume removal, CR% and assortment percentage and are presented in Table 7.7. Product assortment volume cut in the thinned plots ranged from 98.8 m^3/ha in plot 6 to 111.2 m^3/ha in plot 8 and was 508.6 m^3/ha in the clearfell.

Volume of log (combined 495 cm & 315 cm) was greatest in plot 8 where 96.4 m^3 was produced and lowest in plot 2 where 76.7 m^3 was produced. 411.9 m^3 was produced in the clearfell.

Table 7.7 Summary of volume production by assortment

PLOT	frame 1	group 2	low 3	frame 4	low 5	group 6	clearfell 7	creaming 8
Mean felled tree diameter (cm)	35.9	31.7	30.3	34.8	31.5	31.4	34.8	41.0
CR%	87.3	87.1	87.0	87.3	87.1	87.1	87.3	87.4
Standing volume cut (m^3/ha)	115.7	116.0	123.3	114.0	121.9	113.5	582.6	127.2
Assortment volume cut (m^3/ha)	101.0	101.1	107.3	99.5	106.2	98.8	508.6	111.2
Log volume (m^3/ha)	83.2	76.7	78.2	80.6	80.2	74.4	411.9	96.4
Bar volume (m^3/ha)	6.1	10.2	12.8	6.9	10.9	10.3	35.2	3.6
Stake volume (m^3/ha)	1.4	2.4	3.2	1.6	2.6	2.5	8.1	1.1
Pulp volume (m^3/ha)	10.3	11.7	13.1	10.4	12.4	11.6	53.4	10.1

7.4.4.3 Mean Piece Volumes

Mean piece volumes were calculated for all assortment products and combined log and bar using $\bar{d}_{thin}$ and the regressions derived in section 5.3.2.4. Mean piece volumes for all plots are presented in Table 7.8.

Mean piece volume for 495 cm logs varied between 0.27 m^3 in plot 3 and 0.41 m^3 in plot 8 and was 0.33 m^3 in the clearfell. Combined log mean piece volume varied between 0.22 m^3 in plot 3 and 0.33 m^3 in plot 8 with a value of 0.27 m^3 in the clearfell.

Table 7.8 Summary of mean piece volume

All volumes in m^3.

PLOT	log 495	log 315	bar 375	bar 254	stake 172	pulp 300	log 495 + 315	bar 375 + 254
1 frame	0.35	0.17	0.11	0.07	0.02	0.09	0.28	0.09
2 group	0.29	0.15	0.11	0.07	0.02	0.08	0.23	0.09
3 low	0.27	0.14	0.11	0.07	0.02	0.08	0.22	0.09
4 frame	0.33	0.16	0.11	0.07	0.02	0.09	0.27	0.09
5 low	0.29	0.15	0.11	0.07	0.02	0.08	0.23	0.09
6 group	0.29	0.15	0.11	0.07	0.02	0.08	0.23	0.09
7 clearfell	0.33	0.16	0.11	0.07	0.02	0.09	0.27	0.09
8 creaming	0.41	0.19	0.12	0.08	0.02	0.10	0.33	0.09

7.4.5 Synthetic Harvester Productivity (P_e)

Two estimates of harvester productivity were calculated, the first using $\bar{d}_{thin}$ and $\bar{h}_{thin}$ in the regression derived in section 7.3.2, and the second using $\bar{d}_{thin}$ in the regression derived in section 5.5.8.3. Values of $\bar{d}_{thin}$ and $\bar{h}_{thin}$ were provided by plot normalisation in section 7.4.3.

Productivity values are presented in Figure 7.8.

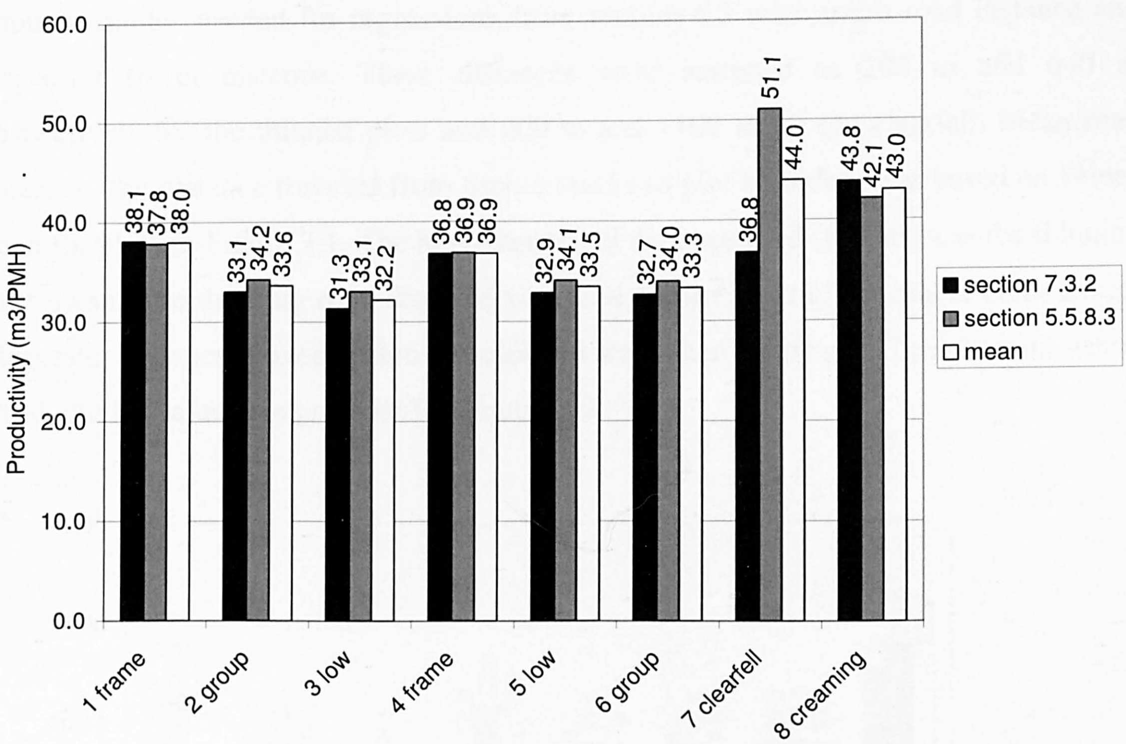


Figure 7.8 Estimated harvester productivity values

Productivity in thinning plots can be seen to vary with thinning type, productivity increasing with mean felled tree diameter.

The two methods of estimation do not agree on the productivity of clearfelling however, the regression of section 5.5.8.3 predicting a higher value in clearfelling. This is due to regressions in 5.5.8.3 being specific to either clearfelling or thinning whilst the 7.3.2 regression was for all plots.

If the mean of the two estimates is taken, productivity in low and group thinning can be seen to be equivalent, around 33.2 m^3/PMH. The productivity of around 37.5 m^3/PMH in the neutral thinning of the frame tree plots is around 13% more productive, and 44.0 m^3/PMH in clearfelling and 43.0 m^3/PMH in creaming plots are 33% and 30% more productive respectively.

7.4.6 Synthetic Forwarder Productivity (P_e)

Two estimates of forwarder productivity were calculated, the first using $\bar{v}_{thin}$ in the regression derived in section 7.3.2, and the second using the regressions derived in section 6.5. Values of $\bar{v}_{thin}$ were provided by plot normalisation in section 7.4.3. Other input variables needed for regressions from section 6.5 were mean road distance and harvester travel distance. These distances were assumed as 200 m and 640 m respectively for the thinned plots and 200 m and 1100 m for the clearfell. Mean road distance, the distance traveled from timber stacks to plot boundary was based on values seen for plots in Figure 7.1. The harvester travel distance used (640 m) was the thinning plot mean. The thinning road distance was used for the clearfell to enable comparison. Harvester distance moved within the clearfell was taken as the plot 7 per hectare value. Productivity values are presented in Figure 7.9.

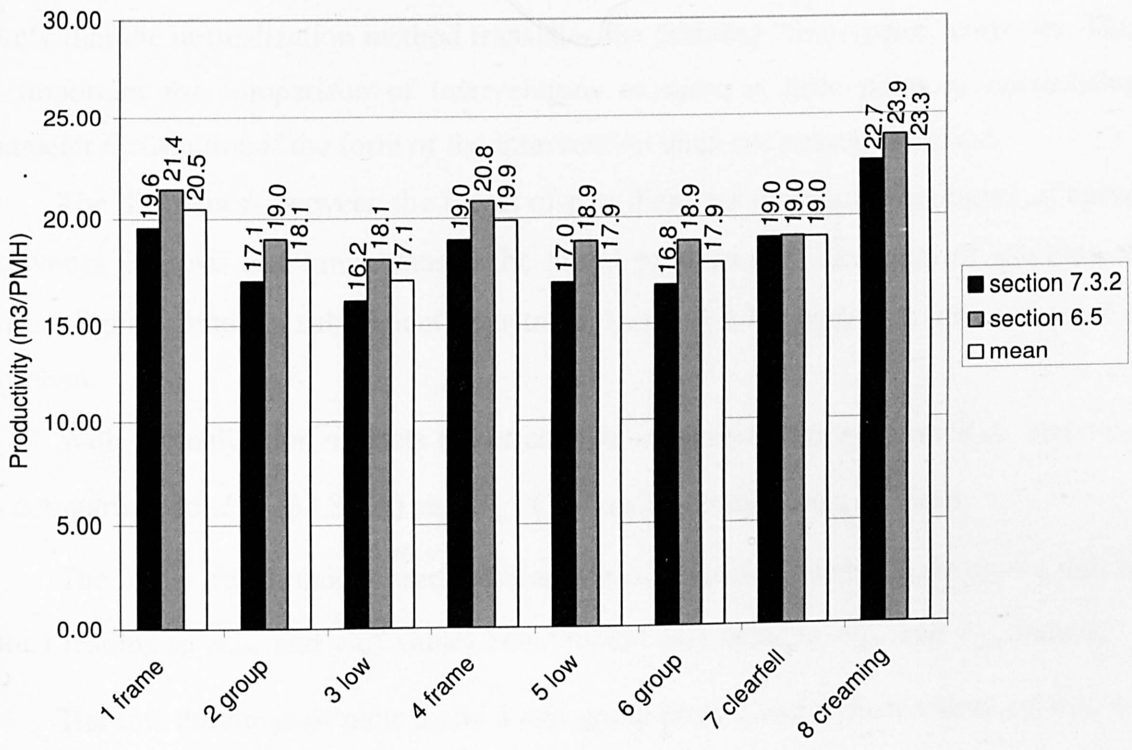


Figure 7.9 Estimated forwarder productivity values

Productivity in thinning plots can be seen to increase with mean felled tree volume.

The two methods of estimation do not agree on the productivity of clearfelling, the regression of section 7.3.2 tending to produce a higher value than that of section 6.5.

If the mean of the two estimates is taken, productivity in low thinning can be seen to be around 17.5 m^3/PMH. Group thinning has 3% higher productivity with a value of 18.0 m^3/PMH. The productivity of around 20.2 m^3/PMH in the neutral thinning of the frame tree plots is around 15% more productive. Clearfelling is 9% more productive with a productivity of 19.0 m^3/PMH and creaming is 33% more productive with a rate of 23.2 m^3/PMH.

7.4.7 Discussion of Plot Normalisation

The approach used to normalise plot diameter distributions to enable direct comparison has provided the plot parameters required to compare the interventions and calculate productivity.

As the normalised plot values of N reduction, $\bar{d}_{thin}$ and $\bar{v}_{thin}$ correlate well with the thinning index SG-ratio produced by the non-normalised plots (see 7.4.3) it seems likely that the normalization method translates the thinning "fingerprint" correctly. This is important for comparison of interventions as there is little point in normalising diameter distribution if the form of the intervention does not remain the same.

The differences between the forms of plot diameter distribution in terms of curve skewness, kurtosis and range caused the initial proportional allocation of stocking to differ slightly although subsequent adjustment (see 7.4.2.1) appears to have solved this problem.

With normalisation of plots the effect size of intervention type on $\bar{d}_{thin}$ and $\bar{v}_{thin}$ in comparison to $\bar{d}_{pre}$ (34.8 cm) and $\bar{v}_{pre}$ (1.06 m^3) becomes more obvious.

The frame tree thinnings were neutral in plot 4 and achieved a slight crown thin in plot 1 leading to $\bar{d}_{thin}$ and $\bar{v}_{thin}$ values equal to and very close to $\bar{d}_{pre}$ and $\bar{v}_{pre}$ values.

The low thinnings of plots 3 and 5 and group plots 2 and 6 show values of $\bar{d}_{thin}$ to be between 9.0% and 12.9% lower than neutral thin values, equivalent to 17.0% to 24.6% smaller values of $\bar{v}_{thin}$.

Creaming values show the greatest difference from neutral values, $\bar{d}_{thin}$ being 17.9% higher and $\bar{v}_{thin}$ 36.5% higher.

As explored in 5.3.2, mean felled tree size controls product assortment proportions, cubic recovery percentage (CR%) and mean piece volumes.

Log percentage is therefore highest in the creaming plot, 87% of volume produced being in this bracket compared with 81% in neutral interventions and between 73% and 76% in the low thinned interventions.

Similarly, CR% is highest in the creaming treatment (87.4%) and lowest in low thinning (87.0%), the difference not being so marked due to rate of change of CR% being low for diameters over 28 cm.

Mean piece volume does however show a large difference between treatments, 495 cm logs averaging 0.41 m^3 in the creaming plot compared with 0.33 m^3 in a neutral intervention and as little as 0.27 m^3 in low thinning. The mean volumes are equivalent to 25.3% higher and 17.3% lower than the mean volume of a neutral intervention.

As explored in Chapter 5, harvester time consumption per unit volume decreases with increasing tree size, leading to a rise in productivity (7.3.2). The rise in productivity from the low thinning and group plots to frame tree and creaming plots was around 13% and 30% respectively. Published studies comparing harvester productivity between thinning types also note a productivity increase between low and crown thinning. Lageson (1996) reported between 20% and 40% increase, Lageson (1997) a 39% increase and Eliasson & Lageson (1999) a 36% increase in a simulation. The three studies compared low thinning of a thinning index similar to those of plots 3 and 5 to thinning from above with a thinning index similar to the frame tree plots 1 and 4. Stands studied also have considerably lower tree sizes than Trallwm, mean diameters being in the 13-19 cm range. The difference between the 12% increase predicted in 7.4.5 and the 36% to 40% increase in other studies may therefore be due to the disparity in tree sizes and the non-linear diameter : rate relationship.

The productivity estimates made for the clearfell, as stated in 7.4.5, differ from those of 5.5.8.3 due to one using a clearfell-specific relationship and the other a relationship derived for all plots in 7.3.2. The mean value of 44.0 m^3/PMH compares well with figures published by Nurminen *et al.* (2006) of around 41 m^3/PMH for the same mean tree volume in spruce clearfell although similar levels of productivity have also been recorded by others for smaller tree sizes e.g. Eliasson (1999) (41.3 m^3/PMH for $\bar{v}_{thin}$=0.46 m^3), Hanell *et al.* (2000) (42.2 m^3/PMH, $\bar{v}_{thin}$=0.47 m^3) and Spencer (1998) (42.1 m^3/PMH, $\bar{v}_{thin}$=0.6 m^3). The productivity recorded in plot 7 was 39.7 m^3/PMH for a mean tree volume of 1.04 m^3 compared to a mean tree volume in the normalised clearfell of 1.06 m^3. The productivity estimate of 36.8 m^3/PMH using the relationship from 7.3.2 would therefore seem to be too low and the mean including the value from the 5.5.8.3 estimate of 51.1 m^3/PMH more realistic.

Forwarder productivity, like that of the harvester and as explored in Chapter 6, rises with mean felled tree size. The rise in productivity from the low thinning and group plots to frame tree and creaming plots was around 15% and 33% respectively. This increase can be seen to be due to mean piece volume increasing due to increasing $\bar{d}_{thin}$ and agrees broadly with the findings of Kellogg & Bettinger (1994) although the productivities presented by them were lower, in the range of 10-15 m^3/PMH with smaller mean tree volumes.

Nurminen *et al.* (2006) found forwarder productivity to be higher in clearfelling than thinning noting the higher concentration of produce at rack-side as a factor, although it should also be noted that $\bar{v}_{thin}$ was also higher in the clearfell than in thinning.

The estimated clearfell productivity of 19.0 m^3/PMH is lower than would be expected. Given that the normalised clearfell has a value for $\bar{v}_{thin}$ of 1.06 m^3 compared to 1.04 m^3 in plot 7, modeled productivity would be expected to be slightly higher than is than the productivity of 20.7 m^3/PMH recorded in plot 7. The relationship defined in 7.3.2 was defined for all plots and so is biased towards thinning productivity and so underestimates. The value given by it is the same as that for plot 4 as both represent neutral interventions. The estimate produced using relationships defined in 6.5 provides the same estimate. The estimate assumes that rack use in the clearfell is higher, 1100 m/ha compared to 640 m/ha in thinning. When rack use is lowered to that of the thinning plots productivity rises to 21.6 m^3/PMH which is far closer to expected levels.

7.5 FUTURE GROWTH

7.5.1 Calculation of Basal Stem Taper

Butt logs were separated from the assortment data and the rate of taper from mid-length to butt calculated for each using the mid, and end diameter measurements recorded by the harvester head. Assuming that all trees were felled at 30 cm above root collar and so 1 m below dbh, the rate of taper was used to calculate the critical diameter corresponding to a butt diameter of 60 cm. Taper rates and critical diameters are presented in Table 7.9.

Plot tapers suggest that a critical diameter of around 55 cm will correspond to butt end diameters exceeding 60 cm. This analysis is based on the current 60 cm butt-diameter limit in sawmills. It is likely that sawmills will adapt to utilize future resources and so in future will accept the larger dimension trees likely to be produced by CCF management. This analysis can be repeated for future diameter limits or to compare the effects of different potential limits on plot oversize growth.

Table 7.9 Summary of plot stem tapers and critical diameters

Plot	cm taper per cm length	cm taper in 1m	mean critical dbh	stand deviation (cm)
plot 1 frame	0.041	4.14	55.86	2.35
plot 2 group	0.038	3.76	56.88	2.12
plot 3 low	0.035	3.53	56.47	1.98
plot 4 frame	0.046	4.56	55.44	2.16
plot 5 low	0.041	4.06	55.94	2.46
plot 6 group	0.052	5.17	54.83	2.66
plot 7 clearfell	0.041	4.07	55.93	2.10
plot 8 creaming	0.047	4.72	55.28	2.22
Mean all plots	0.043	4.25	55.83	2.26

7.5.2 Future Growth of Plots

7.5.2.1 Plot Growth

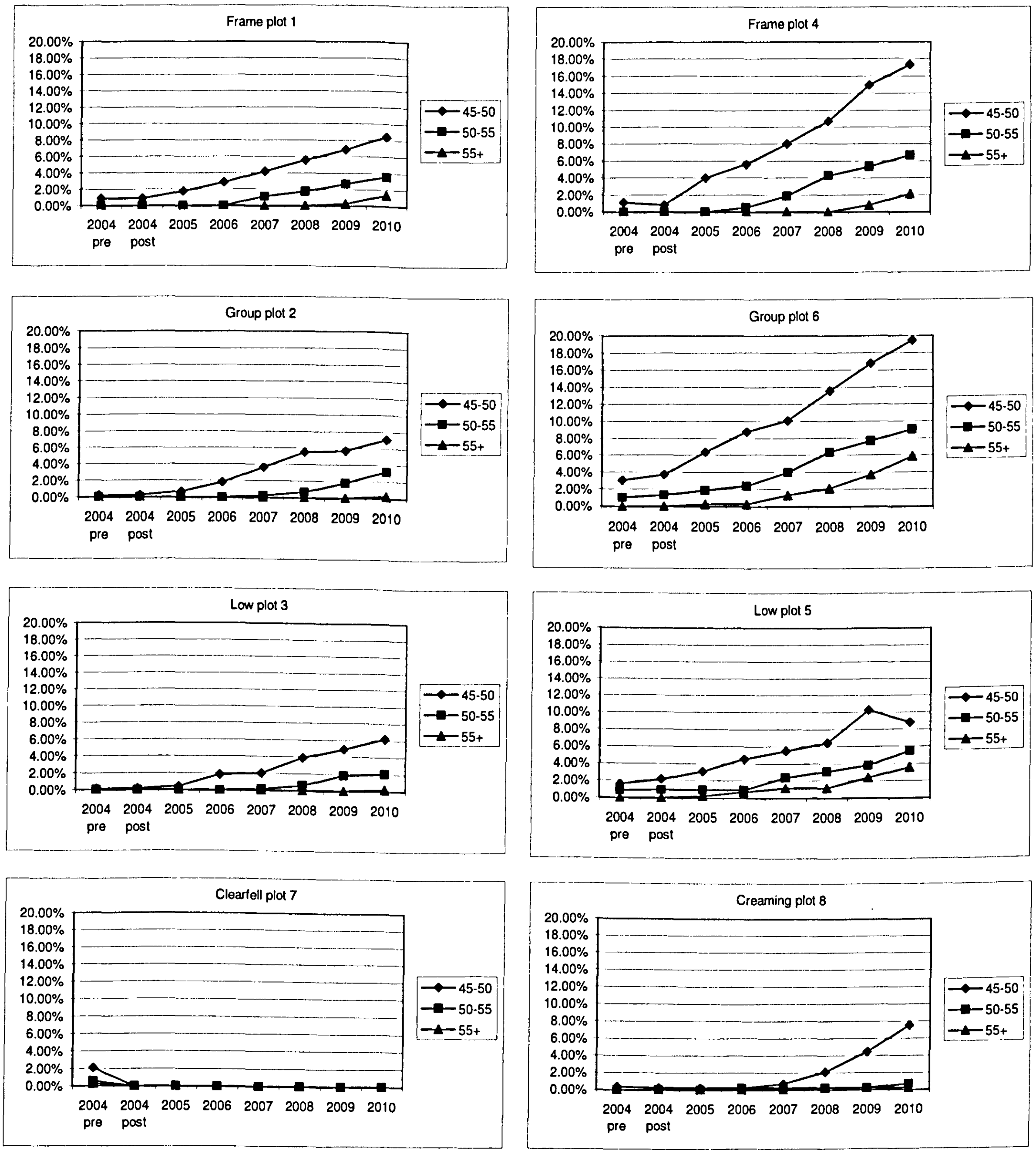
Stand diameter increment was calculated in section 2.5.4 using data from destructive sampling. The regression in 2.6.2.3 derived for combined plot 6 & 8 diameter growth in relation to present diameter was used to calculate future diameter growth for all retained plot trees. The assumption inherent in this is that growth rates do not change from those of the previous ten years due to stand age or change in thinning regime and inter-tree relationships.

Annual increment was applied to the plot distributions to investigate the effect of six years growth on the diameter distributions. Six years was chosen as the duration between transformation thinnings at Trallwm is likely be between three to six years.

Three diameter classes were recorded; 45-50 cm, 50-55 cm and >55 cm. The largest size of 55 cm or above was seen to represent oversize trees that had grown to produce butt-logs of end-diameter greater than 60 cm. Trees of between 50 and 55 cm were seen as becoming close to over-size and trees of between 45 and 50 cm were seen as becoming large.

The proportion of plot stocking within the three diameter classes is presented in Figure 7.10.

Figure 7.10 Prediction of the future proportions of plot stocking



The analysis suggests that six years after thinning a mean of 17% of trees would be within one of the three classes, increased from a mean of 1.5% after the intervention. Plot 6 has the highest proportion of 34.31%, 5.85% being oversize whilst plot 3 has the lowest proportion of 8.44% with only 0.21% being oversized.

7.5.3 Volume Loss Through Growing Oversize

Using mean butt-log taper, the volume of stem-wood of diameter greater than 60 cm was calculated for increasing tree diameter. This volume can be seen as that which would be trimmed to reduce logs to saleable size.

Volume loss starts at 55.1 cm and follows the quadratic curve $v_{loss} = 0.257936 - 0.07698 \cdot d + 0.001315 \cdot d^2$.

Plot volume loss through oversize growth was estimated by calculating plot diameters for the six consecutive years after the intervention (as in 7.5.2.1) and applying the volume loss relationship to trees exceeding 55 cm.

Table 7.10 presents the estimated volume that would be needed to be trimmed from stems to reduce the butt log end diameter to 60 cm.

Table 7.10 Number of oversize trees and volume loss to trim to 60cm butt diameter

PLOT		Year 1	Year 2	Year 3	Year 4	Year 5	Year 6
1	N oversized trees	0	0	0	0	1	6
Frame	Volume loss (m3)	0	0	0	0	0.01	0.48
2	N oversized trees	0	0	0	0	0	1
Group	Volume loss (m3)	0	0	0	0	0	0.05
3	N oversized trees	0	0	0	0	0	1
Low	Volume loss (m3)	0	0	0	0	0	0.09
4	N oversized trees	0	0	0	0	3	8
Frame	Volume loss (m3)	0	0	0	0	0.16	0.75
5	N oversized trees	1	2	5	5	10	15
Low	Volume loss (m3)	0.07	0.25	0.81	1.60	2.71	4.62
6	N oversized trees	1	1	5	8	14	22
Group	Volume loss (m3)	0.04	0.20	0.83	1.94	3.49	6.19
7	N oversized trees	0	0	0	0	0	0
Clearfell	Volume loss (m3)	0	0	0	0	0	0
8	N oversized trees	0	0	0	1	1	1
Creaming	Volume loss (m3)	0	0	0	0.06	0.20	0.34

The analysis suggests that six years after the intervention a mean of 1.79 m^3/ha would need to be trimmed to reduce butt log diameter to 60 cm. Plot 6 would have the highest volume loss of 6.19 m^3/ha and plot 2 the lowest with 0.05 m^3/ha.

7.5.4 Increment Discussion

The proportional increase of large diameter classes within plots can be seen to be due as much to the initial diameter distribution as the intervention type.

The frame tree plots, 1 and 4, whilst having undergone a very similar intervention, show different proportions of larger trees, plot 4 having more due a to larger initial mean diameter. This is also obvious in plot 6 which, whilst subjected to a low thinning characterized as nearly identical by thinning indices to that in plot 5, has double the proportion of large trees due to a higher initial mean diameter.

Plot 8 is of interest as although the mean diameter was initially equal to those in plots 1 and 5, due to the felling of the largest trees, only 8.45% of its trees are classed as large at six years, compared to 13.27% in plot 1 which had a neutral thin and 17.9% in plot 5 which was low thinned.

As would be expected, by reducing the numbers of larger diameter stems in an intervention (crown thinning), the proportion of trees becoming oversize in the future will be less than where only smaller stems were removed (low thinning).

As stated in 7.5.1, this analysis is based on current market limits of a 60 cm maximum butt diameter for log material. There is likely to be an increase in larger diameter log material if CCF management is pursued which may lead to a development of sawmilling infrastructure allowing larger diameter logs to be handled as standard.

If large diameter butt material is to be trimmed and left in the stand, another option may be for it to be counted as coarse woody debris which can be used to fulfill conservation targets, potentially swapping timber revenue for grant revenue.

7.6 GENERAL CONCLUSIONS

7.6.1 Summary of Chapter 1

Chapter 1 provides initial description of the Trallwm field-site as well as a background to the instigation of the research project of which this study is a part.

The project was initiated by Forestry Commission Wales to provide economic analysis of CCF working on which to help base decisions on the level of grant funding required for forest managers wishing to convert to CCF.

This study was conducted to provide productivity outputs from operational working which could be used to furnish economic analysis in the wider project. The study area was chosen as it provided a good example of the upland Sitka spruce plantation that would be involved in many transformation attempts in Wales; the typical type of woodland that policy and grants that promote conversion to CCF would target.

The topographical limits of the study site combined with the area requirements for permanent sample plots limited the number that could be installed at Trallwm to eight (see section 1.1.2 & 2.3). The inclusion of the group shelterwood treatment prohibited the subdivision of plots as the spatial diversity of the treatment required a larger minimum area than the other treatments. These restrictions limited the number of treatment replicates that could be used and so limited the statistical analysis of treatment outputs.

Whilst the study site was chosen for being an upland Sitka spruce plantation, the most common commercial forest type in Wales, and so likely to be most targeted by policy encouraging conversion to CCF, there is a considerable diversity of other stand types to be encountered. Variations in stand age, species, structure, management history and topography will lead to different management objectives and strategies and so greatly alter the harvesting situations encountered.

The study can be seen as a case study of different transformation strategies for a particular stand type and machine/operator combination. Whilst a great deal can be learnt from the study, the models produced would require validation in other similar stands and with other machine/operator pairings before being generally used, and even then would only be applicable to similar interventions in similar Sitka spruce stands.

7.6.2 Summary of Chapter 2

Chapter 2 covered initial plot layout and presented pre-intervention stand parameters. The plots were found to be more heterogeneous than ideal for direct comparison, diameter distributions differing significantly between plots. Site index and stocking density were also found to be different between plots leading to differing standing plot volumes. One of the conclusions drawn from the chapter was a concern that trees of equal diameter felled in different plots were not directly comparable due to effects of differing site index and that some form of normalisation would be required. Another concern was the relationship between felled tree diameter, stem taper, and product assortment. Due to the differing stem tapers between plots of dissimilar site index, it was seen as possible that different product assortments would be cut from trees of equal diameter causing problems in direct comparison.

Included in the plot layout and measurement was an initial survey of the rack network which found layouts and densities to differ due to initial ploughing pattern, topography and ground conditions. The racking density of the plots demonstrates the importance topography and ground conditions plays on rack density and layout. The optimal racking density can be seen as the lowest density required that provides full and unhindered machine access to the stand. The lowest racking densities will be seen in flat stands with good ground conditions, allowing an evenly spaced, parallel network. Steep ground such as in plot 3, or difficult terrain such as boggy areas in plot 1, were seen to increase the racking density. Increasing racking density will decrease the productive matrix area, so lowering stand productivity.

Destructive sampling was also carried out to calculate diameter and height increment which could be used in any future modelling effort. Diameter increment for trees of equal diameter was not found to differ between plots of disparate site index (plot 8 YC 16 and plot 6 YC 24), allowing a common relationship to be used for all plots in modelling diameter growth in chapter 7, albeit with some the assumptions made that future growth will not alter with tree age or changes in growing space. These assumptions form much of the reason for, and the difficulties faced in single-tree modelling. Increment rates will change through time with tree maturity, but will also be influenced by inter-tree competition, something that is influenced by different management regimes.

7.6.3 Summary of Chapter 3

Chapter 3 covered the silvicultural application within the plots. The effects of the thinnings on stand parameters were explored and so the thinning types and intensities defined. Target basal area reduction of around 20% was achieved in all thinning plots and the type of thinning defined through the SG ratio and S1 parameter. Weibull curves and their parameters defined for the plots after the intervention were also compared with those defined in chapter 2 as an additional indicator of thinning type and for use in later modelling.

By comparing the mean values of the marking class parameters of diameter, height, c/h, h/d and crown depth, it was found that trees within marking classes showed the desired morphological characteristics of their class thus confirming marking decisions.

Stand structural diversity as measured by the Shannon and Simpson indices dropped due to thinning reducing the diameter range of five of the seven thinned plots. The exceptions were the neutral frame tree plots where diameter range was not reduced but kurtosis was, thus increasing the relative abundance of diameter classes.

Stability indices (c/h and h/d) were found to improve in low thinning and reduce in crown thinning although the value changes were small and stand and diameter class means remained within "safe" values.

The reduction of standing basal area in transformation thinnings is the mechanism by which forest floor light levels are raised to establish and sustain natural regeneration. The 20% reduction of basal area was a light thinning which was seen as a balance of reducing basal area whilst trying not to destabilise the exposed upland stands. A concern with light thinnings is that the intervention is "not strong enough" and the increase in light levels and crown space is too short lived. The length of the effect caused by an intervention is also associated with thinning type. Crown thinning, as it removes dominant trees, is likely to disrupt the stand canopy more than a low or intermediate thinning, resulting in a longer-lasting effect for a given intensity. The use of lower intensity interventions will also require a shorter thinning cycle if a decrease of basal area is to be maintained and levels dropped below the 30 m2/ha identified as critical for Sitka spruce by Hale (2004). Lower intensity interventions will also have an effect on vehicle working and productivity and is discussed further later sections. The effects of the studied intervention on natural regeneration levels are not yet known. Although there was a survey in summer 2007 by a Bangor University undergraduate, no results have yet been produced. The results should help to provide a clearer picture of how the different thinning types have succeeded in improving stand conditions for natural regeneration. It would also be interesting to investigate if intervention type has an effect on regeneration response for stands thinned to the same basal area.

7.6.4 Summary of Chapter 5

Chapter 5 assessed harvester working during the intervention and the products produced during cutting.

The accuracy of the measurements recorded by the harvester head was investigated to check the validity of their use in calculating the volumes of cut products. Head calibration showed acceptable accuracy when compared to manual measures of produce, errors likely to have been caused by measuring wheel problems and rough tree form. Verification of these data allowed the records of products cut from each tree to be appended to mensuration and time study data.

The use of the vehicle production-log to provide assortment volume data instead of manual measuring is a new method, only appearing in the literature very recently in the study by Nurminen et al. (2006). The method has great potential, both to reduce the amount of measuring time used by the studyman, and to provide individual-tree time-consumption and volume production data. The use of this data source and method in further studies is constrained by the quality of the crop. As previously discussed in Chapter 4, the roughness of a crop can severely impair the accuracy of measurements, leading to unreliable data. When vehicle-log data are to be used, it is recommended that accompanying check measurements be taken to estimate accuracy. The findings of Nieuwenhuis & Dooley (2006) also suggest that the head measuring system should be calibrated frequently to maintain accuracy.

The details of products cut were used to investigate how assortment proportions and cubic recovery percentage (CR%) changed with different thinning types. CR%, log percentage and mean piece volume all increasing with mean felled tree diameter.

The CR% and product proportion relationships identified are specific to the product assortment mix studied at Trallwm; 495 cm & 315 cm logs, 375 cm & 254 cm bar, 300 cm pulp and 172 cm stake. Increasing the number of products will increase the flexibility of processing and so increase CR% for a given diameter. This could also be achieved through the cutting of log-poles. Changing the product assortment cut will also alter the relative proportions of product types cut for a given mean felled tree diameter.

As crown thinning would take proportionately larger trees from a stand, a higher percentage of their volume would be cut into produce of a larger mean piece size with a higher percentage of log material than in a low thinning. The impacts of these relationships are also larger when working in smaller tree sizes. The change in CR% and log percentage between mean felled tree diameters of 20 and 25 cm is much greater than that between 25 and 30 cm. The difference between a low thinning and crown thinning for a crop is, therefore, greater for a value of of 20 cm than for 30 cm. This has a greater relevance for younger crops and earlier thinnings, where a move away from low thinning could greatly increase the volumes and revenues produced.

The forcing of a limited set of assortments is conventional practice as harvesters will cut to fulfil mill demands and specifications. Cutting an unusually wide range of products, whilst increasing CR%, will have a detrimental effect on machine productivity, particularly that of the forwarder. There is a conceptual scenario that a limited product range might cause a dramatically different assortment to be cut from two stands that straddle a border between product types. A small change in mean felled tree diameter would cause a large "step" change in the proportion of a product. For this to occur it would seem that the stands being compared would have to have diameter distributions showing extreme kurtosis and the felled trees would have to have almost identical stem taper and either no defect or identically placed defect. Only in this very contrived situation would this scenario seem possible. The data and analysis from section 5.3 do not present any evidence for the "stepping" effect, but rather suggest a more regular relationship between the proportion of product and mean felled tree diameter. The theoretical stepped relationship is smoothed by the greater diameter range cut and heterogeneity of felled trees.

The use of the plot rack system was also investigated, finding that access was gained or possible to the majority of plot areas. Proportional rack use was found to be partly influenced by treatment although this was considered likely to be due to experimental setup. Brash laydown within thinning plots was found to be unrelated to treatment. For a constant rack layout and a greater coupe size (i.e. not a restricted plot) it seems likely that rack use will be equal between treatments. Brash mat created in the clearfell was, of course, much heavier and more robust than that in thinning plots. Although a greater length of rack was used by the harvester in the clearfell compared to the thinning plots (c. 1100 m compared to a mean of 640 m), the greater intensity of working inherent in clearfelling, a 100% reduction of basal area compared to 20% in the thinning plots, provides a far higher density of brash in used racks.

A criticism of CCF working has been that it does not produce enough brash for mats and can lead to rack damage (Mason et al., 1999; Mason & Kerr, 2001). The results of this study suggest that the transformation thinnings used produced brash mats equivalent to those from conventional thinning. Much of the reason that CCF has acquired this reputation is that thinning intensity is often lower and thinning cycle (harvesting return period) shorter than in conventional working. At the same intensity however (e.g. 20% basal area reduction using crown thinning compared with low thinning), there appears to be nothing inherent in CCF working that makes it less likely to produce sufficient brash matting.

The spatial analysis of harvester working also suggests that on a stand level, and given the same optimally spaced regular racking network, the harvester will use the same amount of racking in CCF working as in conventional working. These findings are important as they suggest that CCF stands do not require a higher intensity of racks than conventional stands, only that they are maintained well. This is important as CCF management will consist of a continued series of interventions on a short intervention cycle, whereas after clearfelling, no vehicle entry into the stand is likely until first thinning at around year 20.

Harvester work was divided into cyclic and non-cyclic elements, cyclic work being concerned with the move towards, felling and processing of a tree and non-cyclic work being unrelated to any particular tree.

Cyclic work generally related to tree size, spacing and morphology; total time consumption rising with tree size and crown size and decreasing with intensity of working caused by closer spacing of felled trees.

Non-cyclic work was generally influenced by the regularity of the rack system, irregular systems leading to more movement, manoeuvre and consideration time consumption. The exception was log stacking which was related to felling time consumption.

A difference was also found between the cyclic work rate of clearfell and thinning, the clearfell rate being higher due to higher intensity working and freedom of harvester movement.

Whilst total time consumption per tree increased with diameter, the rate of harvester working was found to increase. The decrease in time spent to fell and process each unit volume increases the volume produced per hour (m3/PMH), larger trees therefore being more productive. The implication of this rise in productivity with diameter in terms of thinning type is that an equal intensity crown thinning will have a higher rate than low or intermediate thinning as the mean felled tree diameter is greater. This is important in the comparison of CCF thinning to conventional (low thinning) working in this intervention as it shows that for a given stand, low thinning will provide the lowest productivity.

The harvester study covers predominantly mid-diameter trees of 20-40 cm compared with Scandinavian studies which are generally of small diameters of the order of 10-25 cm. The distribution of diameters at Trallwm was such that 90% of felled trees had a diameter between 20 and 40 cm. The reliability of the per tree time consumption and rate curves could well be suspect outside these limits due to the scarcity of data points. Future work is needed on the "large" diameter classes of 40 cm and above, investigating harvester working in diameters close to machine upper limits. This is of particular importance as there is likely to be a future increase of larger trees due to retention of overstorey and seed trees if CCF management is pursued. The use of crown thinning during later stages of stand development could also result in larger trees being cut on average.

The overall rise in time consumption associated with increasing depth of crown for a given diameter indicates a potential disadvantage of CCF management, albeit a small one. If early crown thinning is pursued in a stand to increase individual tree stability, the reduced inter-tree competition will cause an increase in mean c/h ratio. Likewise, if regeneration of a crop is poor and stocking low, a similar increase in c/h is likely to occur. The greater prevalence of CCF management could therefore lower harvesting productivity in the future when compared to thinning of non-CCF crops; a rise in mean c/h of around 0.1 leading to a decrease in productivity of around 3%. This may be balanced partly by the increase in brash production for mats.

This study was of the initial transformation intervention carried out in even-aged and fairly uniform stands and as such aspects of later transformation working may well differ.

Later transformation interventions where the overstorey is gradually removed to favour the developing but still unthinnable understorey of regeneration are likely to be characterised by less intense working as removed trees will become more widely spaced. This in itself is not very different from this study as the overstorey crop is still quite uniform and the intervention can still be characterised through thinning type (and hence) and thinning intensity. The relationship between productivity and is likely to change due to greater distance between trees. Figure 7.11 is presented as a conceptual illustration of what form this change might take, using the conceptual Figure 7.3 as a comparison. Maximum vehicle productivity would only be achieved by harvesting at higher values of , favouring crown thinning again rather than low thinning, or further increasing intensity.

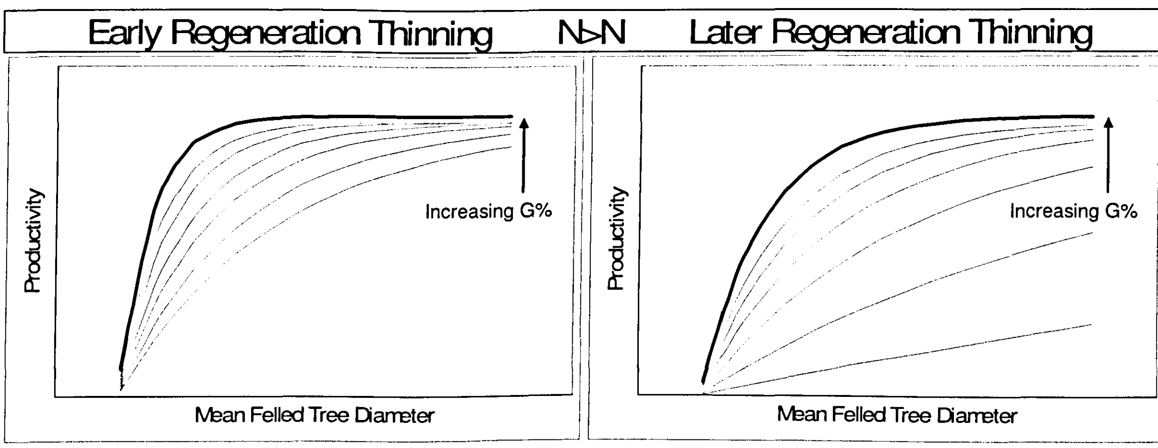


Figure 7.11 Conceptual illustration of the possible productivity decrease due to the reduction in stocking density

The increasing presence of an understorey will also have an effect on working. Research by Forestry Commission Forest Research is already under way into the effects of understorey on machine working (Ireland, 2007. Pers. Comm.). Initial results indicate that working is slowed by the understorey obscuring the base of the mature trees, so hampering their acquisition with the harvesting head and the observation of the head when repositioning during cutting. The large trees involved can also cause working problems as their diameters and weights (as in some cases at Trallwm) are often close to or exceeding the vehicle capacity. The combined problems of tree weights exceeding the capacity of the machine to control felling adequately, the need to take multiple cuts to fell large diameters, and the poor visibility of the operation due to obscuring regeneration, can undermine the safety of felling. The use of larger machines could help mitigate the problems caused by large trees, however, their use comes at the cost of their larger dimensions and running weight and their interaction with the rack network. The problems posed by poor visibility could be solved by machine modifications such as a camera on the head or pre-marking and area preparation by chainsaw operator.

The regeneration period of the crop will also play a large part in the future organisation of harvesting as it will dictate the regularity of the future stand (Matthews, 1991). A shorter regeneration period will include fewer interventions, each of greater intensity and so higher productivity, and would lead to a more regular structure. A longer regeneration period will require a greater number of weaker interventions, each of lower productivity, and lead to a more irregular structure. As this research is based on a uniform stand it is not possible to predict how machine working will be affected by the multiple strata of an irregular system. There is concern (e.g. Mason et al., 1999) that machine working will become fragmented and diffuse with irregular structures, leading to lower productivity. This may not be the case at all if machine working could be developed to tend and manage all strata in one pass during an intervention. Research is certainly needed to develop and assess these methods.

More regular stands and their shorter regeneration periods are likely more attractive economically. Machine working will be very similar to "conventional" stands as the crop will consist of a single stratum, something that will also ease management. The shorter regeneration period is also more attractive as it minimises the regeneration time of the stand and hence the risk associated from factors such as wind. A shorter period will also help minimise some of the problems associated with overstorey and seed trees growing oversize or past their financial rotation. Adapting a version of the creaming treatment will also help in this case, cutting trees before they grow oversize and increasing intervention and so productivity. This method would be reliant on the felled trees not being the only seed bearers in the stand. The continual targeting of the largest and most dominant trees within the stand also raises concerns regarding the long-term genetic quality of the stand.

Another question also remains over how harvester productivity will vary between different intervention types when applied in the "real world". All treatments at Trallwm were pre-marked to normalise for the harvester operator's lack of familiarity with some of them compared to low thinning. If operator select is to be used it is possible that crown thinning may lose some productivity owing to the need for the operator to shift in his seat frequently to assess the canopy rather than relying more on the view of the lower trunk as in low thinning. Pre-marking of stands could be used but the cost would have to be less than any harvester productivity losses for it to be viable. The issue of the application of stand marking and its cost will have to be addressed for some systems anyway. Frame trees, groups and their shelter-building trees may well have to be marked as a matter of course. The benefit of the creaming treatment in this respect is that it is as easily applied using operator select as low thinning.

7.6.5 Summary of Chapter 6

Forwarder working was covered in Chapter 6. Cyclic work time consumption was found to be heavily influenced by thinning type through its effect on assortment; and thinning intensity, through its effect on volume cut. Non-cyclic work was less strongly influenced by these factors. Movement was found to be related to the type of intervention carried out, the felling pattern and intensity dictating the distance between loading stops and the forwarder mean speed increasing with longer distances. For a given intensity, crown thinning produces longer distances between loading stops than low thinning with a resultant higher mean speed. The group plots represented a spatially more irregular system, and, whilst the mean speed is related to thinning type, variance is higher due to the greater irregularity of movement. This pattern was also observed in the clearfell where many small loading moves due to the density of working were mixed with some larger moves to and from start of loading. The total distance moved by the forwarder was found to relate to harvester movement, the distance increasing with harvester rack use and the number of loading cycles undertaken by the forwarder.

Mean bunk volumes were found to rise with increasing percentage of log assortment, so reducing the total number of loading cycles for a given volume and reducing total moved distance.

The mean piece volume was found to affect loading and unloading grapple volumes and pieces per grapple, both time per grapple and productivity increasing with mean piece volume.

Crown thinning can therefore be seen to increase productivity. Larger trees produce greater proportions of log material and larger mean piece sizes which in turn will increase mean bunk volumes, decrease the number of loading cycles and increase loading and unloading rate.

The study of forwarders still has great potential to be developed. Nurminen et al. (2006) measured the volumes of piles of produce which could then be related to the time taken to load them. This works only if the whole pile is picked up however, the pile mean piece volume having to be used if the pile is split. The next logical step in refining measurement of load handling would be to individually measure and tag produce so as to be identifiable in filmed footage of working. This would be extremely resource intensive but would be able to fully refine the relationships between load and unload time consumption, pieces per grapple and volume per grapple. The relationship between pile size and forwarder working is heavily dependent on the capacity (measured as an area) of the forwarder grab. Changes in grab capacity will alter these identified relationships. The "optimal pile size", one that will fill a forwarder grab to capacity either once or number of times, so optimising loading, will also vary with grab capacity and the dimensions of felled produce. The presentation of produce in the drift represents the interface of harvester and forwarder working. Forwarder productivity is likely to be increased by several general practices; increasing product density and pile size, increasing grab capacity and improving product presentation.

The effects of future interventions and stand development were discussed for the harvester and similar aspects of the regeneration process will be likely to affect forwarder working.

Later transformation interventions where the overstorey is removed are likely to result in less intense working, leading to higher speeds between stops. The increasingly large values of will increase mean piece volume and log percentage and so increase bunk volumes and handling rates. Harvester working should use the same density of racking for these interventions, so total distance travelled will be a function of thinning intensity, and hence total volume cut, and its interaction with piece size and bunk volume.

As mentioned previously, research is currently underway to investigate machine working during interventions later in the regeneration period (Ireland, 2007. Pers. Comm.). Initial results indicate that advanced regeneration obscures cut produce by the rack-side leading to produce being overlooked and misidentified, both leading to drops in productivity.

The regularity of regenerated stands will also be likely to affect forwarder working. In more regular stands derived from shorter regeneration periods, forwarder working, like that of the harvester, is likely to be very similar to "conventional" working. For a more irregular stand, assuming that the stand is thinned and tended in one pass, the number of produce types and the product size range are likely to be greater than in conventional working. This would lead to a decrease in the mean piece volume and an increase in the complexity of working, so decreasing productivity. The mix of tree size classes and the operations carried out in them will be likely to dictate the intensity of working and volume to be forwarded.

7.6.5 Summary of Chapter 7

Chapter 7 first presents harvester and forwarder productivity calculated for the plots. Productivity was shown to rise with tree size. Harvester productivity was best described through mean felled tree diameter and height, indicating a sensitivity to stand form-height. Forwarder productivity was best described through mean felled tree volume.

The productivity of both machines was best described through the size of felled trees, mean felled tree diameter and height accounting for 96.2% of variation for the harvester and mean felled tree volume describing 80.3% of variation for the forwarder. This finding illustrates that thinning type has a very direct influence on intervention productivity. The thinning type will dictate the value of mean felled tree diameter in relationship to pre-felling mean diameter. Trees removed by crown thinning will be, on average, larger than the stand mean, leading to higher machine productivity. The converse will apply in low thinning. The intensity of an intervention is the other main factor in productivity. Removing more volume from an area will cause more intense vehicle working and increase productivity.

Harvester productivity (Pe) was calculated using the volume of cut produce and the cyclic time taken to do so. This is opposed to using the value of standing commercial volume that is felled (to 7 cm top diameter OB or UB). The use of standing volume will provide higher values of Pe than if using cut product volume as it does not include adjustment for CR%. As the felled-tree : diameter relationship is not linear, the difference between the two methods will vary with mean felled tree size. As the use of cut volume to calculate productivity provides a value based on what is actually produced it should be used instead in all studies.

Methods of calculating forwarder productivity were also found to provide cause for concern. The method of using average forwarder speed to estimate productivities over a range of distances is flawed as the forwarder distance : speed relationship is not linear and the assumption of it being so can provide erroneous estimates. Where studies with different extraction distances are compared, the study with a higher extraction distance will have a higher mean speed and so will have a higher estimate of productivity. Where studies are to be compared, it is therefore very important that extraction distances are similar in all treatments. The use of average speeds to estimate productivities over a wide range of extraction distances is also questionable.

Plot heterogeneity was shown to limit direct comparison so the plots were normalised by proportional breakdown of diameter distributions produced from Weibull curves. Plot normalisation provided an estimate of the difference in mean felled tree diameter and volume if the initial diameter had been equal, the estimate using a starting mean tree volume of 1.06m3. The analysis confirmed the findings from the empiric study; low thinning producing the smallest mean tree volume, followed by group shelterwood, frame tree, clearfell, and creaming producing the largest. Variations in mean felled tree diameter could also be seen to affect CR%, assortment breakdown and mean piece volume. The larger mean felled tree diameters provided a higher CR%, a greater percentage of which was sawlog. The estimated productivities for both the harvester and forwarder were higher in clearfelling and in neutral or crown thinning than in low thinning. The percentage increases in productivity, up to 33% for the harvester in the clearfell and 30% for the forwarder in creaming, are however dependent on the parameters of the thinned stand. The difference in productivities from smaller dimension stands is likely to be larger due to the greater change in rate of relationships in the smaller diameters. The relative productivity of thinning types will therefore be proportional to the size of trees encountered in a stand, but their ranking should remain in the same order in all stands.

Modelling of future plot growth investigated the proportion of trees that would grow oversize (>60 cm butt diameter) in the years following intervention. Removal of larger mean tree size in an intervention was found to decrease the proportion of trees that become oversize and so reduce the volume loss associated with this due to current need to trim to 60 cm butt diameter limits. As stated in 7.6.1, the 60 cm butt limit is a current sawmill imposed constraint. There is likely to be future increases in the supply of large diameter timber if CCF management is pursued due the retention of overstorey trees for seed and shelter. Given an influx of large diameter timber, the 60 cm limit is likely to be raised through installation of new mill lines. There will however still be a maximum diameter that can be handled and this is likely to form a new limit. Future management can adopt a target diameter and new critical diameter, equivalent to 50 cm and 55 cm at present. The analysis used in 7.5.3 could easily be adjusted to recalculate for these new diameters.

7.6.6 Implications of the Study and Findings for Management

This study and the project of which it is part were commissioned to investigate the economic effects of CCF management. The results cannot claim to be comprehensive however as they describe only a case study of working in a specific stand type and machine/operator combination. As stated in 7.6.1, variations in stand age, species, structure, management history and topography will lead to different management objectives and strategies and so greatly alter the harvesting situations encountered.

The largest problem involved in comparing transformation of stands towards CCF with conventional thinning and rotation clearfell is summarising the multitude of approaches the former will take. In this respect, CCF is an unhelpful term as it covers nearly every other silvicultural system aside from clearcutting. Whilst conventional rotation forestry has a well established management-table framework of first and successive thinnings at marginal thinning intensity and clearfelling at maximum mean annual increment (MAI), CCF management does not. Of great use would be a series of examples of typical working scenarios for the common species and site types found in Wales and the wider UK context. Once agreed upon, these scenarios could be used as exemplars on which to base economic models. The exemplars could be used to provide a chronosequence of stand development. Interventions throughout the sequences could then be characterised by their effect on diameter distribution, their thinning type, intensity, productivity and output. These data could then be used as a framework for predicting machine productivity and output over a wide range of intervention types and intensities.

It must always be borne in mind however, that CCF management, due to its more reactive nature, will not necessarily follow a rigid management-table prescription. The early or late appearance of natural regeneration would for example probably require rescheduling of thinning interventions and removal of the overstorey accelerated if stability was becoming a problem.

Another point that must be borne in mind when comparing CCF working is that the same thinning type is unlikely to be used throughout the entire development of a crop. Early crown thinning may well be used to improve individual-tree stability, with successive thinning types become more neutral or low.

The findings of this study do however indicate that, for a stand that is reasonably regular, there is no inherent cost penalty associated with thinning types other than conventional low thinning. In fact the opposite is true, as for a given thinning intensity low thinning provides the lowest value timber yield and vehicle productivities of the approaches studied.

The intensity of interventions observed in the study was equal across treatments. An area which requires considerably more research is the comparison of typical yields from interventions for CCF management, particularly in the regeneration phase where the overstorey is being removed. This would provide information on whether CCF interventions were always less intense and whether this adversely significantly effected the profitability of working. The use of exemplars would again provide very useful information on this area but more immediate abbreviated studies such as those undertaken at Clocaenog Forest by Forest Research (Ireland, 2007. Pers. Comm.) would provide welcome information on productivity and problems associated with working in this developmental stage. This is the most pertinent area for urgent research as it will provide the productivity and output data for direct comparison to that of clearfelling and replanting.

The study of the plots at Trallwm covers only the first in a series of interventions which are applied to establish, tend and release an understorey of natural regeneration.

The low thinning plot will reach maximum mean annual increment at around 48 and 52 years old for plots 3 and 5 respectively; equivalent to 2015 and 2019 for the two plots. Management is likely to include a single thinning followed by clear felling, site preparation and replanting.

The frame tree plots 1 and 4 will produce a uniform shelterwood. One or two interventions, again thinning to favour the frame trees, will be required to reduce the basal area to below 30 m2/ha to encourage and sustain advanced regeneration. Thinning cycle needs to be quite short, 3 to 4 years, if basal area is to be steadily reduced. Once sufficient advanced regeneration has been secured, it is likely that a further two interventions will be required on the overstorey, the first to remove remaining matrix trees and the second to remove the last remaining overstorey consisting of the frame trees.

The creaming plot, if the same form of management continues, will produce another uniform shelterwood. Basal area will be reduced sufficiently to encourage regeneration in one or two interventions and a further one or two interventions would be needed to remove the overstorey.

The two group shelterwood plots, 2 and 6, will produce a more irregular shelterwood than that of the other plots. As the groups have been opened, the next interventions will continue to thin the stand matrix and open the stand surrounding the groups leaving a number of shelter-building trees standing. Further interventions will continue in response to regeneration response and stand stability.

Experience of CCF in the UK is still in its infancy. Many of the operational aspects of transformation can be advanced through future research, training, and the experience gained through implementation. This includes questions such as whether to fully mark stands, mark "sample areas" for operator reference, or use feller select. This is in particular is another area that requires immediate work. Investigation should assess the level of marking required for different systems and the costs associated with that. This could easily be a factor that would decrease intervention profitability to financially unattractive levels.

Much of the economic benefit associated with CCF systems is thought to be the absence of cultivation and planting costs. The planning of intervention timing pivots on the assumption of sufficient natural regeneration and its later survival and growth. These factors cannot be guaranteed as management may have to wait for mast years or be put back by a dry summer damaging susceptible regeneration. The establishment of healthy and sufficient advanced regeneration is therefore a substantial variable of which policy and management must be sensitive to.

This study is also concerned only with a Sitka spruce monoculture. The acceptance of natural regeneration could increase the species diversity of the stands which will make future harvesting and management more complex. Planting could also be used to supplement regeneration, to deliberately steer species mix or as an attempt to improve genetic quality of the stands. The study of mixed species stands and the economic analysis of the net benefits associated with them or the enrichment planting to develop them is also needed in the future.

Whilst this study has provided a useful first look at machine working and productivity associated with transformation working in UK, it provides only a small part of the information that is needed to fully evaluate CCF. A great deal more research is needed if CCF working is to be accurately assessed throughout the full range of developmental stages, stand, site and species types.

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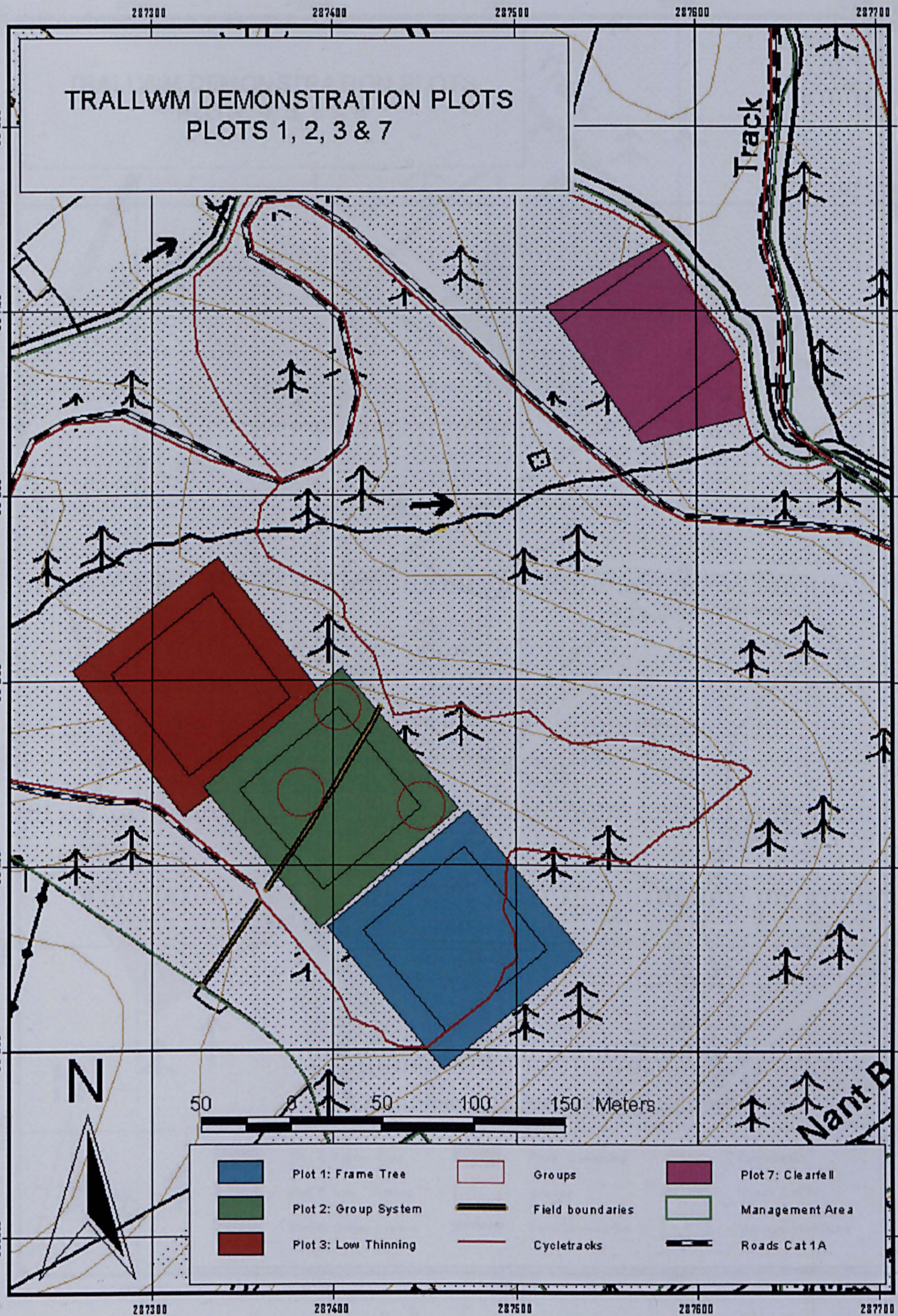
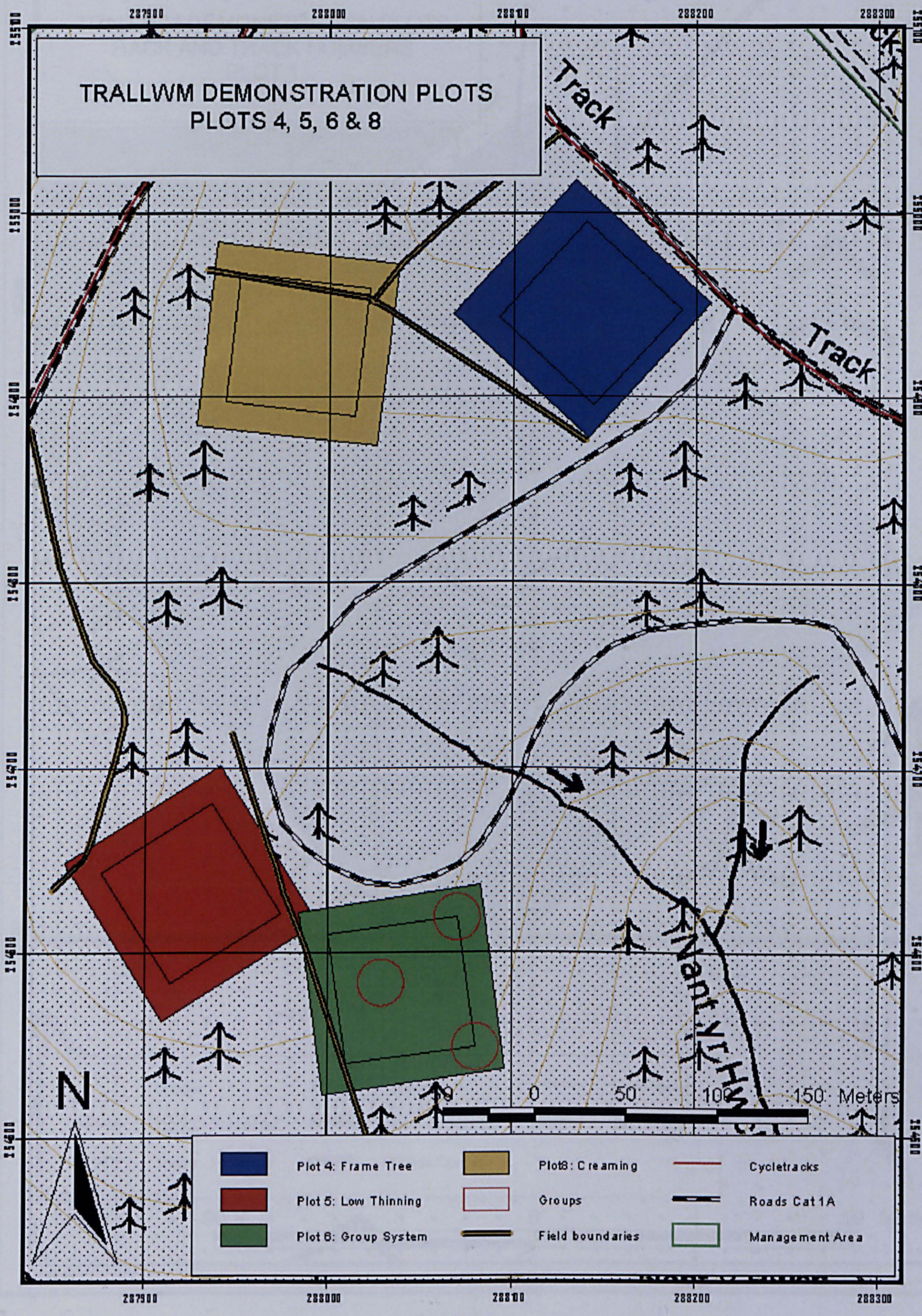
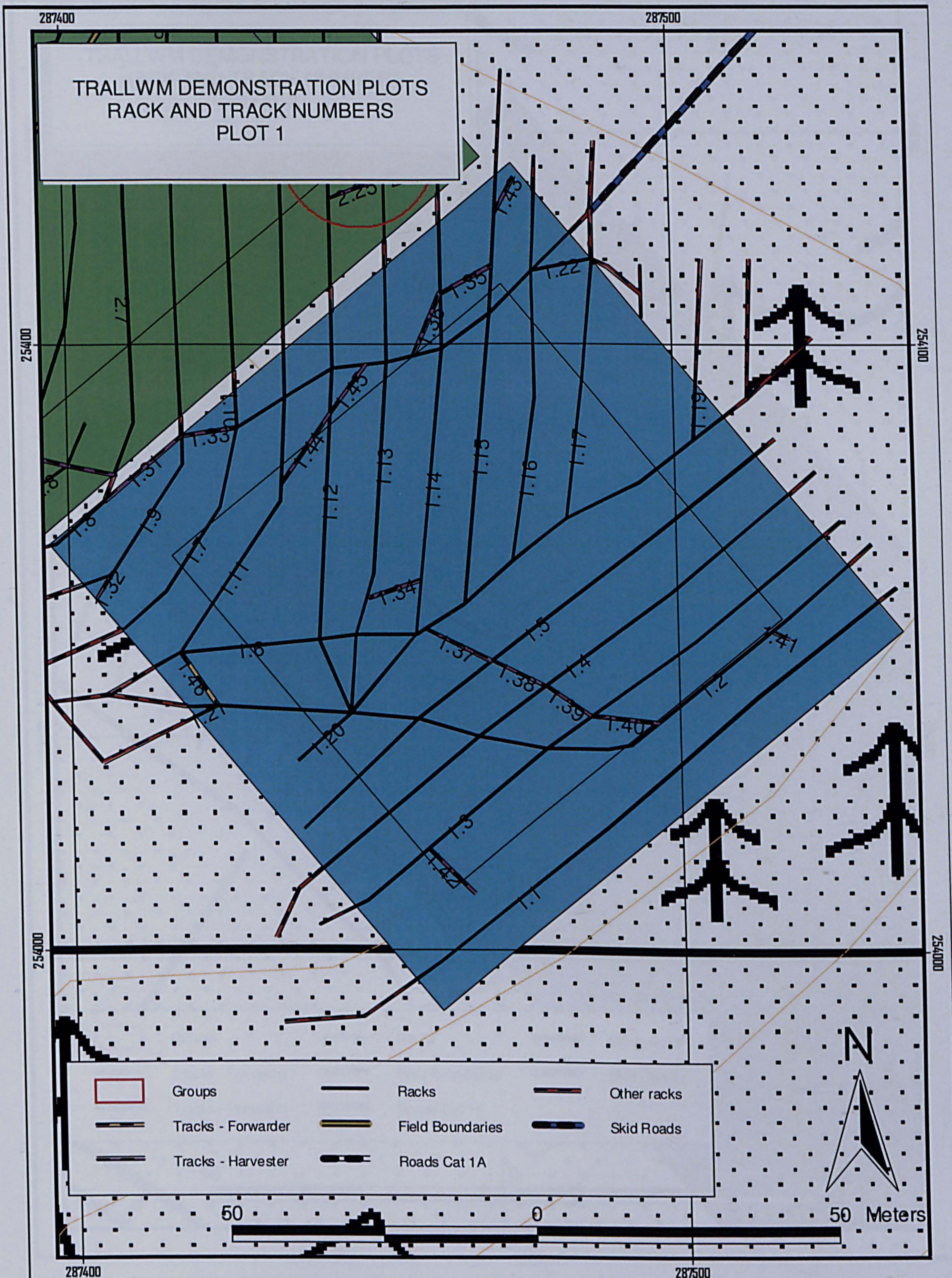
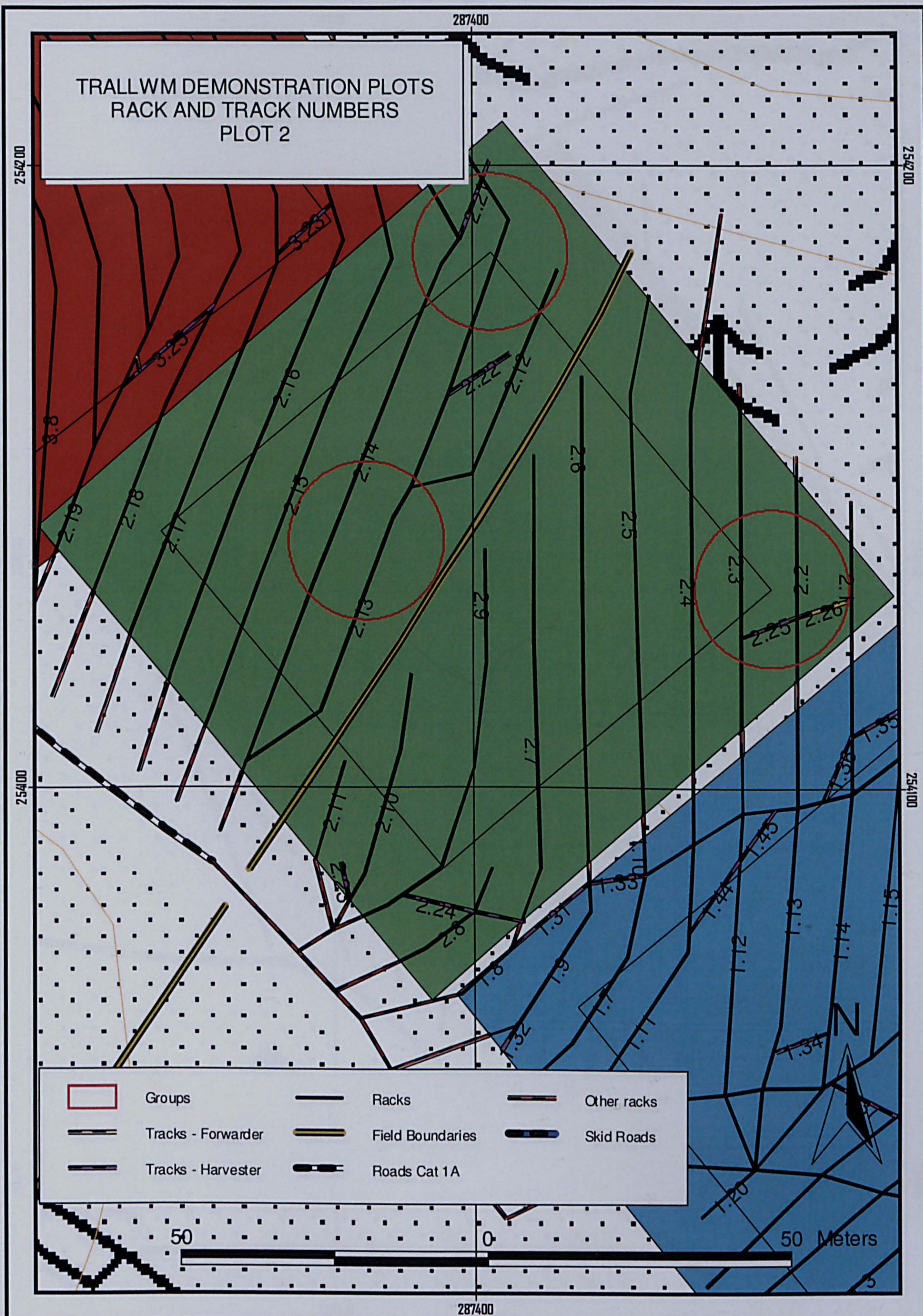
APPENDIX 1: Smaller scale maps of plot layout

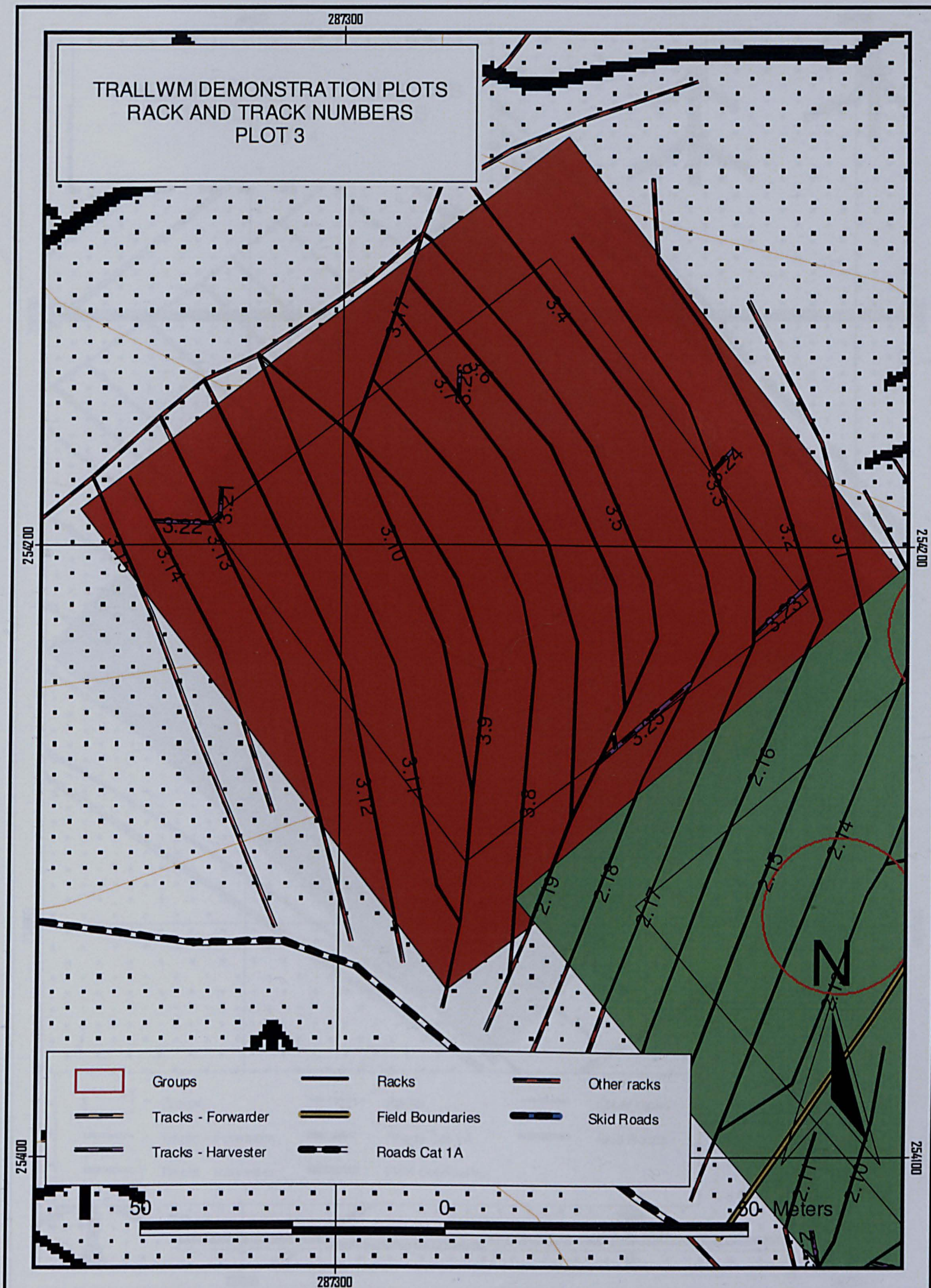


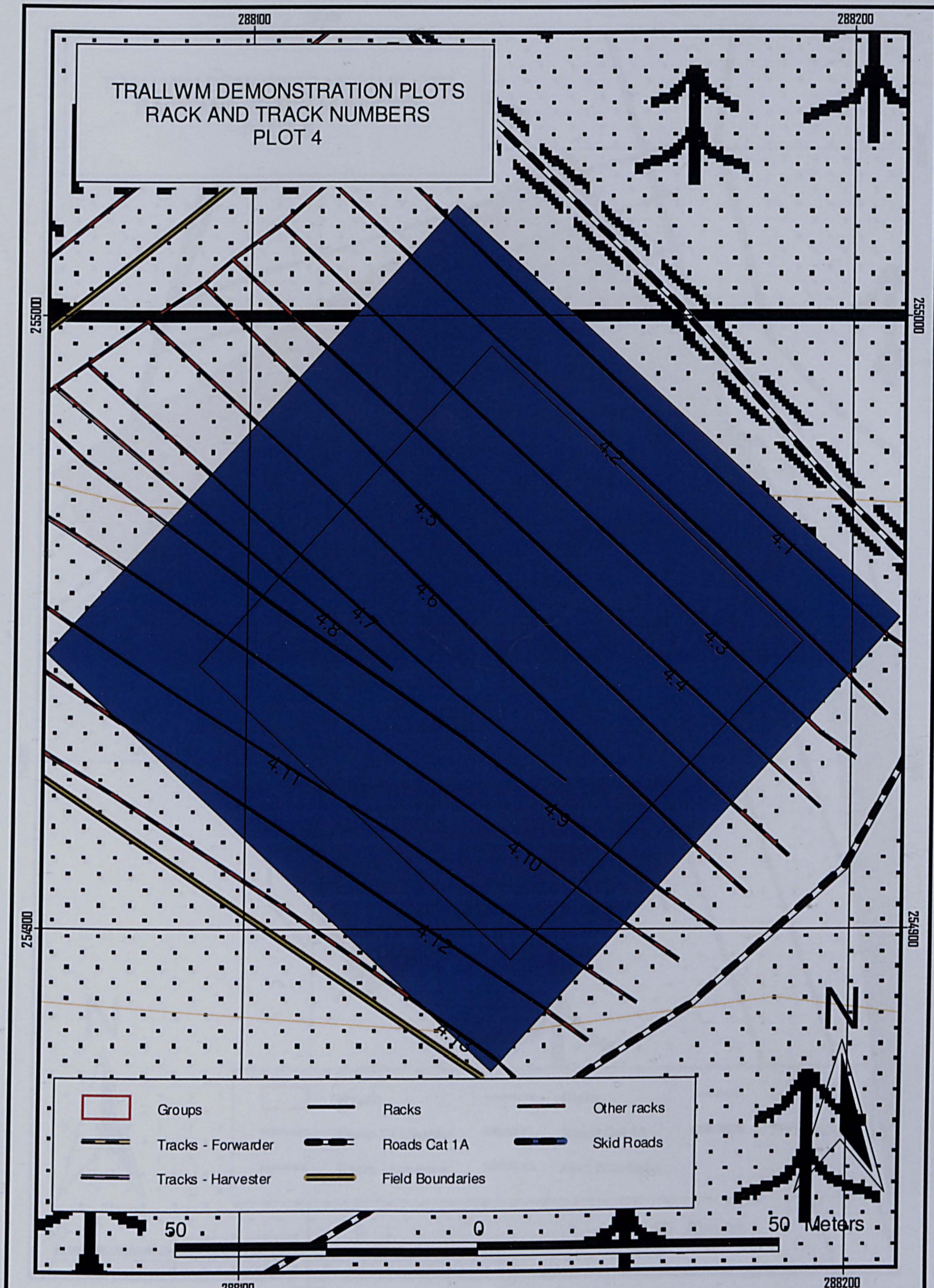

TRALLWM DEMONSTRATION PLOTS
PLOTS 4, 5, 6 & 8
Track
Track
Nant Yr Hwch
N
0 50 100 150 Meters
Plot 4: Frame Tree
Plot 5: Low Thinning
Plot 6: Group System
Plot8: Creaming
Groups
Field boundaries
Cycletracks
Roads Cat 1A
Management Area
287900
288000
288100
288200
288300

APPENDIX 2: Rack and track numbering

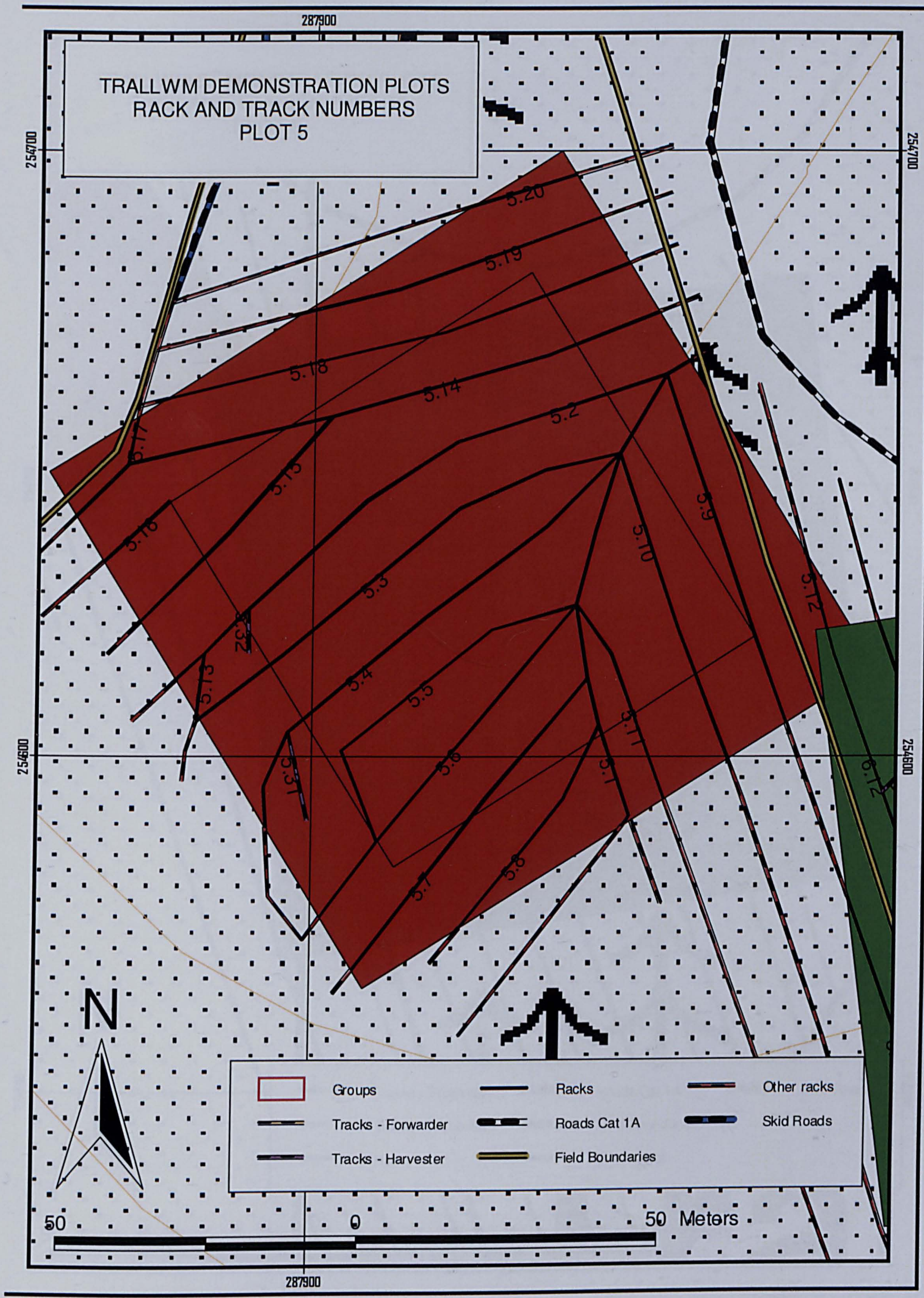


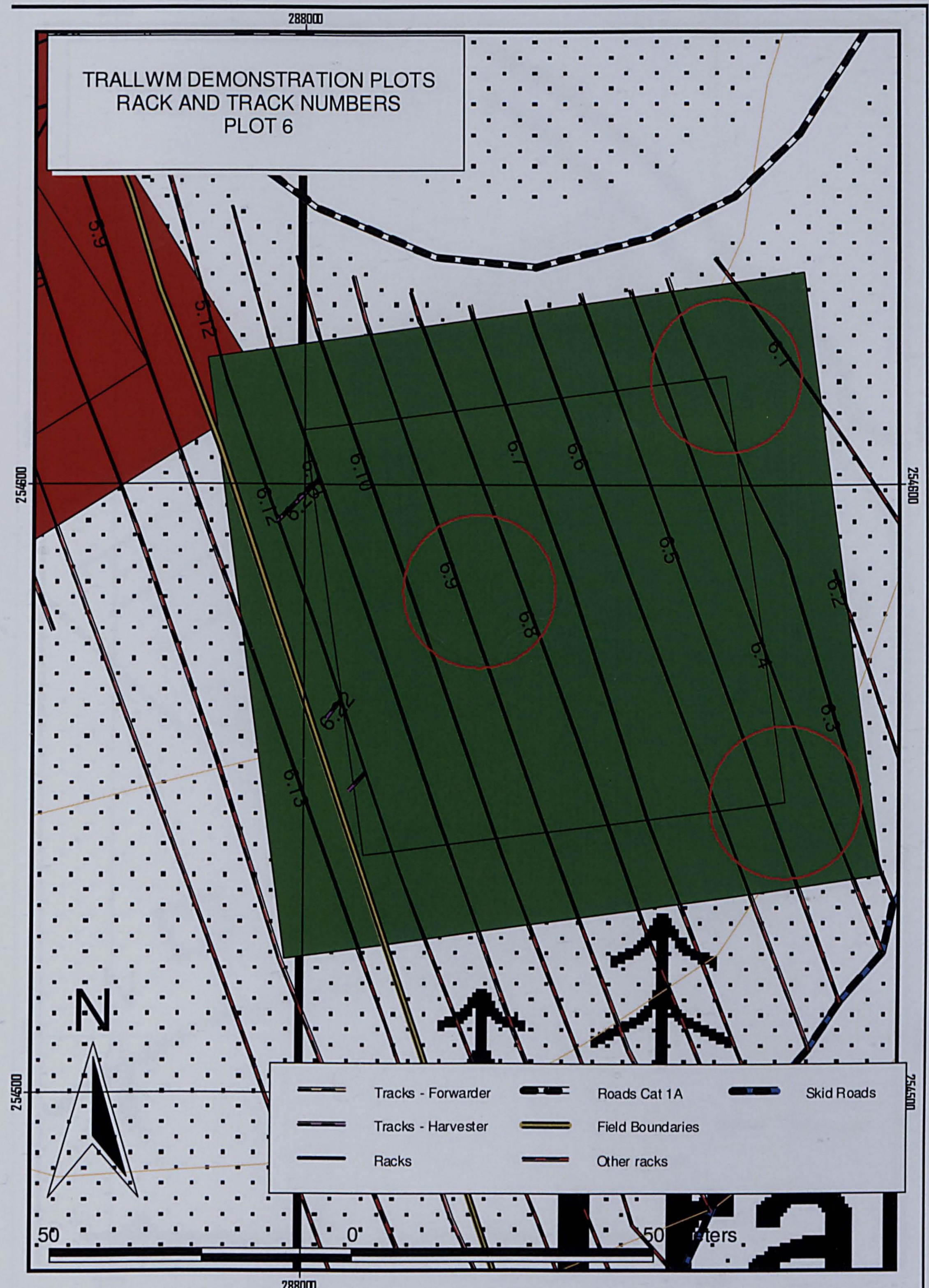

TRALLWM DEMONSTRATION PLOTS
RACK AND TRACK NUMBERS
PLOT 2
287400
254200
254100
Groups
Tracks - Forwarder
Tracks - Harvester
Racks
Field Boundaries
Roads Cat 1A
Other racks
Skid Roads
50
0
50 Meters
N


TRALLWM DEMONSTRATION PLOTS
RACK AND TRACK NUMBERS
PLOT 3
287300
254200
254100
Groups
Tracks - Forwarder
Tracks - Harvester
Racks
Field Boundaries
Roads Cat 1A
Other racks
Skid Roads
50
0
50 Meters
N

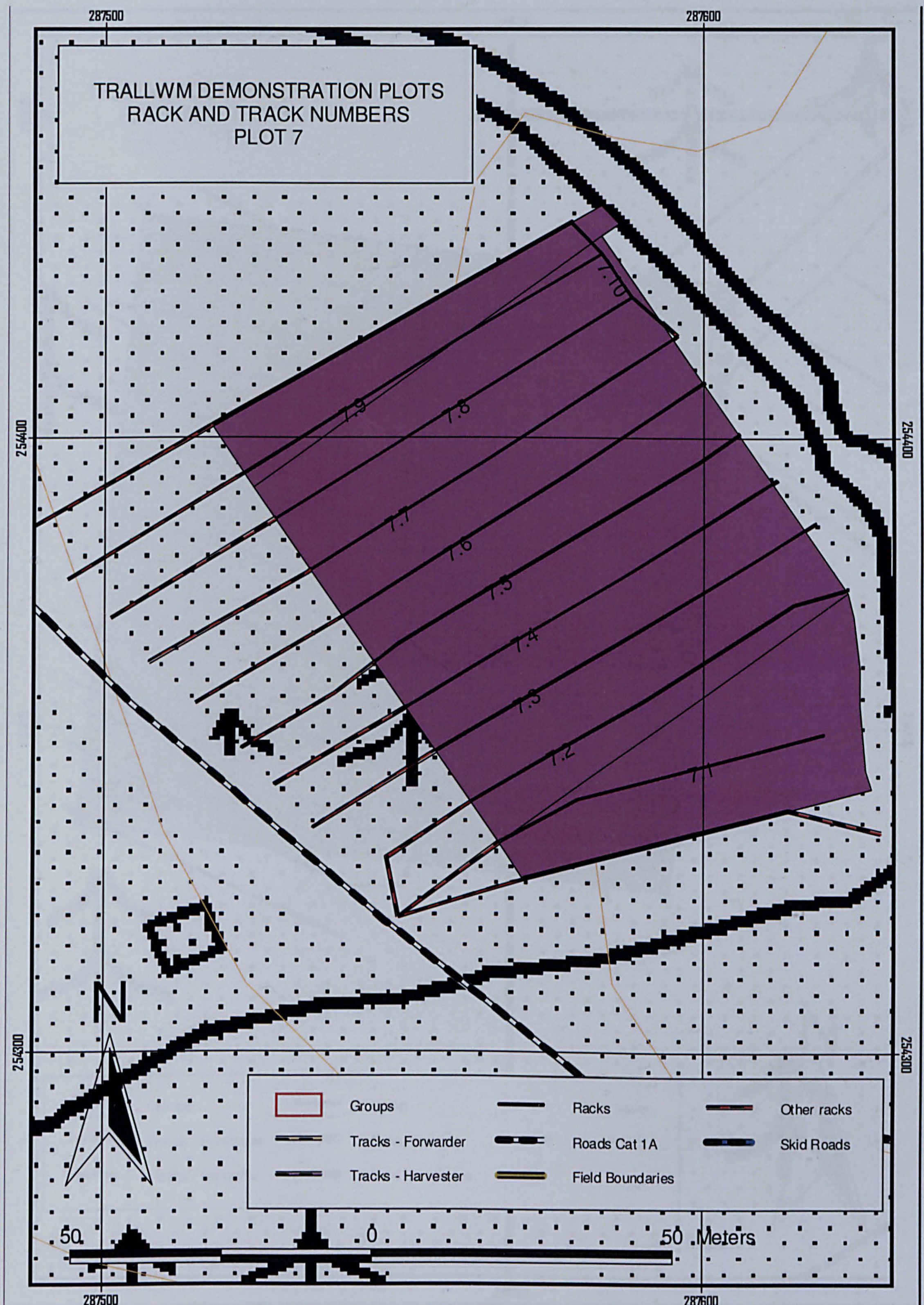


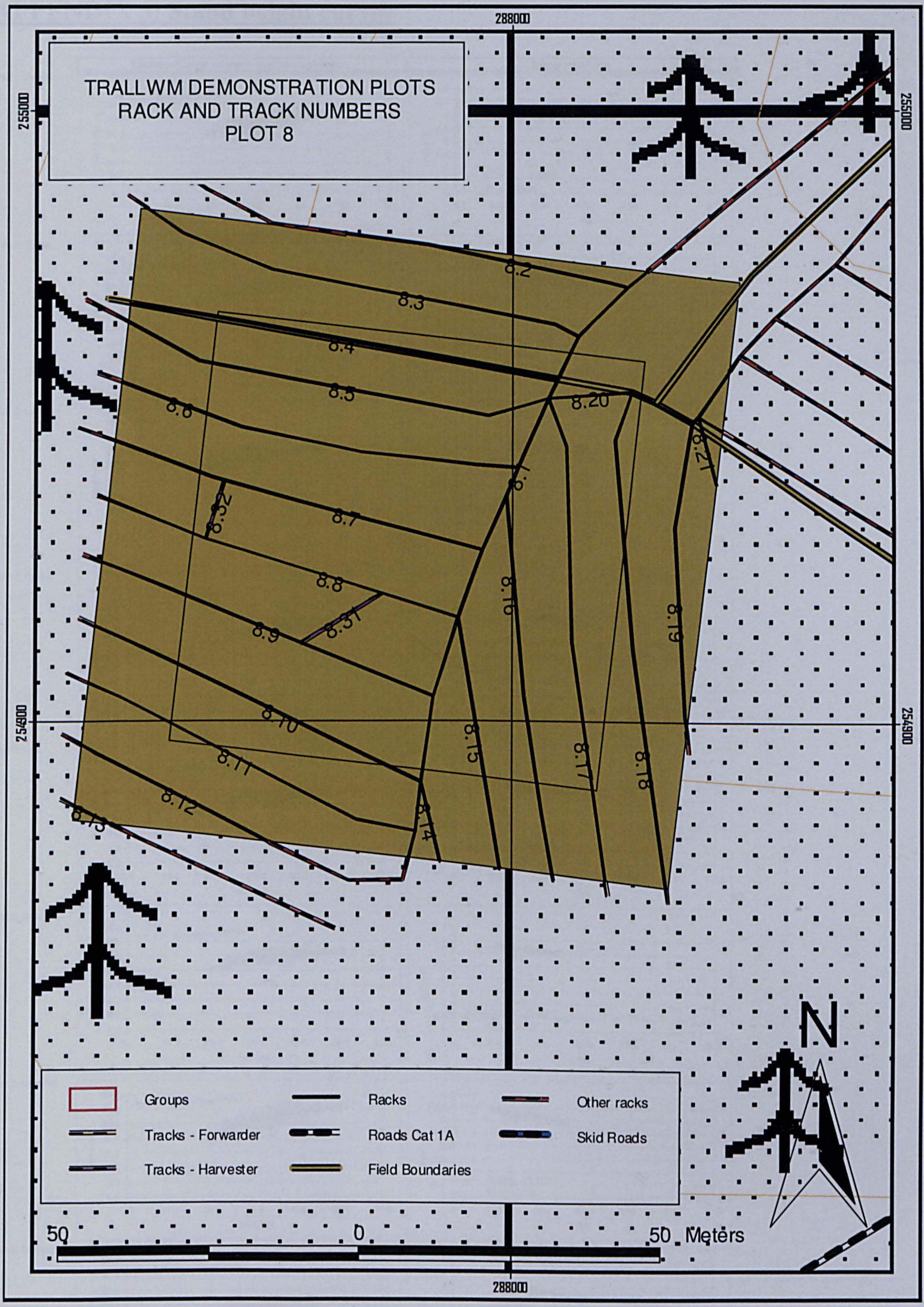
TRALLWM DEMONSTRATION PLOTS
RACK AND TRACK NUMBERS
PLOT 4
288100
288200
255000
254900
4.1
4.2
4.3
4.4
4.5
4.6
4.7
4.8
4.9
4.10
4.11
4.12
4.13
N
Groups
Racks
Other racks
Tracks - Forwarder
Roads Cat 1A
Skid Roads
Tracks - Harvester
Field Boundaries
50
0
50 Meters


287900
TRALLWM DEMONSTRATION PLOTS
RACK AND TRACK NUMBERS
PLOT 5
254700
254600
5.20
5.19
5.18
5.14
5.2
5.17
5.15
5.16
5.3
5.9
5.10
5.12
5.13
5.4
5.5
5.11
5.1
5.6
5.7
5.8
6.12
N
Groups
Tracks - Forwarder
Tracks - Harvester
Racks
Roads Cat 1A
Field Boundaries
Other racks
Skid Roads
50
0
50 Meters
287900



TRALLWM DEMONSTRATION PLOTS
RACK AND TRACK NUMBERS
PLOT 6
288000
254600
254500
6.9
6.12
6.1
6.10
6.7
6.6
6.5
6.2
6.4
6.3
6.8
6.13
N
Tracks - Forwarder
Tracks - Harvester
Racks
Roads Cat 1A
Field Boundaries
Other racks
Skid Roads
50
0
50


TRALLWM DEMONSTRATION PLOTS
RACK AND TRACK NUMBERS
PLOT 7
287500
287600
254400
254300
7.10
7.9
7.8
7.7
7.6
7.5
7.4
7.3
7.2
7.1
Groups
Tracks - Forwarder
Tracks - Harvester
Racks
Roads Cat 1A
Field Boundaries
Other racks
Skid Roads
N
50
0
50 Meters

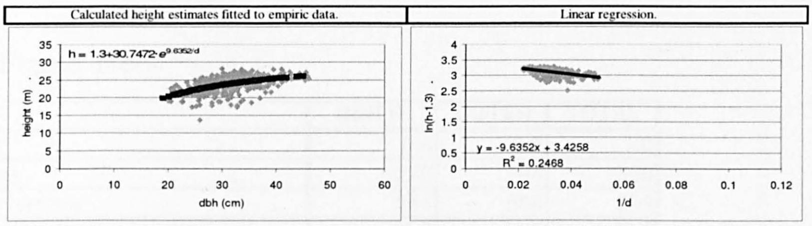


TRALLWM DEMONSTRATION PLOTS
RACK AND TRACK NUMBERS
PLOT 8
288000
255000
254900
8.2
8.3
8.4
8.5
8.6
8.20
8.21
8.1
8.32
8.7
8.8
8.31
8.9
8.16
8.19
8.10
8.15
8.17
8.18
8.11
8.12
8.13
8.14
N
Groups
Racks
Other racks
Tracks - Forwarder
Roads Cat 1A
Skid Roads
Tracks - Harvester
Field Boundaries
50
0
50 Meters

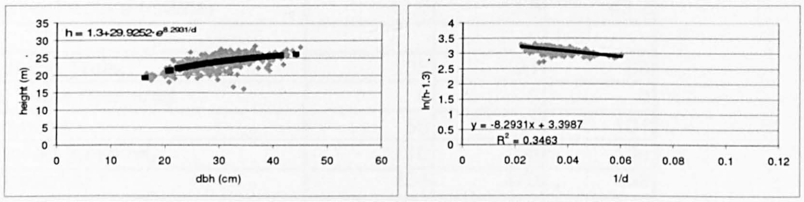
APPENDIX 3: Stand height curves

Calculated height estimates fitted to empiric data.	Linear regression.

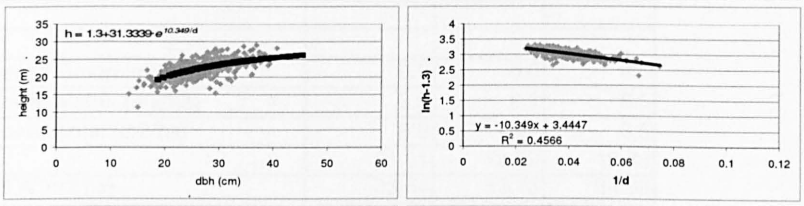
Plot 1: Frame



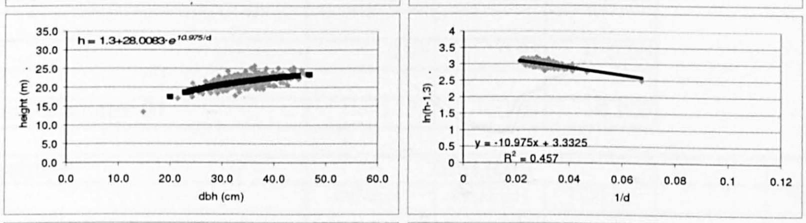
Plot 2: Group



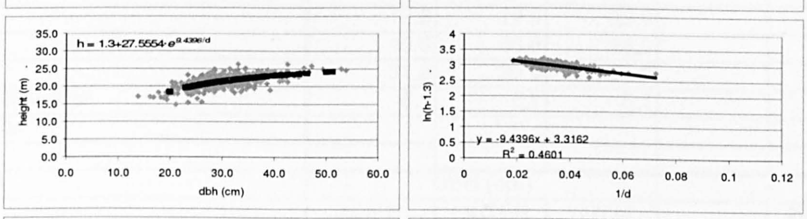
Plot 3: Low



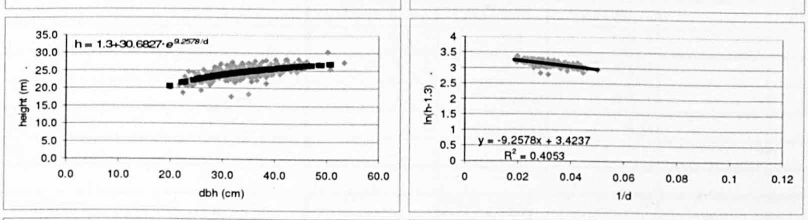
Plot 4: Frame



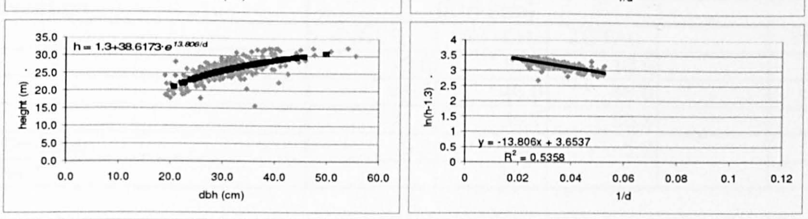
Plot 5: Low



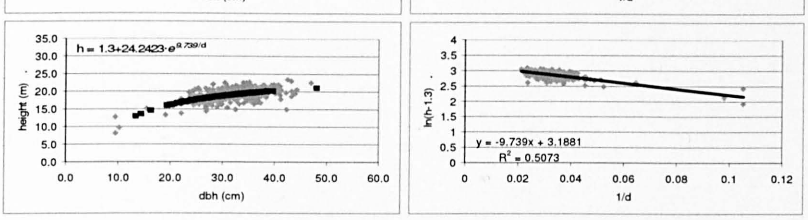
Plot 6: Group



Plot 7: Clearfell



Plot 8: Creaming



APPENDIX 4: Thinning summary data

Plot 1: Frame Tree

	INNER	OUTER	TOTAL
Area (ha)	0.5	0.5	1.0
Total Trees	272	284	556
Trees per hectare	544	568	556
Basal Area per hectare (m2/ha)	42.6	43.8	43.2
Shelter Building Trees	35	31	66
Group Fell Trees Removed	0	0	0
Matrix Removed	55	49	104
Total Removed (trees/ha)	110	98	104
Residual (trees/ha)	434	470	452
B.A. Removed Group (m2/ha)	0.0	0.0	0.0
B.A. Removed Matrix (m2/ha)	8.9	8.1	8.5
B.A. Removed Total (m2/ha)	8.9	8.1	8.5
% B.A.	21.01	18.48	19.73
Residual B.A.(m2/ha)	33.64	35.73	34.69
SG-Ratio	0.96	0.93	0.95
Separation Parameter S1	-0.151	-0.261	-0.206

Pre-Intervention	**DBH (cm)**				**Volume (M3)**		
	INNER	OUTER	TOTAL		INNER	OUTER	TOTAL
Min	19.8	19.0	19.0		0.33	0.31	0.31
Max	45.8	46.0	46.0		1.78	1.80	1.80
Mean	31.2	30.9	31.0		0.85	0.83	0.84
Standard Deviation	5.1	5.1	5.1		0.27	0.28	0.27
Total m3/ha					460.43	473.78	467.11
Removed	**DBH (cm)**				**Volume (M3)**		
	INNER	OUTER	TOTAL		INNER	OUTER	TOTAL
Min	23.7	24.7	23.7		0.48	0.52	0.48
Max	39.4	45.5	45.5		1.32	1.76	1.76
Mean	32.0	32.2	32.1		0.88	0.89	0.89
Standard Deviation	3.9	4.2	4.0		0.21	0.24	0.22
Total m3/ha					96.74	87.55	92.15
Post-Intervention	**DBH (cm)**				**Volume (M3)**		
	INNER	OUTER	TOTAL		INNER	OUTER	TOTAL
Min	19.8	19.0	19.0		0.33	0.31	0.31
Max	45.8	46.0	46.0		1.78	1.80	1.80
Mean	31.0	30.7	30.8		0.84	0.82	0.83
Standard Deviation	5.3	5.2	5.3		0.29	0.28	0.28
Total m3/ha					363.69	386.23	374.96

Plot 2: Group

	INNER	OUTER	TOTAL
Area (ha)	0.5	0.5	1.0
Total Trees	279	298	577
Trees per hectare	558	596	577
Basal Area per hectare (m2/ha)	40.8	42.1	41.4
Shelter Building Trees	11	8	19
Group Fell Trees Removed	32	39	71
Matrix Removed	42	26	68
Total Removed (trees/ha)	148	130	139
Residual (trees/ha)	410	466	438
B.A. Removed Group (m2/ha)	4.2	4.6	4.4
B.A. Removed Matrix (m2/ha)	4.5	3.3	3.9
B.A. Removed Total (m2/ha)	8.7	7.9	8.3
% B.A.	21.37	18.81	20.07
Residual B.A.(m2/ha)	32.05	34.17	33.11
SG-Ratio	1.24	1.16	1.20
Separation Parameter S1	0.852	0.523	0.679

Pre-Intervention	**DBH (cm)**				**Volume (M3)**		
	INNER	OUTER	TOTAL		INNER	OUTER	TOTAL
Min	17.1	16.3	16.3		0.25	0.23	0.23
Max	44.3	45.0	45.0		1.67	1.75	1.75
Mean	30.1	29.5	29.8		0.79	0.78	0.78
Standard Deviation	4.9	5.2	5.1		0.26	0.27	0.26
Total m3/ha					440.62	464.23	452.43
Removed	**DBH (cm)**				**Volume (M3)**		
	INNER	OUTER	TOTAL		INNER	OUTER	TOTAL
Min	17.1	16.6	16.6		0.25	0.24	0.2
Max	37.0	43.5	43.5		1.16	1.64	1.6
Mean	27.0	27.4	27.2		0.64	0.67	0.7
Standard Deviation	4.5	5.3	4.8		0.20	0.26	0.2
Total m3/ha					94.15	87.33	90.74
Post-Intervention	**DBH (cm)**				**Volume (M3)**		
	INNER	OUTER	TOTAL		INNER	OUTER	TOTAL
Min	20.7	16.3	16.3		0.36	0.23	0.23
Max	44.3	45.0	45.0		1.67	1.75	1.75
Mean	31.2	30.1	30.6		0.85	0.81	0.83
Standard Deviation	4.6	5.0	4.8		0.25	0.27	0.26
Total m3/ha					346.47	376.91	361.69

Plot 3: Low Thinning

	INNER	OUTER	TOTAL
Area (ha)	0.5	0.4415	0.9
Total Trees	363	314	677
Trees per hectare	726	711.2118	719.0653
Basal Area per hectare (m2/ha)	44.8	46.5	45.7
Shelter Building Trees	0	0	0
Group Fell Trees Removed	0	0	0
Matrix Removed	103	88	191
Total Removed (trees/ha)	206	199.3205	202.8678
Residual (trees/ha)	520	511.8913	516
B.A. Removed Group (m2/ha)	0.0	0.0	0.0
B.A. Removed Matrix (m2/ha)	9.5	9.3	9.4
B.A. Removed Total (m2/ha)	9.5	9.3	9.4
% B.A.	21.12	19.89	20.49
Residual B.A.(m2/ha)	35.37	37.29	36.33
SG-Ratio	1.34	1.41	1.38
Separation Parameter S1	1.031	1.080	1.059

Pre-Intervention	**DBH (cm)**				**Volume (M3)**		
	INNER	OUTER	TOTAL		INNER	OUTER	TOTAL
Min	13.4	16.1	13.4		0.15	0.22	0.15
Max	39.5	45.4	45.4		1.32	1.79	1.79
Mean	27.6	28.3	27.9		0.67	0.72	0.69
Standard Deviation	5.1	5.7	5.4		0.24	0.29	0.27
Total m3/ha					484.75	513.42	498.20
Removed	**DBH (cm)**				**Volume (M3)**		
	INNER	OUTER	TOTAL		INNER	OUTER	TOTAL
Min	13.4	16.1	13.4		0.15	0.22	0.15
Max	36.1	36.3	36.3		1.11	1.14	1.14
Mean	23.8	23.9	23.8		0.50	0.51	0.50
Standard Deviation	4.6	4.4	4.5		0.19	0.20	0.19
Total m3/ha					102.39	102.11	102.26
Post-Intervention	**DBH (cm)**				**Volume (M3)**		
	INNER	OUTER	TOTAL		INNER	OUTER	TOTAL
Min	17.2	18.7	17.2		0.25	0.31	0.25
Max	39.5	45.4	45.4		1.32	1.82	1.82
Mean	29.1	30.0	29.5		0.74	0.82	0.77
Standard Deviation	4.4	5.2	4.8		0.22	0.29	0.26
Total m3/ha					382.36	419.51	399.78

Plot 4: Frame Tree

	INNER	OUTER	TOTAL
Area (ha)	0.5	0.5	1.0
Total Trees	225	240	465
Trees per hectare	450	480	465
Basal Area per hectare (m2/ha)	41.1	43.3	42.2
Shelter Building Trees	36	36	72
Group Fell Trees Removed	0	0	0
Matrix Removed	44	47	91
Total Removed (trees/ha)	88	94	91
Residual (trees/ha)	362	386	374
B.A. Removed Group (m2/ha)	0.0	0.0	0.0
B.A. Removed Matrix (m2/ha)	7.6	8.9	8.2
B.A. Removed Total (m2/ha)	7.6	8.9	8.2
% B.A.	18.46	20.59	19.55
Residual B.A.(m2/ha)	33.50	34.38	33.94
SG-Ratio	1.06	0.95	1.00
Separation Parameter S1	0.258	-0.205	0.004

Pre-Intervention	**DBH (cm)**				**Volume (M3)**		
	INNER	OUTER	TOTAL		INNER	OUTER	TOTAL
Min	21.4	14.8	14.8		0.35	0.17	0.17
Max	45.9	46.8	46.8		1.60	1.67	1.67
Mean	33.8	33.5	33.6		0.88	0.87	0.88
Standard Deviation	4.6	5.3	5.0		0.24	0.27	0.26
Total m3/ha					398.16	419.51	408.84
Removed	**DBH (cm)**				**Volume (M3)**		
	INNER	OUTER	TOTAL		INNER	OUTER	TOTAL
Min	26.8	14.8	14.8		0.55	0.17	0.17
Max	45.5	44.7	45.5		1.58	1.52	1.58
Mean	32.9	34.4	33.6		0.84	0.92	0.88
Standard Deviation	4.2	5.2	4.8		0.23	0.25	0.24
Total m3/ha					73.50	86.38	79.94
Post-Intervention	**DBH (cm)**				**Volume (M3)**		
	INNER	OUTER	TOTAL		INNER	OUTER	TOTAL
Min	21.4	20.0	20.0		0.35	0.30	0.30
Max	45.9	46.8	46.8		1.60	1.67	1.67
Mean	34.0	33.3	33.6		0.90	0.86	0.88
Standard Deviation	4.7	5.3	5.0		0.25	0.27	0.26
Total m3/ha					324.66	333.13	328.89

Plot 5: Low Thinning

	INNER	OUTER	TOTAL
Area (ha)	0.5	0.4901	0.99
Total Trees	282	280	562
Trees per hectare	564	571.312	567.6194
Basal Area per hectare (m2/ha)	42.7	44.6	43.7
Shelter Building Trees	0	0	0
Group Fell Trees Removed	0	0	0
Matrix Removed	75	68	143
Total Removed (trees/ha)	150	138.7472	144.4299
Residual (trees/ha)	414	432.5648	423
B.A. Removed Group (m2/ha)	0.0	0.0	0.0
B.A. Removed Matrix (m2/ha)	9.0	8.8	8.9
B.A. Removed Total (m2/ha)	9.0	8.8	8.9
% B.A.	21.02	19.62	20.30
Residual B.A.(m2/ha)	33.74	35.88	34.81
SG-Ratio	1.27	1.24	1.25
Separation Parameter S1	0.796	0.657	0.727

Pre-Intervention	DBH (cm)				Volume (M3)		
	INNER	OUTER	TOTAL		INNER	OUTER	TOTAL
Min	16.1	13.8	13.8		0.20	0.15	0.15
Max	53.8	52.9	53.8		2.25	2.18	2.25
Mean	30.5	30.9	30.7		0.75	0.78	0.76
Standard Deviation	5.8	6.3	6.1		0.29	0.33	0.31
Total m3/ha					423.79	442.79	433.19
Removed	DBH (cm)				Volume (M3)		
	INNER	OUTER	TOTAL		INNER	OUTER	TOTAL
Min	16.1	13.8	13.8		0.20	0.15	0.15
Max	42.6	52.9	52.9		1.41	2.18	2.18
Mean	27.1	27.6	27.4		0.59	0.63	0.61
Standard Deviation	5.1	6.3	5.7		0.23	0.31	0.27
Total m3/ha					89.08	86.86	87.98
Post-Intervention	DBH (cm)				Volume (M3)		
	INNER	OUTER	TOTAL		INNER	OUTER	TOTAL
Min	20.7	19.9	19.9		0.33	0.31	0.31
Max	53.8	51.2	53.8		2.25	2.04	2.25
Mean	31.7	32.0	31.9		0.81	0.82	0.82
Standard Deviation	5.5	6.0	5.7		0.30	0.32	0.31
Total m3/ha					334.71	355.93	345.21

Plot 6: Group

	INNER	OUTER	TOTAL
Area (ha)	0.5	0.5	1.00
Total Trees	245	250	495
Trees per hectare	490	500	495
Basal Area per hectare (m2/ha)	45.4	46.2	45.8
Shelter Building Trees	6	12	18
Group Fell Trees Removed	28	24	52
Matrix Removed	31	36	67
Total Removed (trees/ha)	118	120	119
Residual (trees/ha)	372	380	376
B.A. Removed Group (m2/ha)	4.4	4.2	4.3
B.A. Removed Matrix (m2/ha)	4.3	4.2	4.3
B.A. Removed Total (m2/ha)	8.7	8.5	8.6
% B.A.	19.23	18.32	18.77
Residual B.A.(m2/ha)	36.69	37.72	37.20
SG-Ratio	1.25	1.31	1.28
Separation Parameter S1	0.896	0.910	0.902

Pre-Intervention	**DBH (cm)**				**Volume (M3)**		
	INNER	OUTER	TOTAL		INNER	OUTER	TOTAL
Min	21.7	19.9	19.9		0.42	0.35	0.35
Max	50.7	53.4	53.4		2.27	2.52	2.52
Mean	34.0	33.7	33.9		1.04	1.04	1.04
Standard Deviation	5.3	6.1	5.7		0.33	0.38	0.36
Total m3/ha					510.98	519.51	515.24
Removed	**DBH (cm)**				**Volume (M3)**		
	INNER	OUTER	TOTAL		INNER	OUTER	TOTAL
Min	21.7	20.0	20.0		0.42	0.35	0.35
Max	45.8	41.9	45.8		1.85	1.55	1.85
Mean	30.9	30.2	30.6		0.86	0.83	0.85
Standard Deviation	4.7	4.9	4.8		0.27	0.26	0.26
Total m3/ha					101.97	99.16	100.56
Post-Intervention	**DBH (cm)**				**Volume (M3)**		
	INNER	OUTER	TOTAL		INNER	OUTER	TOTAL
Min	23.0	19.9	19.9		0.47	0.35	0.35
Max	50.7	53.4	53.4		2.27	2.52	2.52
Mean	34.9	34.9	34.9		1.10	1.11	1.10
Standard Deviation	5.1	6.1	5.6		0.33	0.39	0.36
Total m3/ha					409.01	420.35	414.68

Plot 7: Clearfell

	INNER	OUTER	TOTAL
Area (ha)	0.5	0.1803	0.68
Total Trees	238	100	338
Trees per hectare	476	554.6312	496.8396
Basal Area per hectare (m2/ha)	38.8	49.2	44.0
Shelter Building Trees	0	0	0
Group Fell Trees Removed	0	0	0
Matrix Removed	238	100	338
Total Removed (trees/ha)	476	554.6312	496.8396
Residual (trees/ha)	0	0	0
B.A. Removed Group (m2/ha)	0.0	0.0	0.0
B.A. Removed Matrix (m2/ha)	38.8	49.2	44.0
B.A. Removed Total (m2/ha)	38.8	49.2	44.0
% B.A.	100.00	100.00	100.00
Residual B.A.(m2/ha)	0.00	0.00	0.00
SG-Ratio	1.00	1.00	1.00
Separation Parameter S1			

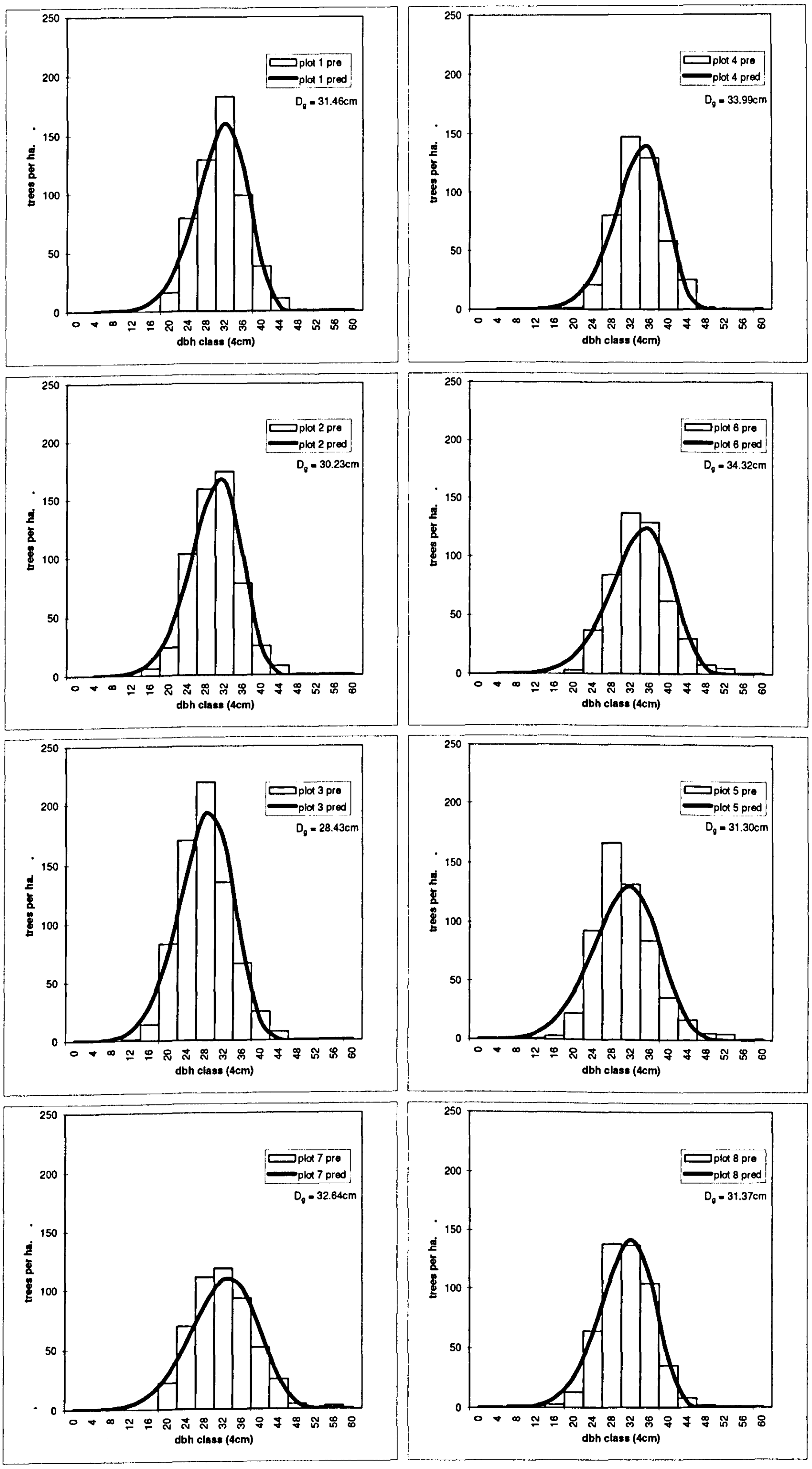
Pre-Intervention	DBH (cm)				Volume (M3)		
	INNER	OUTER	TOTAL		INNER	OUTER	TOTAL
Min	19.0	20.7	19.0		0.36	0.42	0.36
Max	55.6	49.9	55.6		3.05	2.42	3.05
Mean	31.5	33.1	32.0		1.03	1.10	1.05
Standard Deviation	6.7	5.9	6.5		0.44	0.40	0.43
Total m3/ha					488.40	607.74	520.03
Removed	DBH (cm)				Volume (M3)		
	INNER	OUTER	TOTAL		INNER	OUTER	TOTAL
Min	19.0	20.7	19.0		0.36	0.42	0.36
Max	55.6	49.9	55.6		3.05	2.42	3.05
Mean	31.5	33.1	32.0		1.03	1.10	1.05
Standard Deviation	6.7	5.9	6.5		0.44	0.40	0.43
Total m3/ha					488.40	607.74	520.03
Post-Intervention	DBH (cm)				Volume (M3)		
	INNER	OUTER	TOTAL		INNER	OUTER	TOTAL
Min	0.0	0.0	0.0		0.00	0.00	0.00
Max	0.0	0.0	0.0		0.00	0.00	0.00
Mean	0.0	0.0	0.0		0.00	0.00	0.00
Standard Deviation	0.0	0.0	0.0		0.00	0.00	0.00
Total m3/ha					0.00	0.00	0.00

Plot 8: Creaming

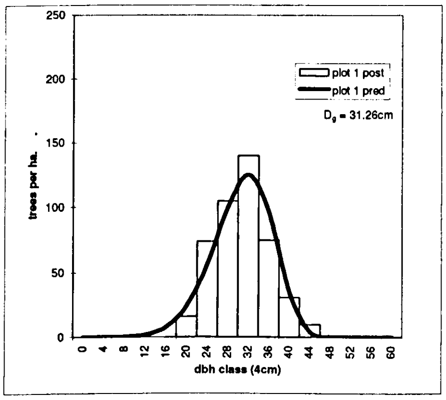
	INNER	OUTER	TOTAL
Area (ha)	0.5	0.5	1.00
Total Trees	249	259	508
Trees per hectare	498	518	508
Basal Area per hectare (m2/ha)	40.3	38.2	39.3
Shelter Building Trees	0	0	0
Group Fell Trees Removed	0	0	0
Matrix Removed	40	42	82
Total Removed (trees/ha)	80	84	82
Residual (trees/ha)	418	434	426
B.A. Removed Group (m2/ha)	0.0	0.0	0.0
B.A. Removed Matrix (m2/ha)	8.9	8.2	8.6
B.A. Removed Total (m2/ha)	8.9	8.2	8.6
% B.A.	22.05	21.55	21.81
Residual B.A.(m2/ha)	31.42	29.97	30.70
SG-Ratio	0.73	0.75	0.74
Separation Parameter S1	-1.203	-1.047	-1.116

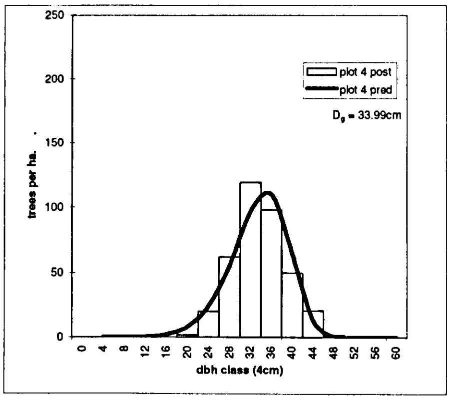
Pre-Intervention	**DBH (cm)**				**Volume (M3)**		
	INNER	OUTER	TOTAL		INNER	OUTER	TOTAL
Min	9.5	13.4	9.5		0.06	0.12	0.06
Max	47.0	48.1	48.1		1.49	1.56	1.56
Mean	31.6	30.2	30.9		0.69	0.63	0.66
Standard Deviation	5.6	5.4	5.5		0.23	0.22	0.23
Total m3/ha					345.88	327.78	336.83
Removed	**DBH (cm)**				**Volume (M3)**		
	INNER	OUTER	TOTAL		INNER	OUTER	TOTAL
Min	30.6	26.9	26.9		0.63	0.49	0.49
Max	47.0	44.3	47.0		1.49	1.32	1.49
Mean	37.5	35.0	36.2		0.95	0.84	0.90
Standard Deviation	3.5	4.7	4.3		0.18	0.22	0.21
Total m3/ha					76.28	70.65	73.46
Post-Intervention	**DBH (cm)**				**Volume (M3)**		
	INNER	OUTER	TOTAL		INNER	OUTER	TOTAL
Min	9.5	13.4	9.5		0.06	0.11	0.06
Max	43.2	48.1	48.1		1.26	1.48	1.48
Mean	30.5	29.2	29.9		0.64	0.56	0.60
Standard Deviation	5.2	5.0	5.1		0.20	0.19	0.20
Total m3/ha					269.61	243.95	256.78

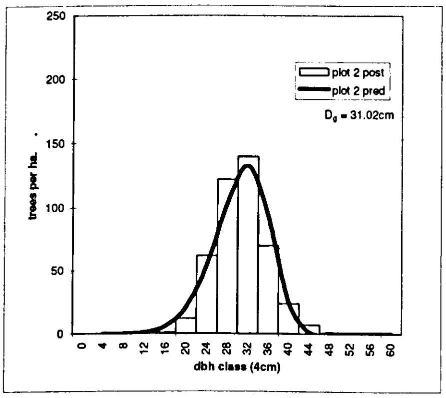
APPENDIX 5: Pre felling diameter distributions overlaid with Weibull curves

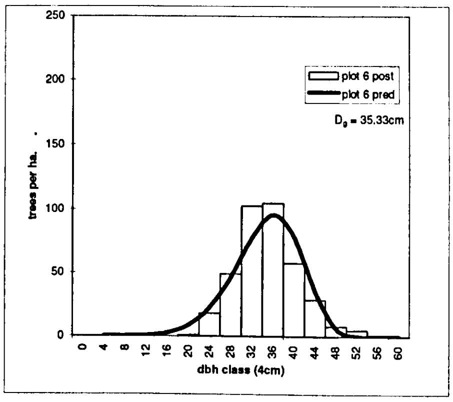


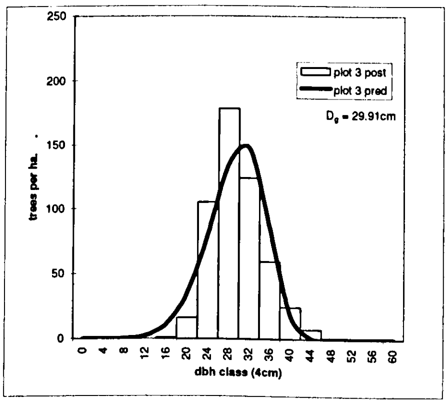
APPENDIX 6: Post felling diameter distributions overlaid with Weibull curves

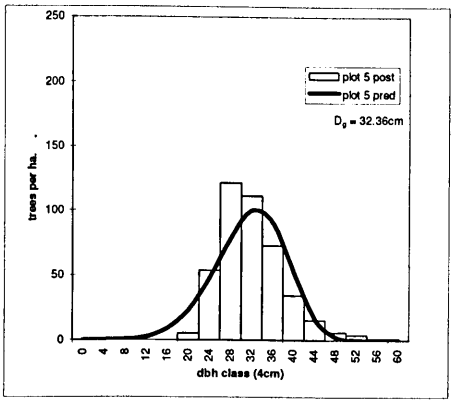


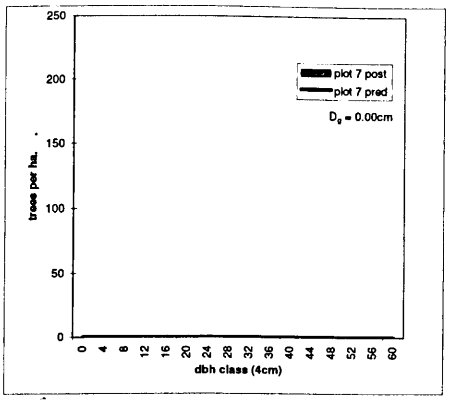


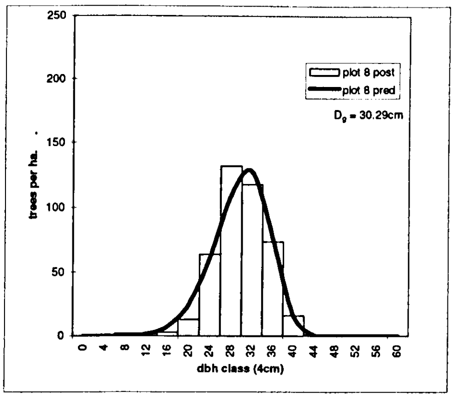




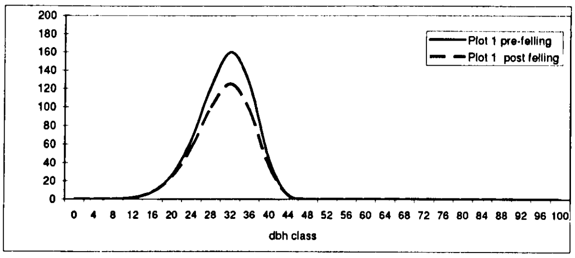


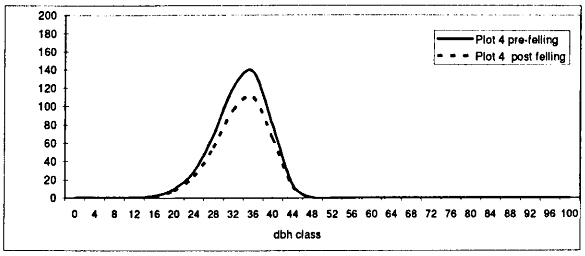


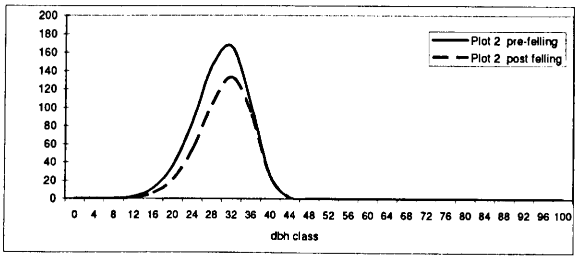


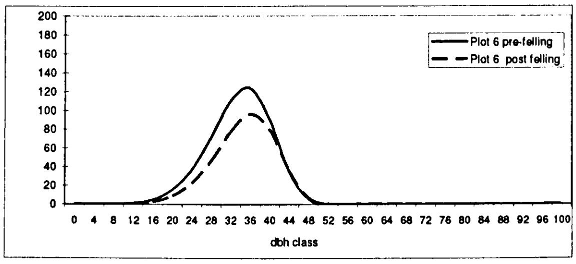


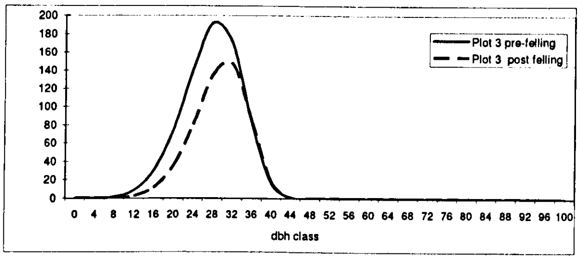
APPENDIX 7: Change in Weibull probability density function curves; pre-harvesting to post-harvesting

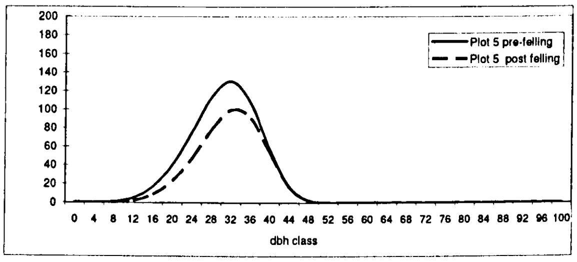


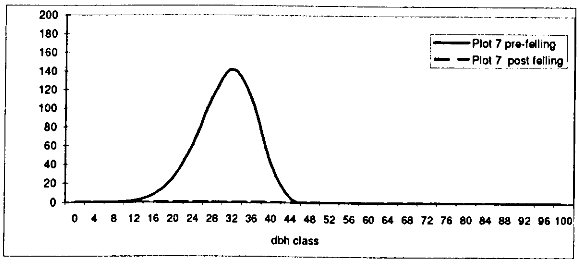


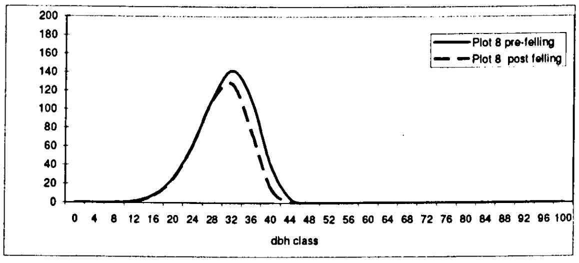




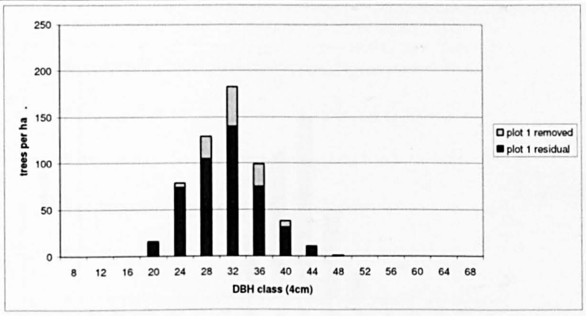


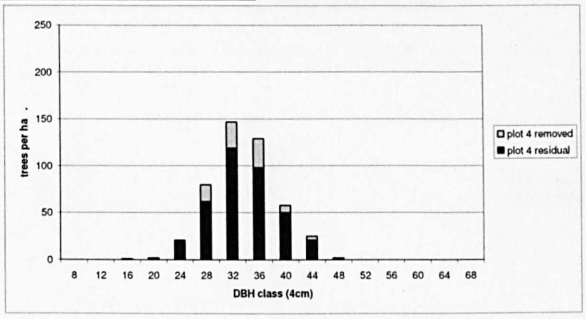


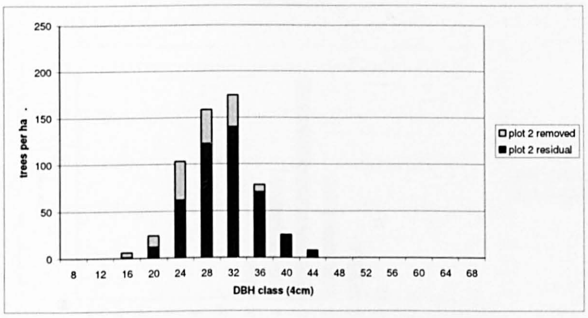


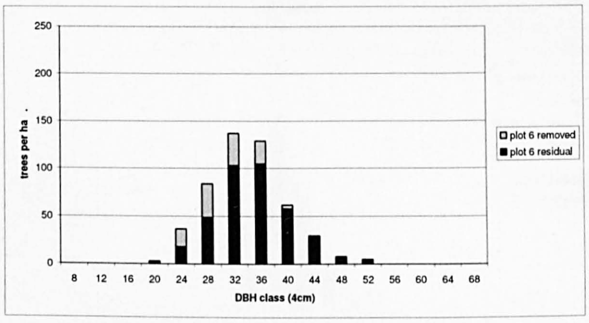


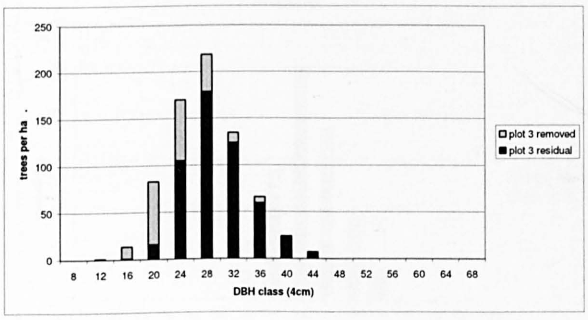
APPENDIX 8: Pre-felling / post-felling diameter distributions

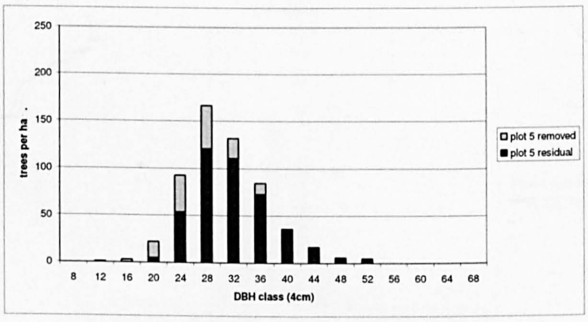


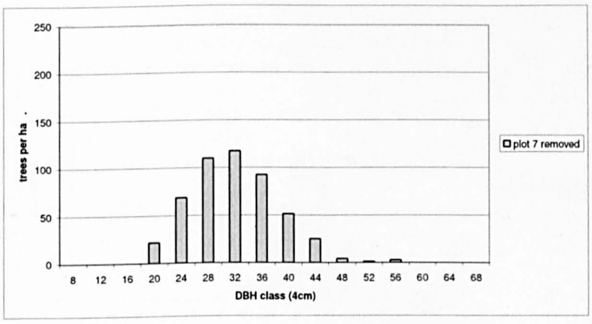


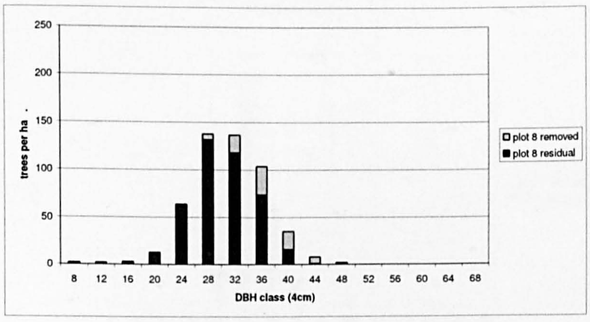




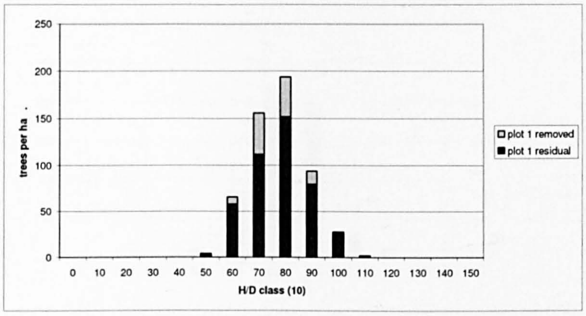


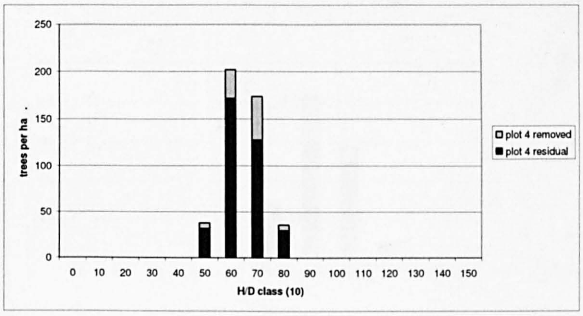


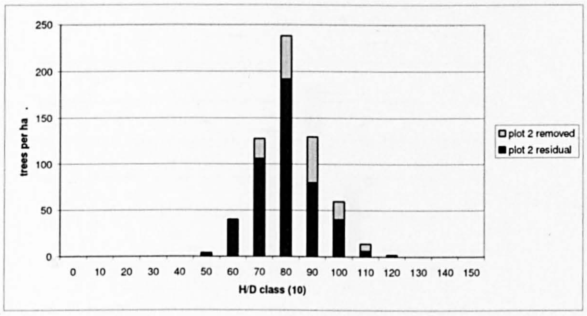


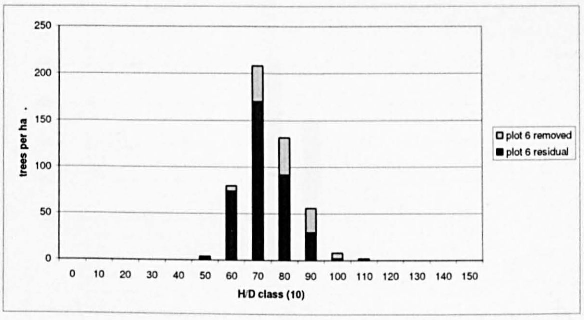


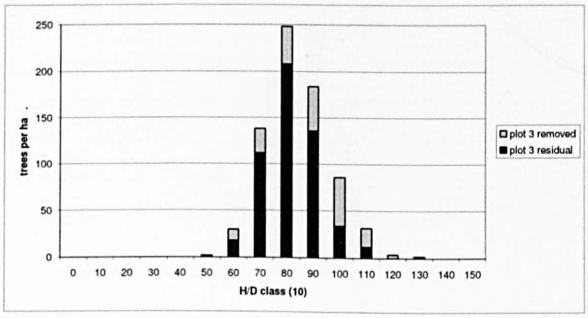
APPENDIX 9: Pre-felling / post-felling height/diameter ratio distributions

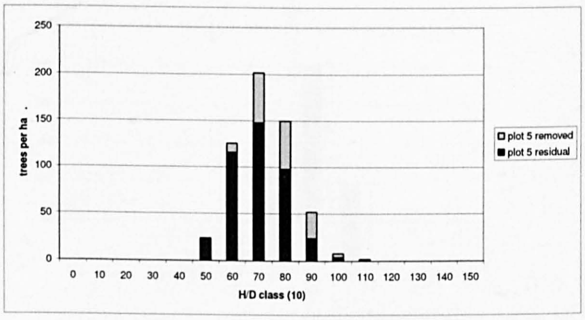


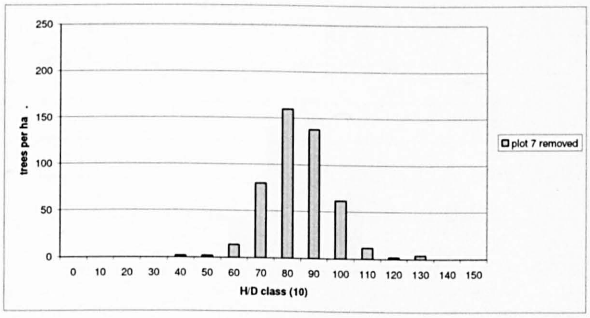


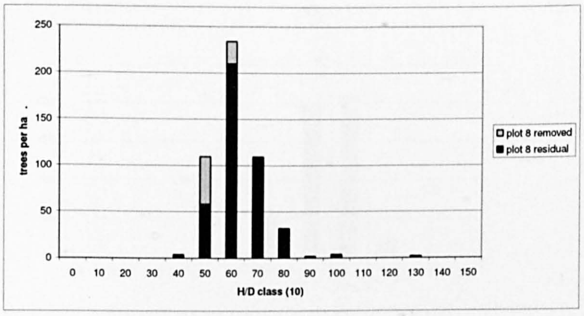




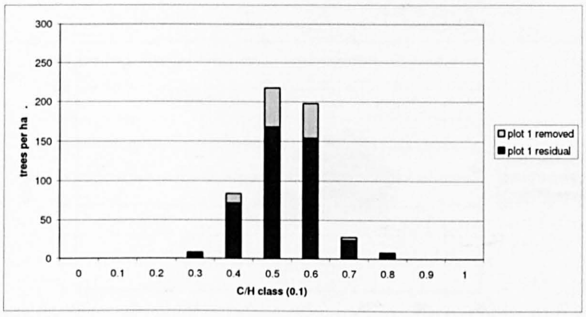


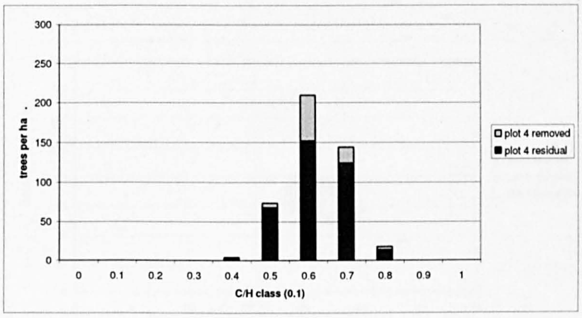


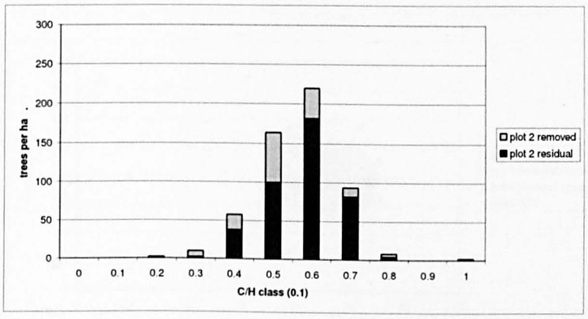


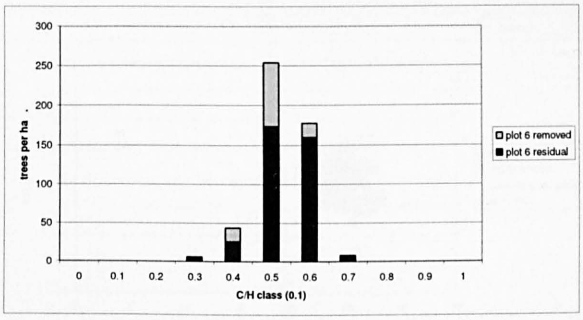


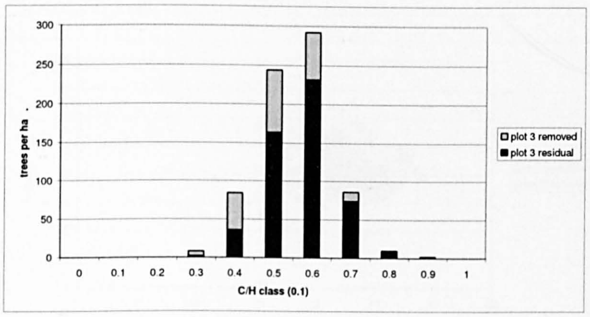
APPENDIX 10: Pre-felling / post-felling crown/height ratio distributions

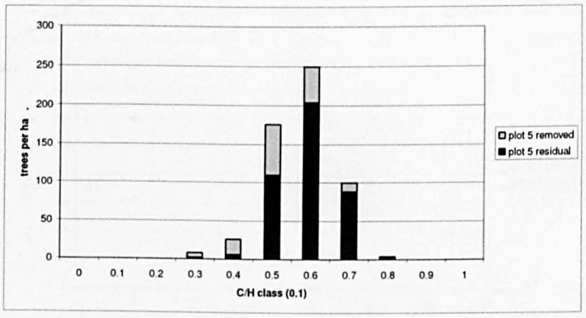


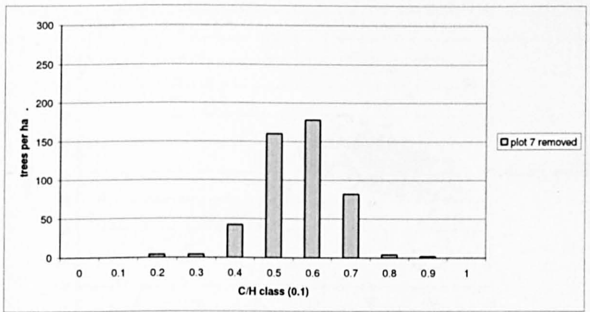


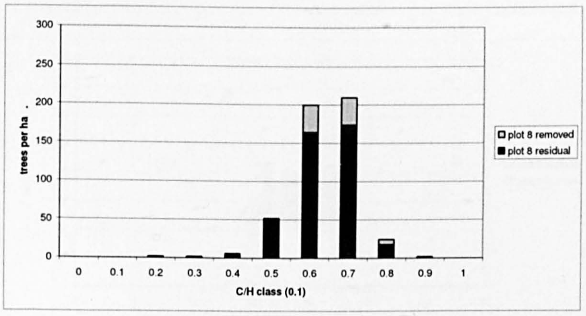




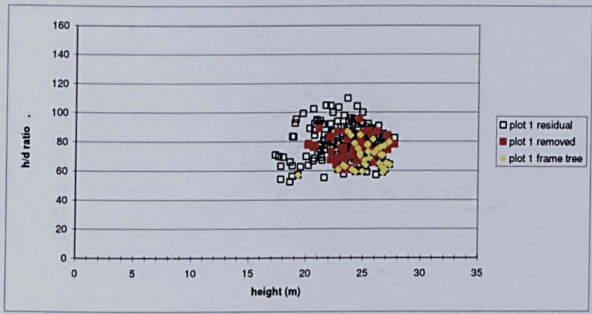


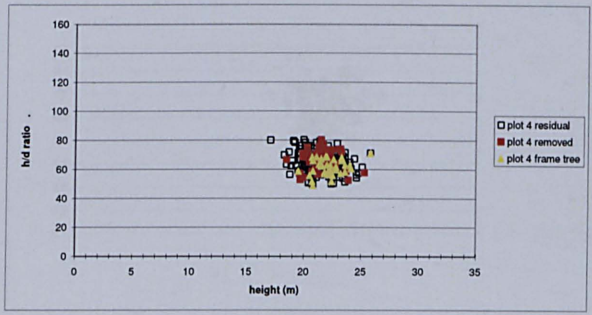


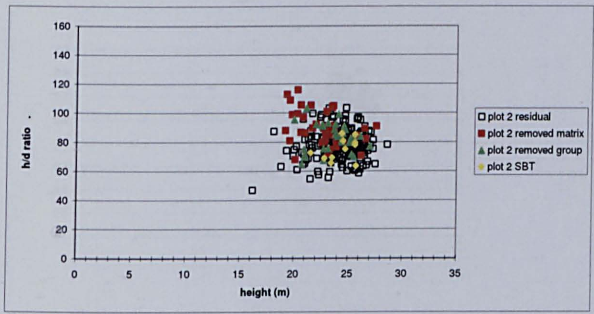


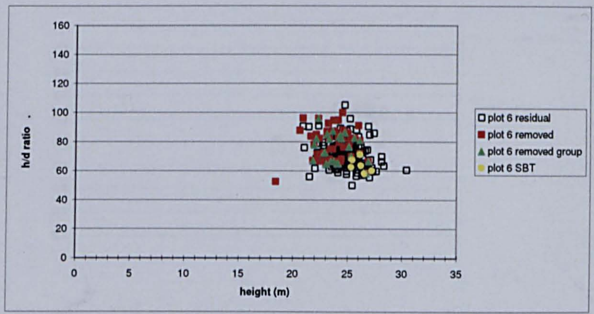


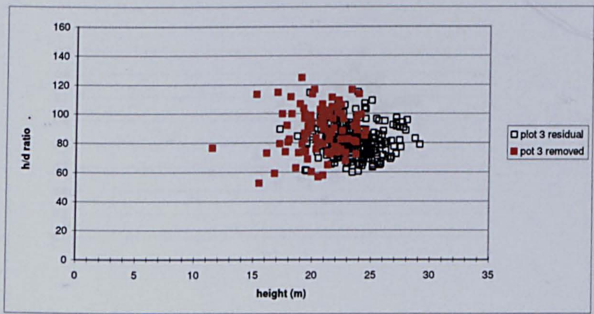
APPENDIX 11: Scatter-plot comparing height and h/d ratio for felling classes

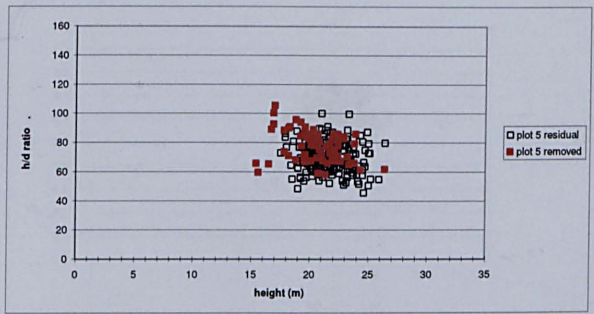


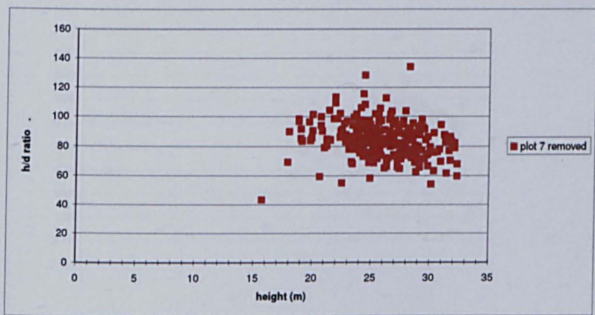


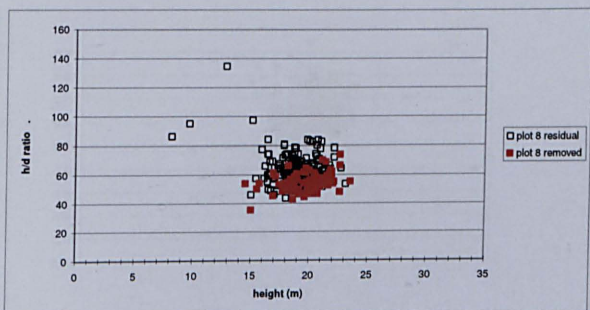




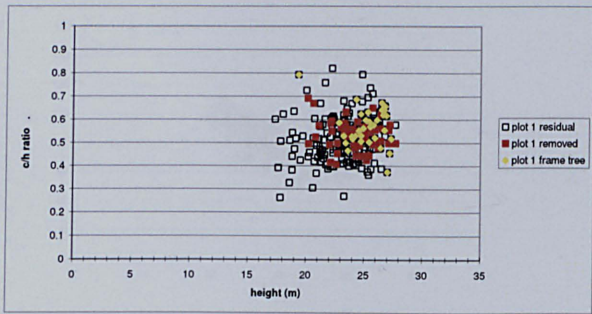


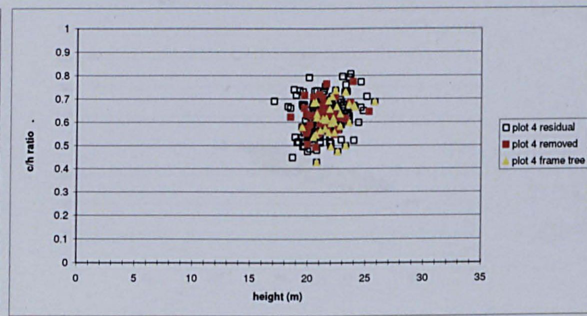


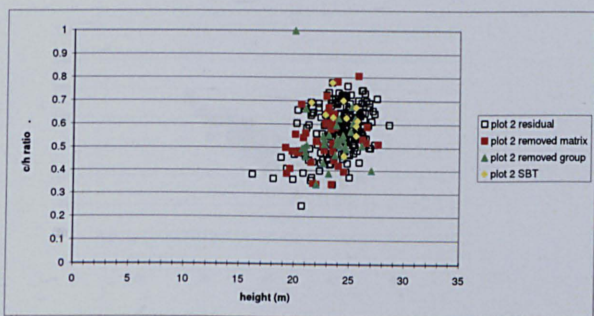


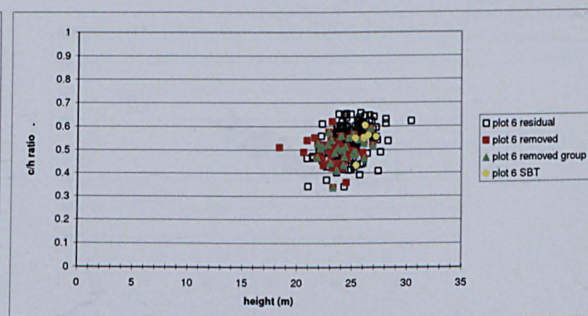


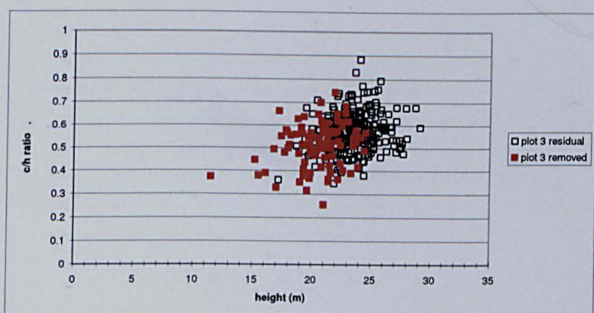
APPENDIX 12: Scatter-plot comparing height and c/h ratio for felling classes

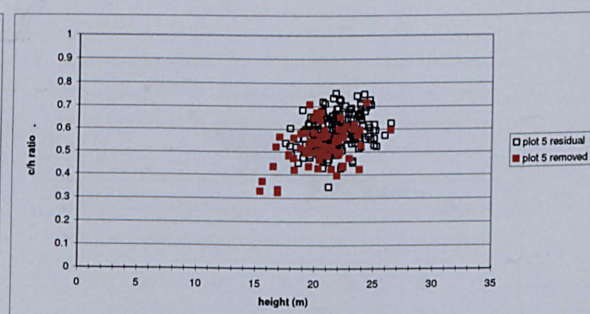


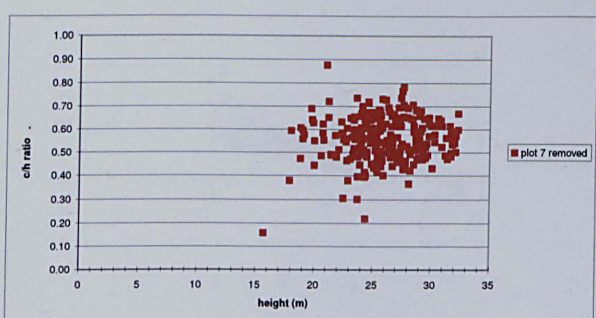


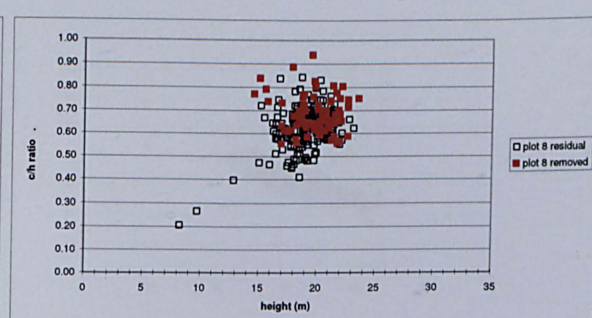




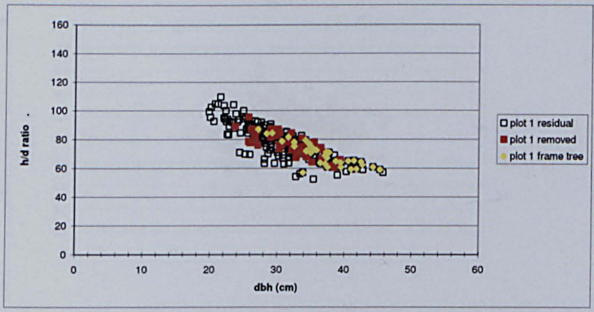


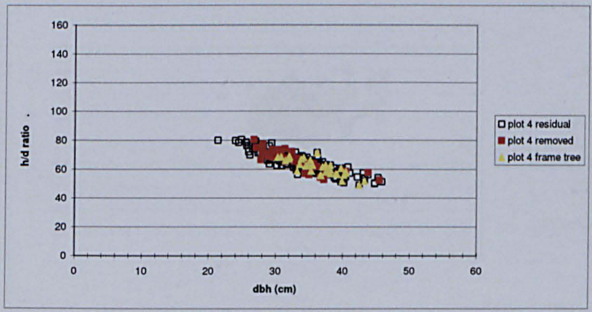


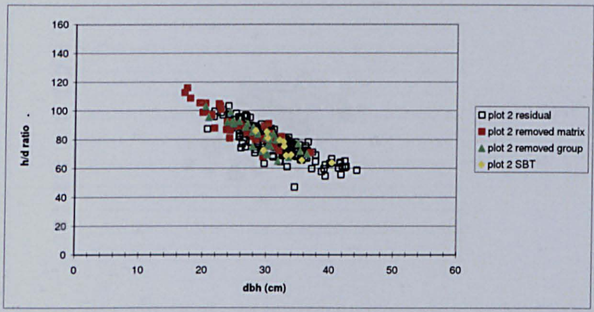


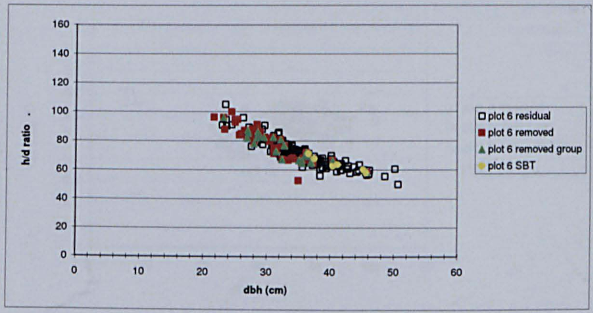


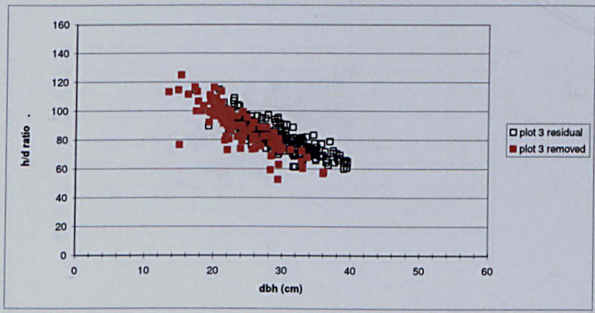
APPENDIX 13: Scatter-plot comparing diameter and h/d ratio for felling classes

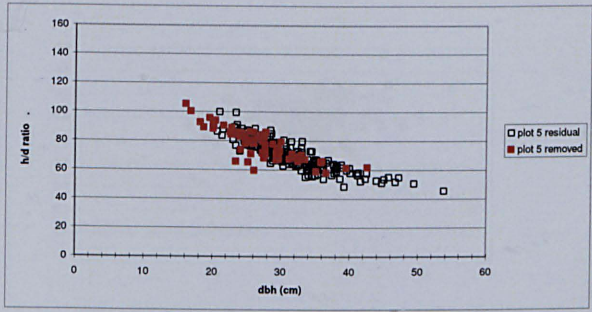


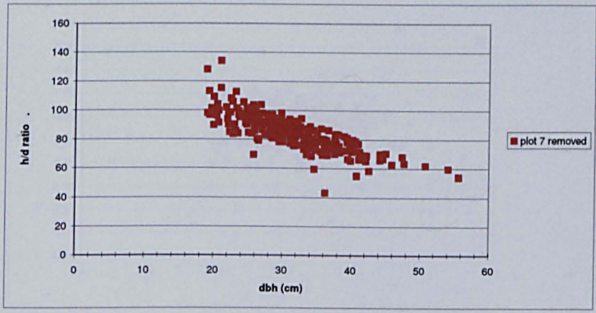


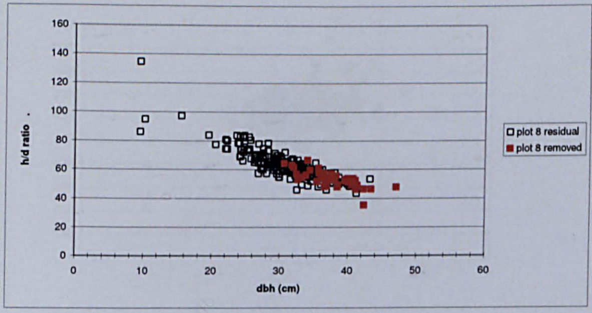




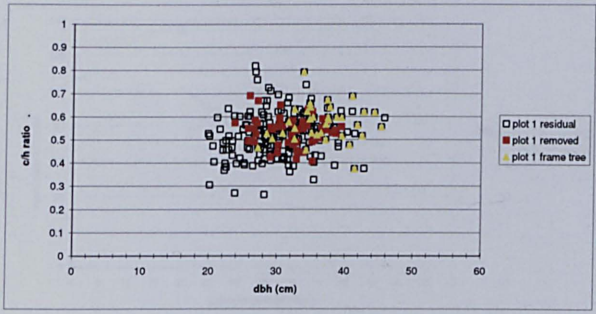


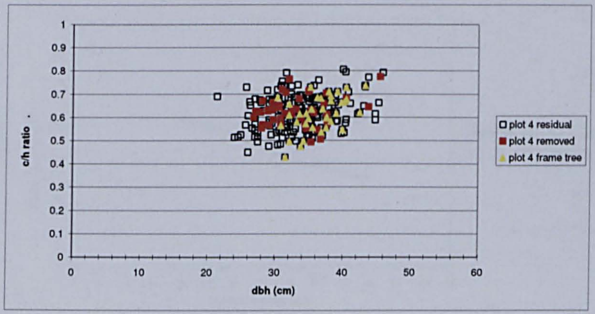


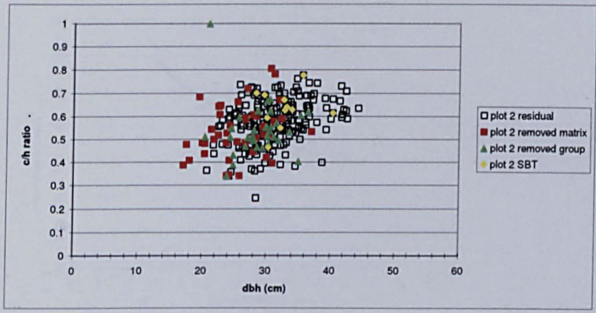


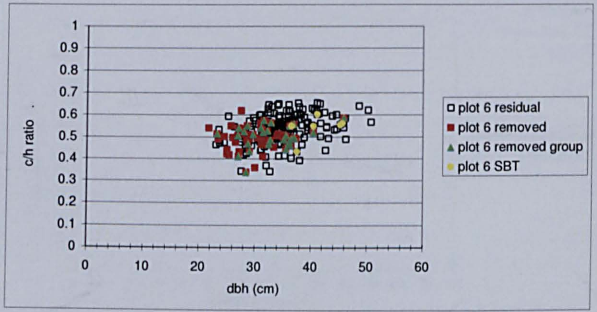


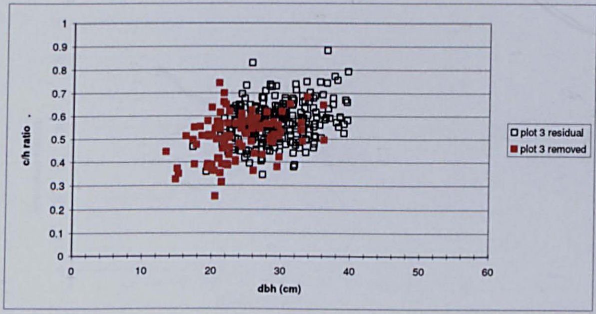
APPENDIX 14: Scatter-plot comparing diameter and c/h ratio for felling classes

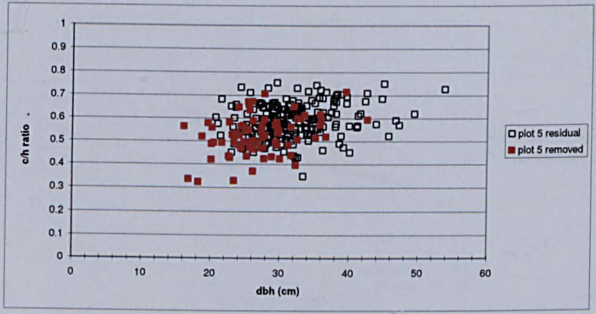


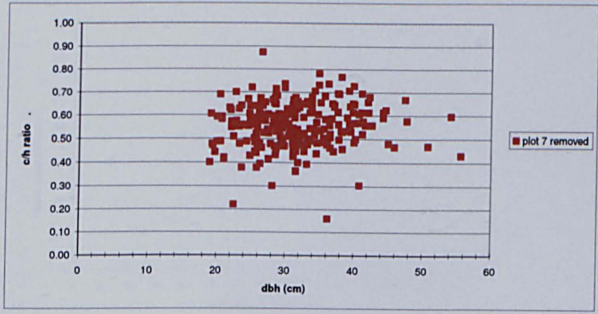


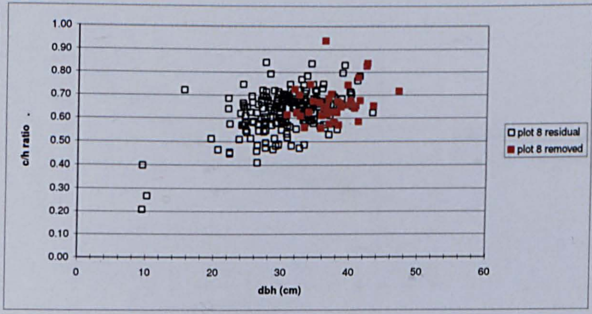




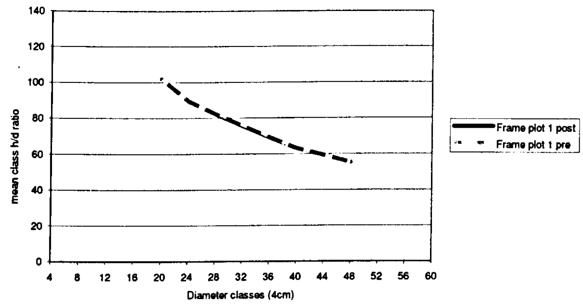


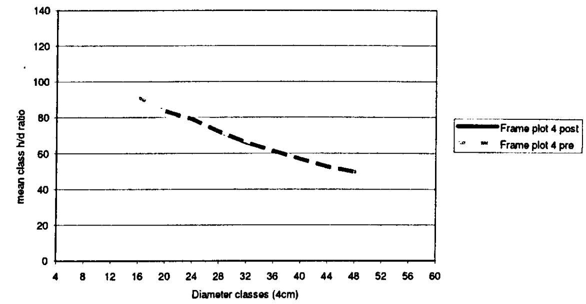


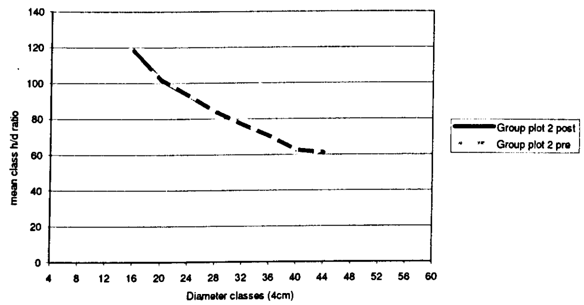


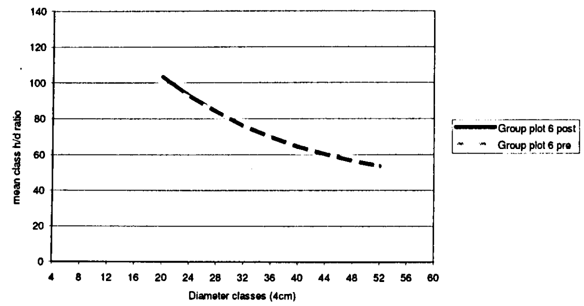


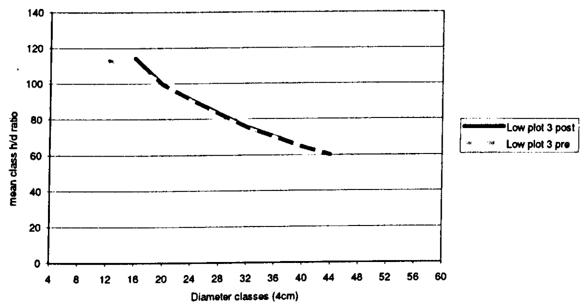
APPENDIX 15: Mean h/d values for 4cm diameter classes

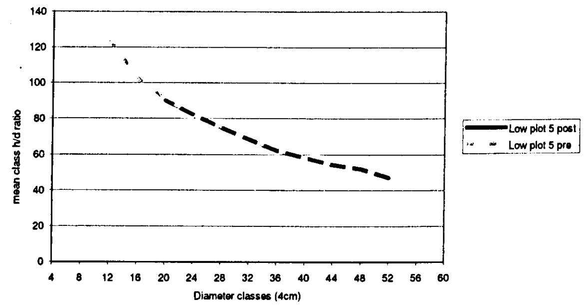


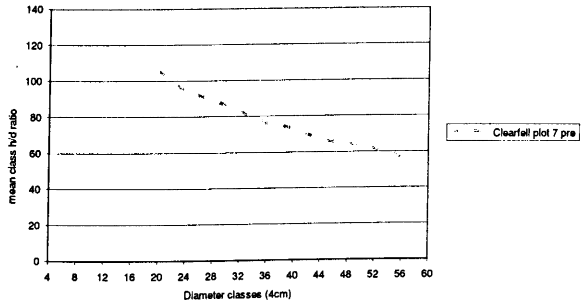


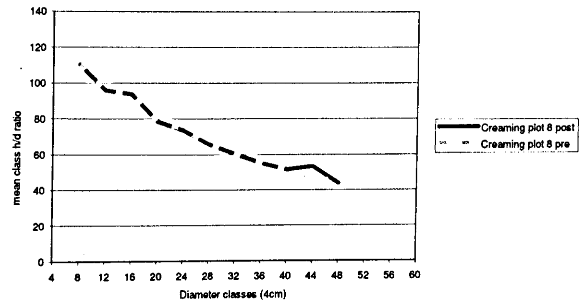




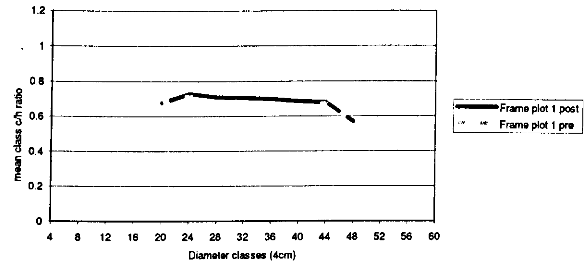


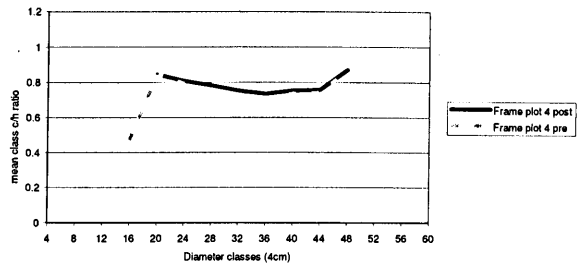


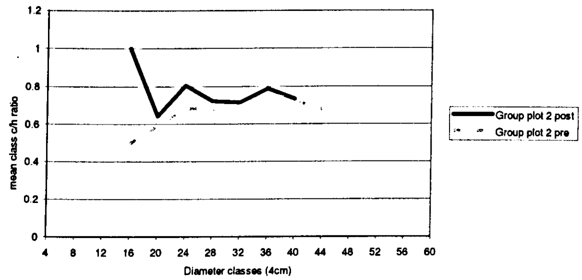


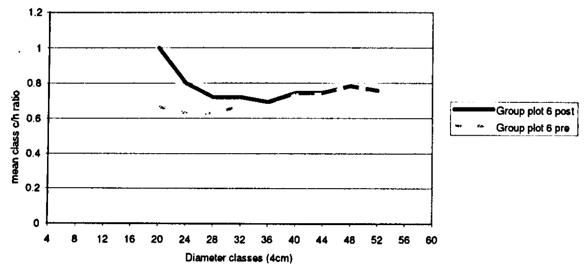


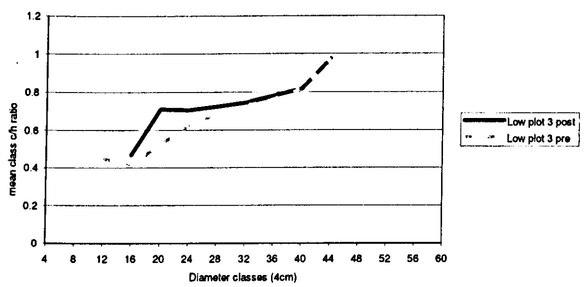
APPENDIX 16: Mean c/h values for 4cm diameter classes

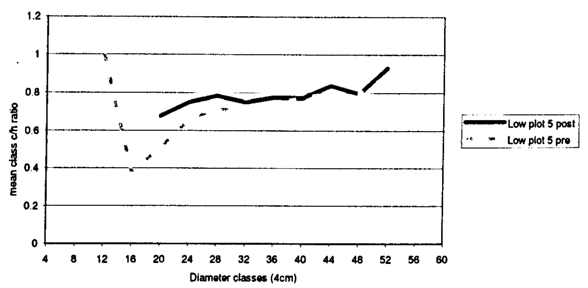


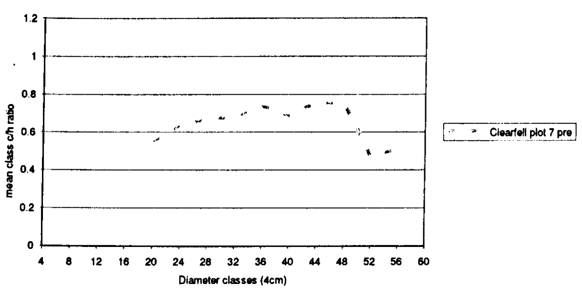


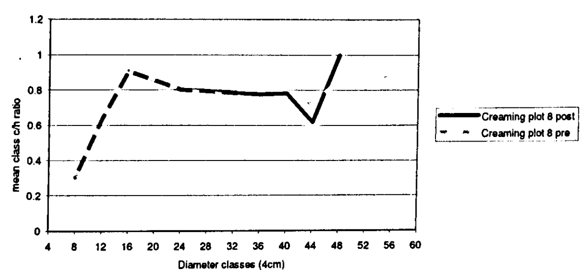












APPENDIX 17: Harvester Head Calibration Check Measurements

Plot	Tree No.	Product Code	Machine Data		Measured		Error	
			Length	Top Diameter	Length	Top Diameter	Length	Top Diameter
1	572	172	172	102	170	105	-1.16%	2.94%
1	572	254	254	147	252	143	-0.79%	-2.72%
1	572	495	496	193	495	193	-0.20%	0.00%
1	572	495	497	254	497	255	0.00%	0.39%
1	572	495	496	284	514	287	3.63%	1.06%
1	305	172	172	83	162	83	-5.81%	0.00%
1	305	172	172	113	170	113	-1.16%	0.00%
1	305	375	375	153	376	155	0.27%	1.31%
1	305	495	496	205	496	206	0.00%	0.49%
1	305	495	496	246	496	245	0.00%	-0.41%
1	305	315	315	276	315	275	0.00%	-0.36%
2	24	172	172	122	171	125	-0.58%	2.46%
2	24	375	375	152	373	152	-0.53%	0.00%
2	24	315	312	200	311	200	-0.32%	0.00%
2	24	495	495	227	495	225	0.00%	-0.88%
2	24	495	496	262	495	262	-0.20%	0.00%
2	761	300	305	87	305	120	0.00%	37.93%
2	761	300	306	171	306	170	0.00%	-0.58%
2	761	315	315	267	313	265	-0.63%	-0.75%
2	761	495	496	313	492	310	-0.81%	-0.96%
2	761	495	493	356	493	355	0.00%	-0.28%
3	987	172	172	76	169	76	-1.74%	0.00%
3	987	172	172	104	171	105	-0.58%	0.96%
3	987	172	172	119	173	119	0.58%	0.00%
3	987	172	172	142	172	142	0.00%	0.00%
3	987	375	375	158	377	153	0.53%	-3.16%
3	987	375	376	172	376	170	0.00%	-1.16%
4	178	172	174	100	174	98	0.00%	-2.00%
4	178	375	375	183	374	183	-0.27%	0.00%
4	178	495	496	236	497	234	0.20%	-0.85%
4	178	495	497	285	494	280	-0.60%	-1.75%
5	639	300	306	140	305	141	-0.33%	0.71%
5	639	315	315	189	315	190	0.00%	0.53%
5	639	300	305	222	303	215	-0.66%	-3.15%
5	639	315	315	243	315	246	0.00%	1.23%
5	573	300	307	128	299	127	-2.61%	-0.78%
5	573	300	305	193	305	185	0.00%	-4.15%
5	573	495	497	231	498	235	0.20%	1.73%
5	573	495	496	277	494	275	-0.40%	-0.72%
6	718	172	172	121	170	115	-1.16%	-4.96%
6	718	375	375	151	373	152	-0.53%	0.66%
6	718	495	496	186	492	184	-0.81%	-1.08%
6	718	495	496	209	493	213	-0.60%	1.91%
6	571	172	170	78	167	78	-1.76%	0.00%
6	571	300	305	107	304	103	-0.33%	-3.74%
6	571	375	376	160	375	157	-0.27%	-1.88%
6	571	495	496	207	495	205	-0.20%	-0.97%
6	571	495	496	250	495	250	-0.20%	0.00%
7	715	300	302	90	302	95	0.00%	5.56%
7	715	315	314	200	314	196	0.00%	-2.00%
7	715	495	495	234	493	234	-0.40%	0.00%
7	715	495	495	271	492	272	-0.61%	0.37%
7	543	172	172	96	171	97	-0.58%	1.04%
7	543	172	172	128	178	120	3.49%	-6.25%
7	543	375	375	150	378	145	0.80%	-3.33%
7	543	495	496	184	499	178	0.60%	-3.26%
7	543	495	496	211	502	209	1.21%	-0.95%
7	543	495	496	229	497	230	0.20%	0.44%
7	672	172	172	86	171	89	-0.58%	3.49%
7	672	172	172	111	172	111	0.00%	0.00%
7	672	172	172	116	173	134	0.58%	15.52%
7	672	375	375	160	383	160	2.13%	0.00%
7	672	495	496	191	583	191	17.54%	0.00%
7	672	495	496	220	498	220	0.40%	0.00%
7	114	172	172	86	171	85	-0.58%	-1.16%
7	114	172	172	115	171	111	-0.58%	-3.48%
7	114	172	172	134	172	131	0.00%	-2.24%
7	114	375	375	159	377	155	0.53%	-2.52%
7	114	495	496	192	500	187	0.81%	-2.60%
7	114	495	496	228	498	228	0.40%	0.00%
7	38	172	172	114	171	112	-0.58%	-1.75%
7	38	172	172	133	172	133	0.00%	0.00%
7	38	375	375	154	375	153	0.00%	-0.65%
7	38	315	314	204	315	204	0.32%	0.00%
7	38	315	314	234	313	234	-0.32%	0.00%
7	38	315	314	267	313	267	-0.32%	0.00%
7	38	495	496	284	495	282	-0.20%	-0.70%
8	595	300	305	105	305	106	0.00%	0.95%
8	595	375	376	174	376	174	0.00%	0.00%
8	595	495	496	267	494	264	-0.40%	-1.12%
8	595	495	496	337	497	335	0.20%	-0.59%
8	183	300	305	89	301	94	-1.31%	5.62%
8	183	254	254	186	252	180	-0.79%	-3.23%
8	183	495	497	246	495	245	-0.40%	-0.41%
8	183	495	496	331	495	332	-0.20%	0.30%

APPENDIX 18: Cut Produce Summary

PLOT 1 - FRAME TREE	log 495cm	short log 315cm	bar 375cm	short bar 254	stake 172cm	pulp 300cm	TOTAL
PIECES CUT	174	97	31	56	126	87	571
PIECES CUT PER HA	174	97	31	56	126	87	571
MEAN PIECE VOLUME (m3)	0.30	0.17	0.10	0.08	0.02	0.10	0.15
STANDARD DEVIATION (m3)	0.07	0.05	0.02	0.02	0.01	0.05	0.12
MEDIAN (m3)	0.29	0.16	0.10	0.07	0.02	0.08	0.12
MINIMUM (m3)	0.16	0.09	0.06	0.05	0.01	0.03	0.01
MAXIMUM (m3)	0.49	0.33	0.14	0.14	0.09	0.27	0.49
VOLUME CUT (m3)	51.34	16.24	3.19	4.42	2.87	8.36	86.41
VOLUME CUT PER HA (m3)	51.34	16.24	3.19	4.42	2.87	8.36	86.41
ASSORTMENT AS % OF TOTAL CUT	59.41%	18.80%	3.69%	5.11%	3.32%	9.67%	100.00%
REVENUE (£ per plot)	867.59	227.43	27.58	29.58	22.92	2.09	1177.19
REVENUE (£ per ha)	867.59	227.43	27.58	29.58	22.92	2.09	1177.19

PLOT 2 - GROUP SYSTEM	log 495cm	short log 315cm	bar 375cm	short bar 254	stake 172cm	pulp 300cm	TOTAL
PIECES CUT	169	96	96	68	183	108	720
PIECES CUT PER HA	169	96	96	68	183	108	720
MEAN PIECE VOLUME (m3)	0.26	0.13	0.10	0.07	0.02	0.09	0.12
STANDARD DEVIATION (m3)	0.07	0.04	0.01	0.02	0.01	0.04	0.10
MEDIAN (m3)	0.24	0.13	0.10	0.06	0.02	0.08	0.09
MINIMUM (m3)	0.15	0.09	0.07	0.04	0.01	0.03	0.01
MAXIMUM (m3)	0.60	0.33	0.14	0.17	0.04	0.23	0.60
VOLUME CUT (m3)	43.13	12.91	9.42	4.50	3.96	9.31	83.23
VOLUME CUT PER HA (m3)	43.13	12.91	9.42	4.50	3.96	9.31	83.23
ASSORTMENT AS % OF TOTAL CUT	51.82%	15.52%	11.31%	5.41%	4.75%	11.18%	100.00%
REVENUE (£ per plot)	728.92	180.80	81.46	30.17	31.65	2.33	1055.33
REVENUE (£ per ha)	728.92	180.80	81.46	30.17	31.65	2.33	1055.33

PLOT 3 - LOW THINNING	log 495cm	short log 315cm	bar 375cm	short bar 254	stake 172cm	pulp 300cm	TOTAL
PIECES CUT	94	119	173	102	376	116	980
PIECES CUT PER HA	100.0	126.6	184.0	108.5	400.0	123.4	1042.6
MEAN PIECE VOLUME (m3)	0.24	0.12	0.10	0.06	0.02	0.08	0.08
STANDARD DEVIATION (m3)	0.06	0.03	0.01	0.02	0.01	0.03	0.07
MEDIAN (m3)	0.23	0.11	0.10	0.06	0.02	0.07	0.07
MINIMUM (m3)	0.16	0.09	0.07	0.04	0.01	0.03	0.01
MAXIMUM (m3)	0.42	0.25	0.14	0.13	0.04	0.19	0.42
VOLUME CUT (m3)	22.82	14.67	16.60	6.43	8.24	8.99	77.74
VOLUME CUT PER HA (m3)	24.27	15.61	17.66	6.85	8.76	9.56	82.70
ASSORTMENT AS % OF TOTAL CUT	29.35%	18.87%	21.35%	8.28%	10.59%	11.56%	100.00%
REVENUE (£ per plot)	385.59	205.37	143.58	43.11	65.89	2.25	845.78
REVENUE (£ per ha)	410.20	218.48	152.74	45.86	70.09	2.39	899.77

PLOT 4 - FRAME TREE	log 495cm	short log 315cm	bar 375cm	short bar 254	stake 172cm	pulp 300cm	TOTAL
PIECES CUT	146	65	18	29	33	104	395
PIECES CUT PER HA	146	65	18	29	33	104	395
MEAN PIECE VOLUME (m3)	0.32	0.16	0.11	0.08	0.03	0.08	0.18
STANDARD DEVIATION (m3)	0.09	0.04	0.01	0.02	0.03	0.04	0.13
MEDIAN (m3)	0.31	0.15	0.11	0.07	0.02	0.06	0.14
MINIMUM (m3)	0.16	0.09	0.08	0.05	0.01	0.03	0.01
MAXIMUM (m3)	0.60	0.26	0.13	0.14	0.17	0.26	0.60
VOLUME CUT (m3)	47.43	10.35	1.97	2.31	0.93	8.32	71.31
VOLUME CUT PER HA (m3)	47.43	10.35	1.97	2.31	0.93	8.32	71.31
ASSORTMENT AS % OF TOTAL CUT	66.52%	14.51%	2.76%	3.24%	1.30%	11.67%	100.00%
REVENUE (£ per plot)	801.59	144.87	17.02	15.47	7.43	2.08	988.45
REVENUE (£ per ha)	801.59	144.87	17.02	15.47	7.43	2.08	988.45

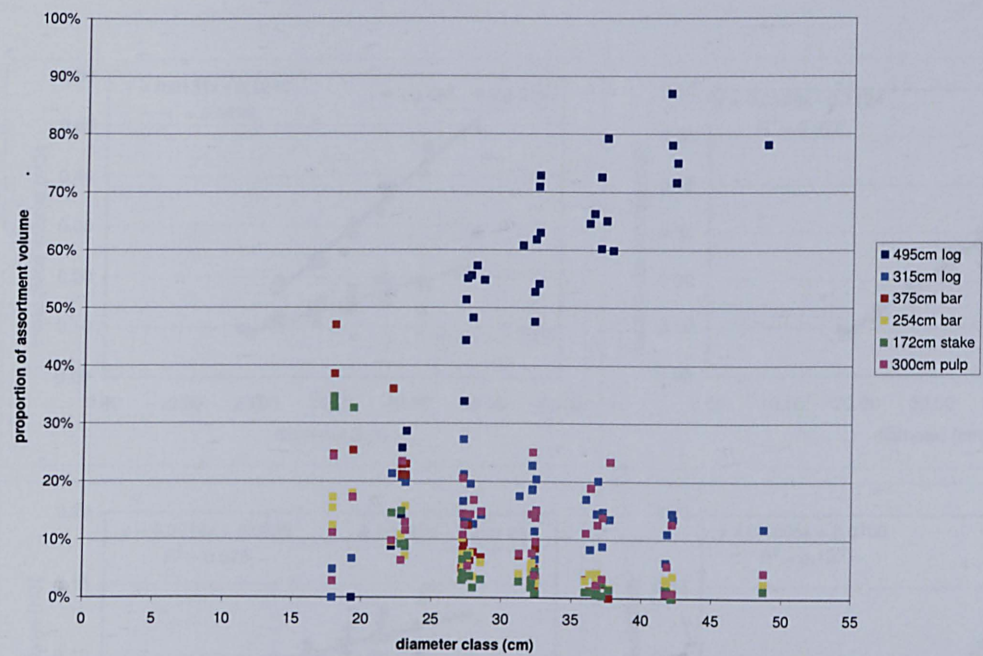
PLOT 5 - LOW THINNING	log 495cm	short log 315cm	bar 375cm	short bar 254	stake 172cm	pulp 300cm	TOTAL
PIECES CUT	103	112	50	79	148	191	683
PIECES CUT PER HA	104.0	113.1	50.5	79.8	149.5	192.9	689.9
MEAN PIECE VOLUME (m3)	0.28	0.15	0.10	0.07	0.02	0.09	0.11
STANDARD DEVIATION (m3)	0.10	0.04	0.01	0.02	0.01	0.04	0.09
MEDIAN (m3)	0.26	0.14	0.10	0.07	0.02	0.08	0.09
MINIMUM (m3)	0.16	0.09	0.07	0.05	0.01	0.03	0.01
MAXIMUM (m3)	0.78	0.28	0.13	0.14	0.04	0.23	0.78
VOLUME CUT (m3)	28.81	16.24	5.08	5.73	3.38	16.84	76.09
VOLUME CUT PER HA (m3)	29.10	16.41	5.13	5.79	3.41	17.01	76.86
ASSORTMENT AS % OF TOTAL CUT	37.86%	21.35%	6.68%	7.53%	4.44%	22.14%	100.00%
REVENUE (£ per plot)	486.92	227.41	43.97	38.40	27.03	4.21	827.94
REVENUE (£ per ha)	491.84	229.71	44.41	38.79	27.31	4.25	836.31

PLOT 6 -GROUP SYSTEM	log 495cm	short log 315cm	bar 375cm	short bar 254	stake 172cm	pulp 300cm	TOTAL
PIECES CUT	170	114	45	71	106	129	635
PIECES CUT PER HA	170	114	45	71	106	129	635
MEAN PIECE VOLUME (m3)	0.28	0.15	0.10	0.07	0.02	0.09	0.14
STANDARD DEVIATION (m3)	0.08	0.05	0.01	0.02	0.01	0.05	0.11
MEDIAN (m3)	0.27	0.14	0.10	0.07	0.02	0.07	0.11
MINIMUM (m3)	0.15	0.09	0.08	0.05	0.01	0.02	0.01
MAXIMUM (m3)	0.59	0.32	0.13	0.14	0.04	0.27	0.59
VOLUME CUT (m3)	48.37	16.80	4.56	5.23	2.37	11.05	88.36
VOLUME CUT PER HA (m3)	48.37	16.80	4.56	5.23	2.37	11.05	88.36
ASSORTMENT AS % OF TOTAL CUT	54.74%	19.01%	5.16%	5.92%	2.68%	12.50%	100.00%
REVENUE (£ per plot)	817.44	235.18	39.41	35.04	18.92	2.76	1148.75
REVENUE (£ per ha)	817.44	235.18	39.41	35.04	18.92	2.76	1148.75

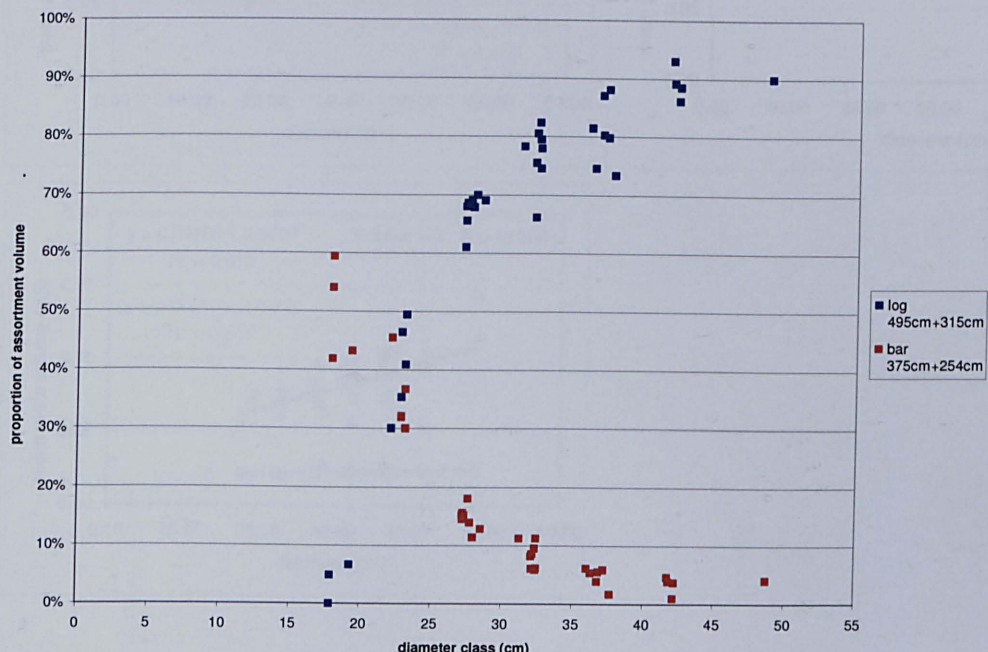
PLOT 7 - CLEARFELL	log 495cm	short log 315cm	bar 375cm	short bar 254	stake 172cm	pulp 300cm	TOTAL
PIECES CUT	665	236	190	189	618	144	2042
PIECES CUT PER HA	977.9	347.1	279.4	277.9	908.8	211.8	3002.9
MEAN PIECE VOLUME (m3)	0.31	0.15	0.10	0.07	0.02	0.09	0.15
STANDARD DEVIATION (m3)	0.11	0.05	0.01	0.02	0.01	0.04	0.14
MEDIAN (m3)	0.34	0.17	0.12	0.08	0.02	0.07	0.10
MINIMUM (m3)	0.17	0.10	0.09	0.06	0.01	0.03	0.01
MAXIMUM (m3)	0.67	0.30	0.16	0.13	0.03	0.26	0.95
VOLUME CUT (m3)	208.76	35.14	18.79	12.81	13.36	13.61	302.47
VOLUME CUT PER HA (m3)	306.99	51.68	27.63	18.84	19.65	20.01	444.80
ASSORTMENT AS % OF TOTAL CUT	69.02%	11.62%	6.21%	4.24%	4.42%	4.50%	100.00%
REVENUE (£ per plot)	3527.98	492.01	162.50	85.84	106.88	3.40	4378.62
REVENUE (£ per ha)	5188.21	723.54	238.97	126.23	157.18	5.00	6439.14

PLOT 8 - CREAMING	log 495cm	short log 315cm	bar 375cm	short bar 254	stake 172cm	pulp 300cm	TOTAL
PIECES CUT	125	46	10	24	13	107	325
PIECES CUT PER HA	125	46	10	24	13	107	325
MEAN PIECE VOLUME (m3)	0.35	0.18	0.12	0.08	0.02	0.08	0.20
STANDARD DEVIATION (m3)	0.10	0.05	0.02	0.02	0.01	0.05	0.15
MEDIAN (m3)	0.29	0.13	0.10	0.06	0.02	0.08	0.16
MINIMUM (m3)	0.15	0.08	0.06	0.04	0.01	0.03	0.01
MAXIMUM (m3)	0.95	0.48	0.15	0.14	0.08	0.23	0.67
VOLUME CUT (m3)	44.17	8.36	1.23	1.94	0.29	8.87	64.85
VOLUME CUT PER HA (m3)	44.17	8.36	1.23	1.94	0.29	8.87	64.85
ASSORTMENT AS % OF TOTAL CUT	68.11%	12.89%	1.90%	2.99%	0.45%	13.67%	100.00%
REVENUE (£ per plot)	746.48	116.99	10.64	12.99	2.31	2.22	891.62
REVENUE (£ per ha)	746.48	116.99	10.64	12.99	2.31	2.22	891.62

APPENDIX 19: Volume assortment distributions

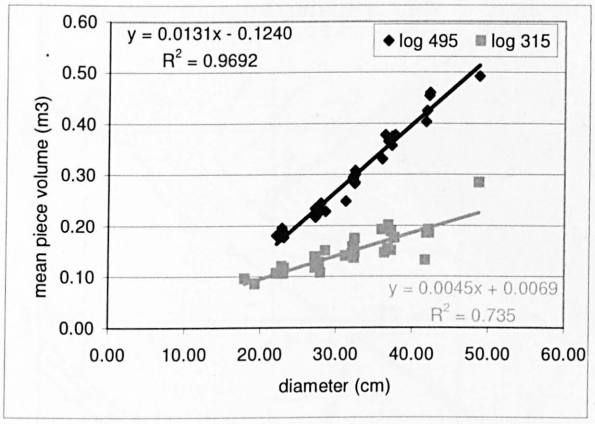


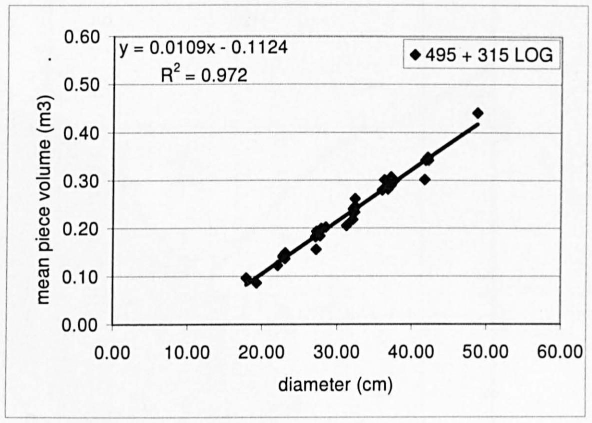
a) All product types.

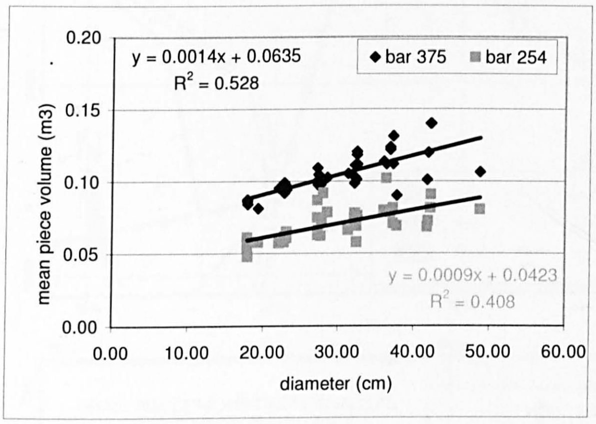


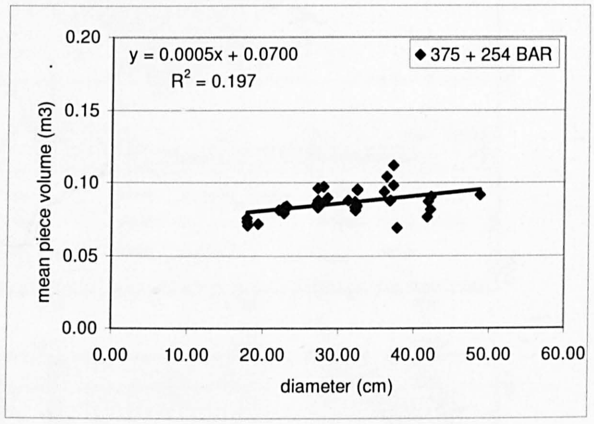
b) Amalgamated logs (495cm + 315cm) and bars (375cm + 254cm).

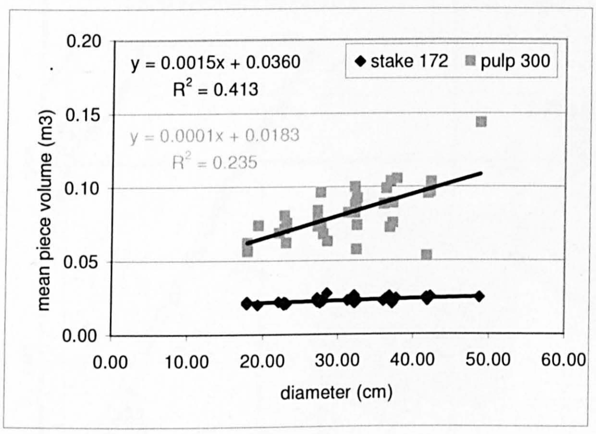
APPENDIX 20: Piece volume in relation to felled tree diameter



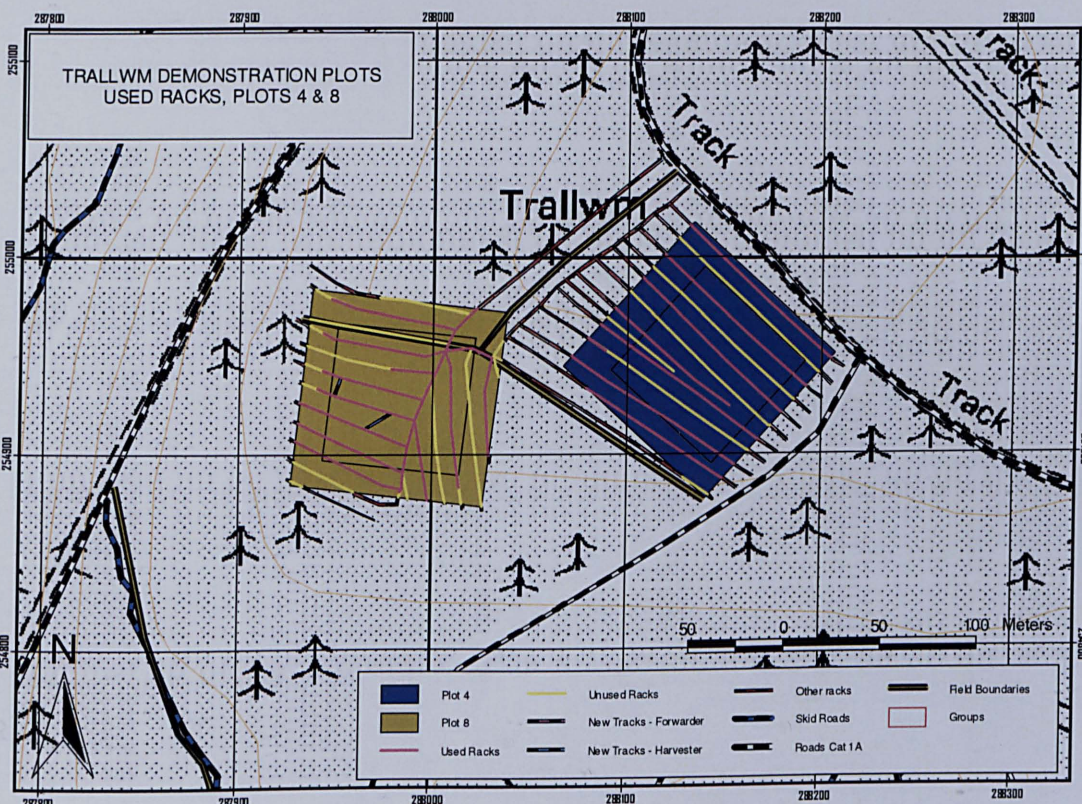


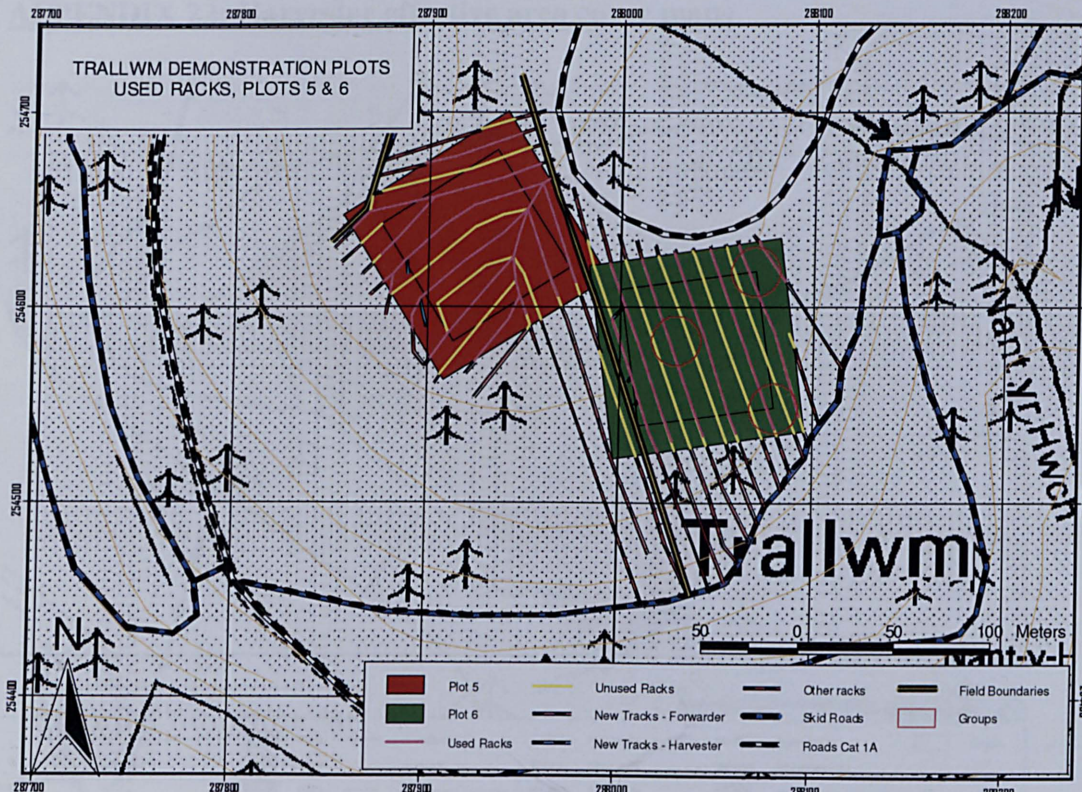




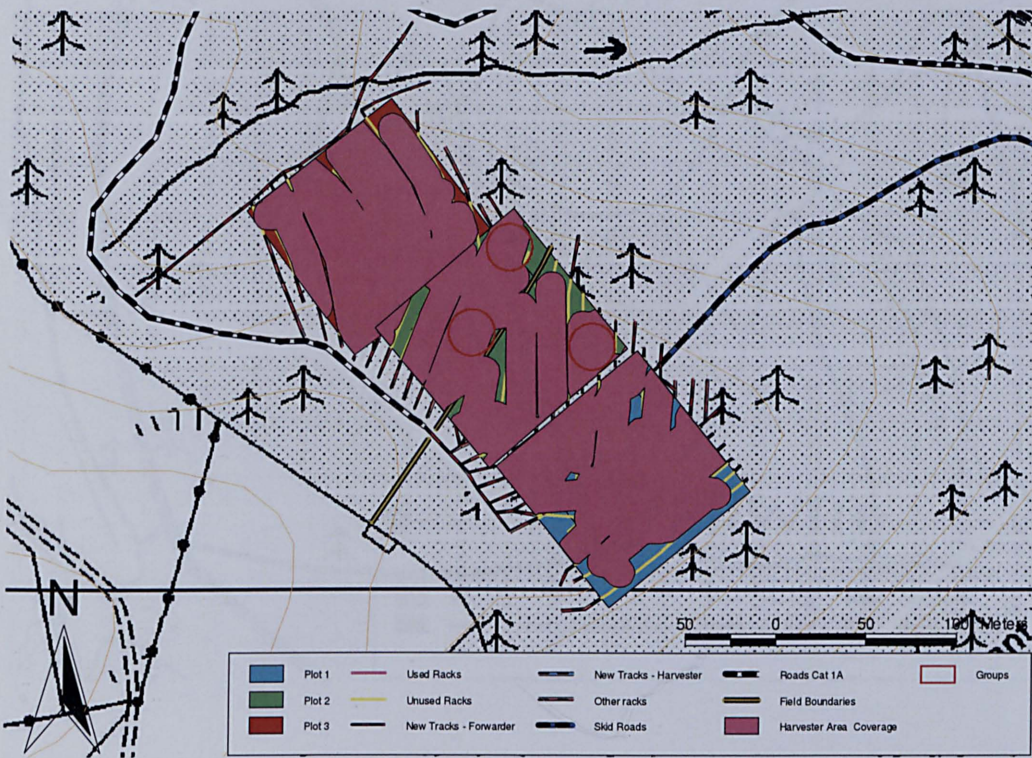


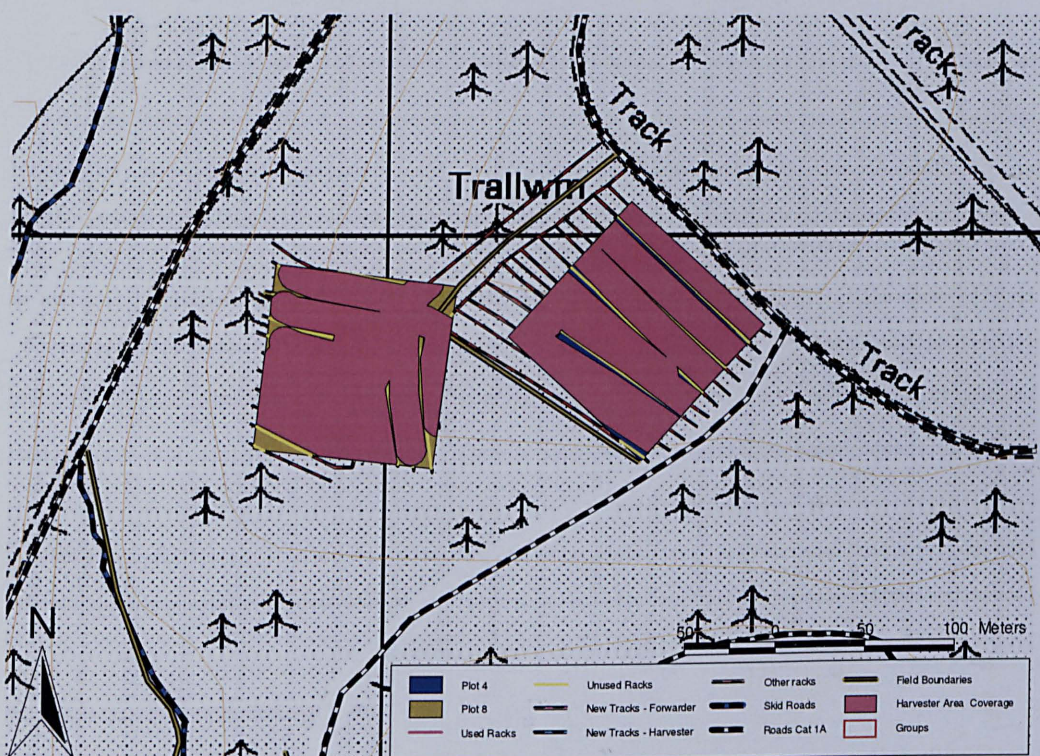
APPENDIX 21: Rack usage and track creation maps




TRALLWM DEMONSTRATION PLOTS
USED RACKS, PLOTS 5 & 6
Trallwm
Nant yr Hwch
50 0 50 100 Meters
Plot 5
Plot 6
Used Racks
Unused Racks
New Tracks - Forwarder
New Tracks - Harvester
Other racks
Skid Roads
Roads Cat 1A
Field Boundaries
Groups

APPENDIX 22: Harvester effective area cover maps






Nant yr Hwch
Trallwm
N
50 0 50 100 Meters
Plot 5
Plot 6
Used Racks
Unused Racks
New Tracks - Forwarder
New Tracks - Harvester
Other racks
Skid Roads
Roads Cat 1A
Field Boundaries
Harvester Area Coverage
Groups

APPENDIX 23: Harvester Element Summary

PLOT 1							
ACTIVITY	CODE	TOTAL TIME	NUMBER OF OCCURENCES	MIN	MAX	MEAN	STDEV
CLOCK READING	B1	0	0	0	0	0.0	0.0
GENERAL PREPARATION	B2	0	0	0	0	0.0	0.0
ON/OFF PROTECTIVE CLOTHING	B3	0	0	0	0	0.0	0.0
TO AND FROM CAMP	B4	682	1	682	682	682.0	0.0
PRODUCTS NOT STUDIED (PNS)	B5	0	0	0	0	0.0	0.0
FETCH TOOLS	B6	0	0	0	0	0.0	0.0
AVOIDABLE DELAY	B7	0	0	0	0	0.0	0.0
UNAVOIDABLE DELAY	B8	0	0	0	0	0.0	0.0
REST AND PERSONAL	B9	5428	1	5428	5428	5428.0	0.0
WAIT OR TALK WORK STUDY	C1	7209	16	5	2820	450.6	832.7
INSPECT AND CONSIDER	C2	1162	37	3	365	31.4	59.9
MOVE BETWEEN RACKS OR DRIFTS	C3	1446	13	30	325	111.2	76.7
ASIDE BRASH	C4	0	0	0	0	0.0	0.0
SHARPEN OR REPLACE CROSS-CUTTING CHAIN	C5	0	0	0	0	0.0	0.0
ROUTINE MAINTENANCE	C6	86	1	86	86	86.0	0.0
REFUEL MACHINE	C7	0	0	0	0	0.0	0.0
UNCLASSIFIED OTHER WORK	C8	106	7	7	32	15.1	8.6
MANOEUVRE	C9	1828	50	3	131	36.6	31.3
SHARPEN OR REPAIR DE-BRANCHER KNIVES	D1	0	0	0	0	0.0	0.0
MINOR REPAIR	D2	5823	1	5823	5823	5823.0	0.0
REPAIR ROLLER CHAINS	D3	0	0	0	0	0.0	0.0
REPAIR	D4	0	0	0	0	0.0	0.0
PREPARE ROUTE	D5	507	23	5	58	22.0	12.3
REPAIR BASE UNIT TRACK & CHAIN	D6	0	0	0	0	0.0	0.0
STACK LOGS	D7	271	7	13	83	38.7	26.9
STACK 3M PULP	D8	0	0	0	0	0.0	0.0
STACK 2M PULP	D9	0	0	0	0	0.0	0.0
MOVE	A	2400	98	2	101	24.5	19.8
CONTINUATION OF MOVE	A1	0	0	0	0	0.0	0.0
TRIM BUTT	A3	907	145	1	67	6.3	7.3
FELL BRASHED TREE	B	0	0	0	0	0.0	0.0
FELL UNBRASHED TREE	C	4294	104	9	95	41.3	17.8
CONTINUATION OF FELL	D	0	0	0	0	0.0	0.0
PROCESS	E	2435	136	3	85	17.9	13.2
PROCESS LOG 495CM	E1	1940	174	3	34	11.1	5.3
PROCESS LOG 315CM	E2	958	97	2	25	9.9	4.2
PROCESS BAR 375CM	E3	322	31	5	25	10.4	5.1
PROCESS BAR 254CM	E4	577	56	5	30	10.3	4.7
PROCESS PULP 300CM	E5	814	87	2	34	9.4	5.7
PROCESS STAKE 172CM	E6	778	126	1	27	6.2	4.4
ASIDE AND CUT UP TOP	F	1062	104	1	37	10.2	6.1
RE-PROCESS	G	366	28	1	45	13.1	11.7
FELL AND ASIDE UNMEASURABLE UNMARKETABLE TREE	A8	193	6	14	94	32.2	30.5
TOTAL CODE TIME (CENTIMIN)		41594					

TIME ON (HR:MIN:CENTIMIN) 085781
TIME OFF (HR:MIN:CENTIMIN) 155375
TOTAL OBSERVED TIME (CENTIMIN) 41594

PLOT 2							
ACTIVITY	CODE	TOTAL TIME	NUMBER OF OCCURENCES	MIN	MAX	MEAN	STDEV
CLOCK READING	B1	0	0	0	0	0.0	0.0
GENERAL PREPARATION	B2	0	0	0	0	0.0	0.0
ON/OFF PROTECTIVE CLOTHING	B3	0	0	0	0	0.0	0.0
TO AND FROM CAMP	B4	143	1	143	143	143.0	0.0
PRODUCTS NOT STUDIED (PNS)	B5	0	0	0	0	0.0	0.0
FETCH TOOLS	B6	0	0	0	0	0.0	0.0
AVOIDABLE DELAY	B7	0	0	0	0	0.0	0.0
UNAVOIDABLE DELAY	B8	0	0	0	0	0.0	0.0
REST AND PERSONAL	B9	0	0	0	0	0.0	0.0
WAIT OR TALK WORK STUDY	C1	3018	11	8	680	274.4	275.1
INSPECT AND CONSIDER	C2	382	10	5	170	38.2	49.4
MOVE BETWEEN RACKS OR DRIFTS	C3	1952	11	40	308	177.5	108.8
ASIDE BRASH	C4	0	0	0	0	0.0	0.0
SHARPEN OR REPLACE CROSS-CUTTING CHAIN	C5	320	1	320	320	320.0	0.0
ROUTINE MAINTENANCE	C6	137	1	137	137	137.0	0.0
REFUEL MACHINE	C7	0	0	0	0	0.0	0.0
UNCLASSIFIED OTHER WORK	C8	91	6	5	36	15.2	11.2
MANOEUVRE	C9	502	16	3	73	31.4	23.8
SHARPEN OR REPAIR DE-BRANCHER KNIVES	D1	0	0	0	0	0.0	0.0
MINOR REPAIR	D2	0	0	0	0	0.0	0.0
REPAIR ROLLER CHAINS	D3	0	0	0	0	0.0	0.0
REPAIR	D4	0	0	0	0	0.0	0.0
PREPARE ROUTE	D5	400	20	7	48	20.0	11.5
REPAIR BASE UNIT TRACK & CHAIN	D6	0	0	0	0	0.0	0.0
STACK LOGS	D7	110	3	13	72	36.7	31.2
STACK 3M PULP	D8	0	0	0	0	0.0	0.0
STACK 2M PULP	D9	0	0	0	0	0.0	0.0
MOVE	A	1670	96	2	100	17.4	15.3
CONTINUATION OF MOVE	A1	0	0	0	0	0.0	0.0
TRIM BUTT	A3	808	163	1	29	5.0	4.6
FELL BRASHED TREE	B	0	0	0	0	0.0	0.0
FELL UNBRASHED TREE	C	4276	139	12	80	30.8	13.2
CONTINUATION OF FELL	D	0	0	0	0	0.0	0.0
PROCESS	E	2207	141	1	58	15.7	10.6
PROCESS LOG 495CM	E1	1669	169	2	35	9.9	4.4
PROCESS LOG 315CM	E2	920	96	5	23	9.6	3.6
PROCESS BAR 375CM	E3	810	96	2	18	8.4	3.1
PROCESS BAR 254CM	E4	636	68	3	45	9.4	5.4
PROCESS PULP 300CM	E5	939	108	2	44	8.7	5.5
PROCESS STAKE 172CM	E6	1093	183	1	21	6.0	3.6
ASIDE AND CUT UP TOP	F	1122	139	1	45	8.1	5.2
RE-PROCESS	G	123	16	1	25	7.7	7.0
FELL AND ASIDE UNMEASURABLE UNMARKETABLE TREE	A8	387	10	3	109	38.7	31.2
TOTAL CODE TIME (CENTIMIN)		23715					

TIME ON (HR:MIN:CENTIMIN)	140838
TIME OFF (HR:MIN:CENTIMIN)	180553
TOTAL OBSERVED TIME (CENTIMIN)	23715

PLOT 3							
ACTIVITY	CODE	TOTAL TIME	NUMBER OF OCCURENCES	MIN	MAX	MEAN	STDEV
CLOCK READING	B1	0	0	0	0	0.0	0.0
GENERAL PREPARATION	B2	0	0	0	0	0.0	0.0
ON/OFF PROTECTIVE CLOTHING	B3	0	0	0	0	0.0	0.0
TO AND FROM CAMP	B4	18	1	18	18	18.0	0.0
PRODUCTS NOT STUDIED (PNS)	B5	0	0	0	0	0.0	0.0
FETCH TOOLS	B6	0	0	0	0	0.0	0.0
AVOIDABLE DELAY	B7	0	0	0	0	0.0	0.0
UNAVOIDABLE DELAY	B8	0	0	0	0	0.0	0.0
REST AND PERSONAL	B9	0	0	0	0	0.0	0.0
WAIT OR TALK WORK STUDY	C1	2294	14	12	1158	163.9	321.0
INSPECT AND CONSIDER	C2	2407	23	3	448	104.7	144.4
MOVE BETWEEN RACKS OR DRIFTS	C3	2182	10	56	330	218.2	86.2
ASIDE BRASH	C4	0	0	0	0	0.0	0.0
SHARPEN OR REPLACE CROSS-CUTTING CHAIN	C5	0	0	0	0	0.0	0.0
ROUTINE MAINTENANCE	C6	1097	1	1097	1097	1097.0	0.0
REFUEL MACHINE	C7	0	0	0	0	0.0	0.0
UNCLASSIFIED OTHER WORK	C8	56	3	15	25	18.7	5.5
MANOEUVRE	C9	1310	34	3	182	38.5	38.3
SHARPEN OR REPAIR DE-BRANCHER KNIVES	D1	0	0	0	0	0.0	0.0
MINOR REPAIR	D2	0	0	0	0	0.0	0.0
REPAIR ROLLER CHAINS	D3	0	0	0	0	0.0	0.0
REPAIR	D4	0	0	0	0	0.0	0.0
PREPARE ROUTE	D5	1233	52	5	92	23.7	14.7
REPAIR BASE UNIT TRACK & CHAIN	D6	0	0	0	0	0.0	0.0
STACK LOGS	D7	304	7	17	66	43.4	20.6
STACK 3M PULP	D8	0	0	0	0	0.0	0.0
STACK 2M PULP	D9	0	0	0	0	0.0	0.0
MOVE	A	2567	134	1	168	19.2	18.9
CONTINUATION OF MOVE	A1	0	0	0	0	0.0	0.0
TRIM BUTT	A3	911	187	1	45	4.9	5.9
FELL BRASHED TREE	B	0	0	0	0	0.0	0.0
FELL UNBRASHED TREE	C	6080	191	10	95	31.8	12.7
CONTINUATION OF FELL	D	0	0	0	0	0.0	0.0
PROCESS	E	2625	179	2	65	14.7	10.8
PROCESS LOG 495CM	E1	988	94	4	36	10.5	5.2
PROCESS LOG 315CM	E2	1074	119	3	20	9.0	3.5
PROCESS BAR 375CM	E3	1448	173	1	30	8.4	4.0
PROCESS BAR 254CM	E4	945	102	3	25	9.3	3.8
PROCESS PULP 300CM	E5	1180	116	3	24	10.2	4.6
PROCESS STAKE 172CM	E6	2004	376	1	20	5.3	3.1
ASIDE AND CUT UP TOP	F	1930	191	2	65	10.1	6.4
RE-PROCESS	G	413	30	1	58	13.8	16.4
FELL AND ASIDE UNMEASURABLE UNMARKETABLE TREE	A8	206	9	3	55	22.9	18.6
TOTAL CODE TIME (CENTIMIN)		33272					

TIME ON (HR:MIN:CENTIMIN)	080133
TIME OFF (HR:MIN:CENTIMIN)	133405
TOTAL OBSERVED TIME (CENTIMIN)	33272

PLOT 4							
ACTIVITY	CODE	TOTAL TIME	NUMBER OF OCCURENCES	MIN	MAX	MEAN	STDEV
CLOCK READING	B1	0	0	0	0	0.0	0.0
GENERAL PREPARATION	B2	0	0	0	0	0.0	0.0
ON/OFF PROTECTIVE CLOTHING	B3	0	0	0	0	0.0	0.0
TO AND FROM CAMP	B4	450	2	100	350	225.0	176.8
PRODUCTS NOT STUDIED (PNS)	B5	0	0	0	0	0.0	0.0
FETCH TOOLS	B6	0	0	0	0	0.0	0.0
AVOIDABLE DELAY	B7	0	0	0	0	0.0	0.0
UNAVOIDABLE DELAY	B8	0	0	0	0	0.0	0.0
REST AND PERSONAL	B9	0	0	0	0	0.0	0.0
WAIT OR TALK WORK STUDY	C1	898	4	10	620	224.5	288.4
INSPECT AND CONSIDER	C2	276	14	4	53	19.7	17.0
MOVE BETWEEN RACKS OR DRIFTS	C3	2052	13	10	347	157.8	115.9
ASIDE BRASH	C4	0	0	0	0	0.0	0.0
SHARPEN OR REPLACE CROSS-CUTTING CHAIN	C5	0	0	0	0	0.0	0.0
ROUTINE MAINTENANCE	C6	0	0	0	0	0.0	0.0
REFUEL MACHINE	C7	0	0	0	0	0.0	0.0
UNCLASSIFIED OTHER WORK	C8	77	5	3	33	15.4	13.0
MANOEUVRE	C9	243	13	3	54	18.7	12.9
SHARPEN OR REPAIR DE-BRANCHER KNIVES	D1	0	0	0	0	0.0	0.0
MINOR REPAIR	D2	0	0	0	0	0.0	0.0
REPAIR ROLLER CHAINS	D3	0	0	0	0	0.0	0.0
REPAIR	D4	0	0	0	0	0.0	0.0
PREPARE ROUTE	D5	533	12	8	147	44.4	47.4
REPAIR BASE UNIT TRACK & CHAIN	D6	0	0	0	0	0.0	0.0
STACK LOGS	D7	163	4	19	75	40.8	24.0
STACK 3M PULP	D8	0	0	0	0	0.0	0.0
STACK 2M PULP	D9	0	0	0	0	0.0	0.0
MOVE	A	2045	96	4	65	21.3	13.1
CONTINUATION OF MOVE	A1	0	0	0	0	0.0	0.0
TRIM BUTT	A3	791	127	1	59	6.2	6.9
FELL BRASHED TREE	B	0	0	0	0	0.0	0.0
FELL UNBRASHED TREE	C	3606	91	14	138	39.6	22.5
CONTINUATION OF FELL	D	0	0	0	0	0.0	0.0
PROCESS	E	2851	103	3	118	27.7	22.9
PROCESS LOG 495CM	E1	1608	146	3	43	11.0	5.4
PROCESS LOG 315CM	E2	729	65	4	40	11.2	5.3
PROCESS BAR 375CM	E3	167	18	5	15	9.3	3.3
PROCESS BAR 254CM	E4	297	29	3	21	10.2	4.7
PROCESS PULP 300CM	E5	933	104	3	22	9.0	3.8
PROCESS STAKE 172CM	E6	226	33	3	14	6.8	3.0
ASIDE AND CUT UP TOP	F	801	91	2	45	8.8	6.6
RE-PROCESS	G	284	23	2	55	12.3	13.2
FELL AND ASIDE UNMEASURABLE UNMARKETABLE TREE	A8	0	0	0	0	0.0	0.0

TOTAL CODE TIME (CENTIMIN)	19030
TIME ON (HR:MIN:CENTIMIN)	083960
TIME OFF (HR:MIN:CENTIMIN)	114990
TOTAL OBSERVED TIME (CENTIMIN)	19030

PLOT 5							
ACTIVITY	CODE	TOTAL TIME	NUMBER OF OCCURENCES	MIN	MAX	MEAN	STDEV
CLOCK READING	B1	0	0	0	0	0.0	0.0
GENERAL PREPARATION	B2	2285	1	2285	2285	2285.0	0.0
ON/OFF PROTECTIVE CLOTHING	B3	0	0	0	0	0.0	0.0
TO AND FROM CAMP	B4	468	2	83	385	234.0	213.5
PRODUCTS NOT STUDIED (PNS)	B5	0	0	0	0	0.0	0.0
FETCH TOOLS	B6	0	0	0	0	0.0	0.0
AVOIDABLE DELAY	B7	0	0	0	0	0.0	0.0
UNAVOIDABLE DELAY	B8	0	0	0	0	0.0	0.0
REST AND PERSONAL	B9	592	1	592	592	592.0	0.0
WAIT OR TALK WORK STUDY	C1	991	2	418	573	495.5	109.6
INSPECT AND CONSIDER	C2	493	14	5	167	35.2	43.9
MOVE BETWEEN RACKS OR DRIFTS	C3	1436	15	2	291	95.7	89.8
ASIDE BRASH	C4	0	0	0	0	0.0	0.0
SHARPEN OR REPLACE CROSS-CUTTING CHAIN	C5	1593	3	310	955	531.0	367.3
ROUTINE MAINTENANCE	C6	0	0	0	0	0.0	0.0
REFUEL MACHINE	C7	0	0	0	0	0.0	0.0
UNCLASSIFIED OTHER WORK	C8	77	5	5	23	15.4	7.0
MANOEUVRE	C9	518	24	6	83	21.6	16.6
SHARPEN OR REPAIR DE-BRANCHER KNIVES	D1	0	0	0	0	0.0	0.0
MINOR REPAIR	D2	0	0	0	0	0.0	0.0
REPAIR ROLLER CHAINS	D3	0	0	0	0	0.0	0.0
REPAIR	D4	0	0	0	0	0.0	0.0
PREPARE ROUTE	D5	506	25	3	85	20.2	18.2
REPAIR BASE UNIT TRACK & CHAIN	D6	0	0	0	0	0.0	0.0
STACK LOGS	D7	175	3	25	117	58.3	51.0
STACK 3M PULP	D8	0	0	0	0	0.0	0.0
STACK 2M PULP	D9	0	0	0	0	0.0	0.0
MOVE	A	2071	121	2	77	17.1	11.5
CONTINUATION OF MOVE	A1	0	0	0	0	0.0	0.0
TRIM BUTT	A3	651	136	1	32	4.8	4.8
FELL BRASHED TREE	B	0	0	0	0	0.0	0.0
FELL UNBRASHED TREE	C	4865	143	12	130	34.0	17.0
CONTINUATION OF FELL	D	0	0	0	0	0.0	0.0
PROCESS	E	3226	139	3	162	23.2	25.2
PROCESS LOG 495CM	E1	1151	103	4	61	11.2	6.5
PROCESS LOG 315CM	E2	1197	112	4	22	10.7	3.7
PROCESS BAR 375CM	E3	414	50	3	16	8.3	2.6
PROCESS BAR 254CM	E4	775	79	1	20	9.8	3.7
PROCESS PULP 300CM	E5	1771	191	1	44	9.3	6.0
PROCESS STAKE 172CM	E6	846	148	1	22	5.7	3.1
ASIDE AND CUT UP TOP	F	1186	143	3	20	8.3	3.4
RE-PROCESS	G	553	33	1	83	16.8	19.3
FELL AND ASIDE UNMEASURABLE UNMARKETABLE TREE	A8	60	2	18	42	30.0	17.0
TOTAL CODE TIME (CENTIMIN)		27900					

TIME ON (HR:MIN:CENTIMIN) 075826
TIME OFF (HR:MIN:CENTIMIN) 123726
TOTAL OBSERVED TIME (CENTIMIN) 27900

PLOT 6							
ACTIVITY	CODE	TOTAL TIME	NUMBER OF OCCURENCES	MIN	MAX	MEAN	STDEV
CLOCK READING	B1	0	0	0	0	0.0	0.0
GENERAL PREPARATION	B2	1932	1	1932	1932	1932.0	0.0
ON/OFF PROTECTIVE CLOTHING	B3	0	0	0	0	0.0	0.0
TO AND FROM CAMP	B4	625	2	60	565	312.5	357.1
PRODUCTS NOT STUDIED (PNS)	B5	0	0	0	0	0.0	0.0
FETCH TOOLS	B6	0	0	0	0	0.0	0.0
AVOIDABLE DELAY	B7	0	0	0	0	0.0	0.0
UNAVOIDABLE DELAY	B8	0	0	0	0	0.0	0.0
REST AND PERSONAL	B9	0	0	0	0	0.0	0.0
WAIT OR TALK WORK STUDY	C1	2338	6	95	788	389.7	313.6
INSPECT AND CONSIDER	C2	156	7	8	59	22.3	17.9
MOVE BETWEEN RACKS OR DRIFTS	C3	2143	10	17	429	214.3	134.6
ASIDE BRASH	C4	0	0	0	0	0.0	0.0
SHARPEN OR REPLACE CROSS-CUTTING CHAIN	C5	1060	2	462	598	530.0	96.2
ROUTINE MAINTENANCE	C6	0	0	0	0	0.0	0.0
REFUEL MACHINE	C7	105	1	105	105	105.0	0.0
UNCLASSIFIED OTHER WORK	C8	138	7	10	35	19.7	8.0
MANOEUVRE	C9	402	14	7	84	28.7	24.8
SHARPEN OR REPAIR DE-BRANCHER KNIVES	D1	0	0	0	0	0.0	0.0
MINOR REPAIR	D2	0	0	0	0	0.0	0.0
REPAIR ROLLER CHAINS	D3	0	0	0	0	0.0	0.0
REPAIR	D4	0	0	0	0	0.0	0.0
PREPARE ROUTE	D5	532	22	7	107	24.2	23.8
REPAIR BASE UNIT TRACK & CHAIN	D6	0	0	0	0	0.0	0.0
STACK LOGS	D7	53	2	20	33	26.5	9.2
STACK 3M PULP	D8	0	0	0	0	0.0	0.0
STACK 2M PULP	D9	0	0	0	0	0.0	0.0
MOVE	A	1503	106	1	80	14.2	12.4
CONTINUATION OF MOVE	A1	0	0	0	0	0.0	0.0
TRIM BUTT	A3	832	171	1	42	4.9	4.8
FELL BRASHED TREE	B	0	0	0	0	0.0	0.0
FELL UNBRASHED TREE	C	4507	119	17	80	37.9	13.2
CONTINUATION OF FELL	D	0	0	0	0	0.0	0.0
PROCESS	E	2564	153	2	88	16.8	11.5
PROCESS LOG 495CM	E1	1620	170	5	20	9.5	2.9
PROCESS LOG 315CM	E2	1136	114	3	25	10.0	3.6
PROCESS BAR 375CM	E3	410	45	5	15	9.1	2.6
PROCESS BAR 254CM	E4	660	71	3	28	9.3	3.6
PROCESS PULP 300CM	E5	1146	129	1	22	8.9	4.3
PROCESS STAKE 172CM	E6	628	106	1	18	5.9	3.1
ASIDE AND CUT UP TOP	F	1018	119	2	20	8.6	3.5
RE-PROCESS	G	144	15	2	23	9.6	6.8
FELL AND ASIDE UNMEASURABLE UNMARKETABLE TREE	A8	0	0	0	0	0.0	0.0
TOTAL CODE TIME (CENTIMIN)		25652					

TIME ON (HR:MIN:CENTIMIN)	080806
TIME OFF (HR:MIN:CENTIMIN)	122458
TOTAL OBSERVED TIME (CENTIMIN)	25652

PLOT 7							
ACTIVITY	CODE	TOTAL TIME	NUMBER OF OCCURENCES	MIN	MAX	MEAN	STDEV
CLOCK READING	B1	0	0	0	0	0.0	0.0
GENERAL PREPARATION	B2	597	1	597	597	597.0	0.0
ON/OFF PROTECTIVE CLOTHING	B3	0	0	0	0	0.0	0.0
TO AND FROM CAMP	B4	185	2	27	158	92.5	92.6
PRODUCTS NOT STUDIED (PNS)	B5	0	0	0	0	0.0	0.0
FETCH TOOLS	B6	0	0	0	0	0.0	0.0
AVOIDABLE DELAY	B7	0	0	0	0	0.0	0.0
UNAVOIDABLE DELAY	B8	0	0	0	0	0.0	0.0
REST AND PERSONAL	B9	4638	2	247	4391	2319.0	2930.3
WAIT OR TALK WORK STUDY	C1	14147	24	4	6485	589.5	1352.6
INSPECT AND CONSIDER	C2	997	43	3	70	23.2	17.1
MOVE BETWEEN RACKS OR DRIFTS	C3	1987	16	6	318	124.2	78.5
ASIDE BRASH	C4	0	0	0	0	0.0	0.0
SHARPEN OR REPLACE CROSS-CUTTING CHAIN	C5	1940	6	28	1190	323.3	457.8
ROUTINE MAINTENANCE	C6	3053	5	265	990	610.6	295.6
REFUEL MACHINE	C7	0	0	0	0	0.0	0.0
UNCLASSIFIED OTHER WORK	C8	2385	88	4	258	27.1	42.5
MANOEUVRE	C9	953	40	5	73	23.8	15.2
SHARPEN OR REPAIR DE-BRANCHER KNIVES	D1	0	0	0	0	0.0	0.0
MINOR REPAIR	D2	178	1	178	178	178.0	0.0
REPAIR ROLLER CHAINS	D3	0	0	0	0	0.0	0.0
REPAIR	D4	0	0	0	0	0.0	0.0
PREPARE ROUTE	D5	2693	100	5	147	26.9	21.7
REPAIR BASE UNIT TRACK & CHAIN	D6	0	0	0	0	0.0	0.0
STACK LOGS	D7	719	28	9	58	25.7	12.1
STACK 3M PULP	D8	0	0	0	0	0.0	0.0
STACK 2M PULP	D9	0	0	0	0	0.0	0.0
MOVE	A	2160	233	1	38	9.3	5.2
CONTINUATION OF MOVE	A1	0	0	0	0	0.0	0.0
TRIM BUTT	A3	3137	372	1	67	8.4	7.9
FELL BRASHED TREE	B	0	0	0	0	0.0	0.0
FELL UNBRASHED TREE	C	11407	338	9	165	33.7	17.8
CONTINUATION OF FELL	D	0	0	0	0	0.0	0.0
PROCESS	E	5918	306	3	95	19.3	14.3
PROCESS LOG 495CM	E1	7158	665	3	35	10.8	4.6
PROCESS LOG 315CM	E2	2461	236	3	37	10.4	5.1
PROCESS BAR 375CM	E3	1899	190	3	37	10.0	5.2
PROCESS BAR 254CM	E4	1993	189	2	31	10.5	5.1
PROCESS PULP 300CM	E5	1703	144	1	42	11.8	7.6
PROCESS STAKE 172CM	E6	3870	618	1	71	6.3	5.1
ASIDE AND CUT UP TOP	F	2515	338	1	25	7.4	3.3
RE-PROCESS	G	685	65	1	56	10.5	10.3
FELL AND ASIDE UNMEASURABLE UNMARKETABLE TREE	A8	831	30	3	55	27.7	14.9

TOTAL CODE TIME (CENTIMIN)	80209
TIME ON DAY 1 (HR:MIN:CENTIMIN)	075866
TIME OFF DAY 1 (HR:MIN:CENTIMIN)	171230
OBSERVED TIME DAY 1 (CENTIMIN)	55364
TIME ON DAY 2 (HR:MIN:CENTIMIN)	080033
TIME OFF DAY 2 (HR:MIN:CENTIMIN)	120878
OBSERVED TIME DAY 2 (CENTIMIN)	24845
TOTAL OBSERVED TIME (CENTIMIN)	80209

PLOT 8							
ACTIVITY	CODE	TOTAL TIME	NUMBER OF OCCURENCES	MIN	MAX	MEAN	STDEV
CLOCK READING	B1	0	0	0	0	0.0	0.0
GENERAL PREPARATION	B2	3440	1	3440	3440	3440.0	0.0
ON/OFF PROTECTIVE CLOTHING	B3	0	0	0	0	0.0	0.0
TO AND FROM CAMP	B4	376	2	183	193	188.0	7.1
PRODUCTS NOT STUDIED (PNS)	B5	0	0	0	0	0.0	0.0
FETCH TOOLS	B6	0	0	0	0	0.0	0.0
AVOIDABLE DELAY	B7	0	0	0	0	0.0	0.0
UNAVOIDABLE DELAY	B8	0	0	0	0	0.0	0.0
REST AND PERSONAL	B9	0	0	0	0	0.0	0.0
WAIT OR TALK WORK STUDY	C1	953	4	16	545	238.3	261.8
INSPECT AND CONSIDER	C2	240	13	5	52	18.5	12.5
MOVE BETWEEN RACKS OR DRIFTS	C3	1455	15	15	226	97.0	70.4
ASIDE BRASH	C4	0	0	0	0	0.0	0.0
SHARPEN OR REPLACE CROSS-CUTTING CHAIN	C5	0	0	0	0	0.0	0.0
ROUTINE MAINTENANCE	C6	0	0	0	0	0.0	0.0
REFUEL MACHINE	C7	0	0	0	0	0.0	0.0
UNCLASSIFIED OTHER WORK	C8	40	2	15	25	20.0	7.1
MANOEUVRE	C9	120	9	6	35	13.3	9.6
SHARPEN OR REPAIR DE-BRANCHER KNIVES	D1	0	0	0	0	0.0	0.0
MINOR REPAIR	D2	0	0	0	0	0.0	0.0
REPAIR ROLLER CHAINS	D3	0	0	0	0	0.0	0.0
REPAIR	D4	0	0	0	0	0.0	0.0
PREPARE ROUTE	D5	564	25	4	75	22.6	15.6
REPAIR BASE UNIT TRACK & CHAIN	D6	0	0	0	0	0.0	0.0
STACK LOGS	D7	53	3	15	20	17.7	2.5
STACK 3M PULP	D8	0	0	0	0	0.0	0.0
STACK 2M PULP	D9	0	0	0	0	0.0	0.0
MOVE	A	1752	88	3	88	19.9	13.9
CONTINUATION OF MOVE	A1	0	0	0	0	0.0	0.0
TRIM BUTT	A3	639	132	1	20	4.8	3.5
FELL BRASHED TREE	B	0	0	0	0	0.0	0.0
FELL UNBRASHED TREE	C	3225	82	15	143	39.3	17.3
CONTINUATION OF FELL	D	0	0	0	0	0.0	0.0
PROCESS	E	3850	117	5	123	32.9	24.0
PROCESS LOG 495CM	E1	1486	125	3	25	11.9	3.9
PROCESS LOG 315CM	E2	492	46	4	32	10.7	5.3
PROCESS BAR 375CM	E3	91	10	5	16	9.1	3.4
PROCESS BAR 254CM	E4	225	24	5	22	9.4	3.4
PROCESS PULP 300CM	E5	882	107	1	31	8.2	5.1
PROCESS STAKE 172CM	E6	113	13	3	29	8.7	6.7
ASIDE AND CUT UP TOP	F	695	82	1	55	8.5	6.6
RE-PROCESS	G	147	13	3	32	11.3	9.5
FELL AND ASIDE UNMEASURABLE UNMARKETABLE TREE	A8	12	1	12	12	12.0	0.0
TOTAL CODE TIME (CENTIMIN)		20850					

TIME ON (HR:MIN:CENTIMIN)	084573
TIME OFF (HR:MIN:CENTIMIN)	121423
TOTAL OBSERVED TIME (CENTIMIN)	20850

APPENDIX 24: Forwarder Element Summary

PLOT 1							
ACTIVITY	CODE	TOTAL TIME	NUMBER OF OCCURENCES	MIN	MAX	MEAN	STDEV
MOVE IN ROAD	A	1608	12	116	177	134.0	17.1
MOVE IN RIDE	B	1335	17	17	228	78.5	46.8
MOVE IN RACK	C	3440	85	8	204	40.5	39.0
MOVE IN WOOD	D	0	0	0	0	0.0	0.0
MOVE OUT WOOD	E	0	0	0	0	0.0	0.0
MOVE OUT RACK	F	4198	95	10	296	44.2	44.7
MOVE OUT RIDE	G	1611	17	33	148	94.8	43.3
MOVE OUT ROAD	H	2044	23	17	177	88.9	61.5
MOVE TO LOAD	J	0	0	0	0	0.0	0.0
MANOEUVRE IN WOOD	K	846	41	3	85	20.6	18.7
LOAD PRODUCT 1 (LOG 495CM)	L1	3971	115	8	62	34.5	11.5
LOAD PRODUCT 2 (LOG 315CM)	L2	1444	42	10	66	34.4	12.7
LOAD PRODUCT 3 (BAR 375CM)	L3	337	13	14	38	25.9	8.5
LOAD PRODUCT 4 (BAR 254CM)	L4	1015	37	12	53	27.4	7.8
LOAD PRODUCT 5 (PULP 300CM)	L5	1832	48	15	87	38.2	15.9
LOAD PRODUCT 6 (STAKE 172CM)	L6	1453	43	10	63	33.8	11.9
UNLOAD PRODUCT 1 (LOG 495CM)	U1	2474	86	11	50	28.8	6.9
UNLOAD PRODUCT 2 (LOG 315CM)	U2	721	25	15	52	28.8	8.3
UNLOAD PRODUCT 3 (BAR 375CM)	U3	237	7	18	53	33.9	10.5
UNLOAD PRODUCT 4 (BAR 254CM)	U4	296	10	17	48	29.6	8.8
UNLOAD PRODUCT 5 (PULP 300CM)	U5	631	20	20	65	31.6	10.6
UNLOAD PRODUCT 6 (STAKE 172CM)	U6	220	9	10	42	24.4	10.9
MOVE TO UNLOAD	A2	131	6	16	30	21.8	4.7
MANOEUVRE ON ROAD	A3	0	0	0	0	0.0	0.0
STACK	A5	363	20	5	38	18.2	9.9
STOW / UNSTOW GRAPPLE	A6	555	37	4	50	15.0	9.7
ADJUST LOAD	A8	657	56	3	48	11.7	8.1
GRADE LOGS AT UNLOADING	A9	0	0	0	0	0.0	0.0
CLOCK READING	B1	0	0	0	0	0.0	0.0
GENERAL PREPARATION	B2	0	0	0	0	0.0	0.0
ON / OFF PROTECTIVE CLOTHING	B3	0	0	0	0	0.0	0.0
TO / FROM CAMP	B4	0	0	0	0	0.0	0.0
FETCH TOOLS	B6	0	0	0	0	0.0	0.0
AVOIDABLE DELAY	B7	11	1	11	11	11.0	0.0
UNAVOIDABLE DELAY	B8	497	8	6	112	62.1	44.9
REST AND PERSONAL	B9	5161	2	214	4947	2580.5	3346.7
WAIT OR TALK WORK STUDY	C1	515	3	78	295	171.7	111.5
INSPECT	C2	273	20	3	35	13.7	8.4
COUNT / CHECK	C3	0	0	0	0	0.0	0.0
ASIDE BRASH	C4	48	4	6	17	12.0	5.0
START MACHINE	C5	82	2	12	70	41.0	41.0
MAINTENANCE	C6	713	4	30	353	178.3	160.3
REFUEL	C7	443	1	443	443	443.0	0.0
FIT / REMOVE CHAINS AND TRACKS	C8	0	0	0	0	0.0	0.0
DEBOG	C9	0	0	0	0	0.0	0.0
ASIDE PRODUCE TO TRAVEL	D1	0	0	0	0	0.0	0.0
ASIDE PRODUCE TO LOAD	D2	3008	108	5	64	27.9	14.0
MOVE HEADBOARD / BOLSTERS	D3	0	0	0	0	0.0	0.0
PREPARE STACKING AREA	D4	239	5	21	79	47.8	27.9
PREPARE ROUTE	D5	2055	12	5	577	171.3	184.8
TRAVEL BETWEEN WORKSITES	D6	0	0	0	0	0.0	0.0
TRAVEL TO / FROM WORKSITE	D7	0	0	0	0	0.0	0.0
WET TIME	D8	0	0	0	0	0.0	0.0
UNPAID MEALBREAKS	D9	0	0	0	0	0.0	0.0
PERIOD NOT STUDIED (PNS)	F9	0	0	0	0	0.0	0.0
TOTAL CODE TIME (CENTIMIN)		44464					

TIME ON (HR:MIN:CENTIMIN) day 1	153101
TIME OFF (HR:MIN:CENTIMIN) day 1	170170
TIME ON (HR:MIN:CENTIMIN) day 2	080761
TIME OFF (HR:MIN:CENTIMIN) day 2	140156
TOTAL OBSERVED TIME (CENTIMIN)	44464

PLOT 2							
ACTIVITY	CODE	TOTAL TIME	NUMBER OF OCCURENCES	MIN	MAX	MEAN	STDEV
MOVE IN ROAD	A	2164	17	65	180	127.3	30.9
MOVE IN RIDE	B	1501	18	25	283	83.4	69.8
MOVE IN RACK	C	3154	96	6	148	32.9	26.8
MOVE IN WOOD	D	0	0	0	0	0.0	0.0
MOVE OUT WOOD	E	0	0	0	0	0.0	0.0
MOVE OUT RACK	F	3671	102	8	152	36.0	28.1
MOVE OUT RIDE	G	1785	20	21	365	89.3	90.9
MOVE OUT ROAD	H	2279	32	15	182	71.2	52.2
MOVE TO LOAD	J	0	0	0	0	0.0	0.0
MANOEUVRE IN WOOD	K	269	18	3	33	14.9	7.1
LOAD PRODUCT 1 (LOG 495CM)	L1	4213	110	19	86	38.3	12.3
LOAD PRODUCT 2 (LOG 315CM)	L2	1724	50	13	62	34.5	10.6
LOAD PRODUCT 3 (BAR 375CM)	L3	1308	41	10	82	31.9	13.9
LOAD PRODUCT 4 (BAR 254CM)	L4	1093	35	12	58	31.2	12.6
LOAD PRODUCT 5 (PULP 300CM)	L5	1284	34	15	79	37.8	15.7
LOAD PRODUCT 6 (STAKE 172CM)	L6	1538	38	19	83	40.5	15.8
UNLOAD PRODUCT 1 (LOG 495CM)	U1	2137	74	15	61	28.9	7.9
UNLOAD PRODUCT 2 (LOG 315CM)	U2	767	25	14	50	30.7	9.3
UNLOAD PRODUCT 3 (BAR 375CM)	U3	512	18	17	41	28.4	7.0
UNLOAD PRODUCT 4 (BAR 254CM)	U4	315	12	14	38	26.3	6.2
UNLOAD PRODUCT 5 (PULP 300CM)	U5	542	18	11	53	30.1	8.9
UNLOAD PRODUCT 6 (STAKE 172CM)	U6	398	13	8	43	30.6	11.2
MOVE TO UNLOAD	A2	330	14	10	45	23.6	8.8
MANOEUVRE ON ROAD	A3	0	0	0	0	0.0	0.0
STACK	A5	621	39	3	48	15.9	9.0
STOW / UNSTOW GRAPPLE	A6	714	37	4	65	19.3	12.2
ADJUST LOAD	A8	1150	62	3	100	18.5	14.7
GRADE LOGS AT UNLOADING	A9	0	0	0	0	0.0	0.0
CLOCK READING	B1	0	0	0	0	0.0	0.0
GENERAL PREPARATION	B2	0	0	0	0	0.0	0.0
ON / OFF PROTECTIVE CLOTHING	B3	0	0	0	0	0.0	0.0
TO / FROM CAMP	B4	0	0	0	0	0.0	0.0
FETCH TOOLS	B6	0	0	0	0	0.0	0.0
AVOIDABLE DELAY	B7	0	0	0	0	0.0	0.0
UNAVOIDABLE DELAY	B8	8612	13	22	3586	662.5	1239.5
REST AND PERSONAL	B9	3928	2	390	3538	1964.0	2226.0
WAIT OR TALK WORK STUDY	C1	68	1	68	68	68.0	0.0
INSPECT	C2	451	25	2	77	18.0	19.9
COUNT / CHECK	C3	0	0	0	0	0.0	0.0
ASIDE BRASH	C4	186	11	5	40	16.9	11.0
START MACHINE	C5	133	3	34	54	44.3	10.0
MAINTENANCE	C6	1092	5	18	442	218.4	163.3
REFUEL	C7	0	0	0	0	0.0	0.0
FIT / REMOVE CHAINS AND TRACKS	C8	0	0	0	0	0.0	0.0
DEBOG	C9	0	0	0	0	0.0	0.0
ASIDE PRODUCE TO TRAVEL	D1	0	0	0	0	0.0	0.0
ASIDE PRODUCE TO LOAD	D2	2610	88	6	88	29.7	16.8
MOVE HEADBOARD / BOLSTERS	D3	0	0	0	0	0.0	0.0
PREPARE STACKING AREA	D4	0	0	0	0	0.0	0.0
PREPARE ROUTE	D5	216	5	11	90	43.2	29.3
TRAVEL BETWEEN WORKSITES	D6	0	0	0	0	0.0	0.0
TRAVEL TO / FROM WORKSITE	D7	0	0	0	0	0.0	0.0
WET TIME	D8	0	0	0	0	0.0	0.0
UNPAID MEALBREAKS	D9	0	0	0	0	0.0	0.0
PERIOD NOT STUDIED (PNS)	F9	0	0	0	0	0.0	0.0
TOTAL CODE TIME (CENTIMIN)		50765					

TIME ON (HR:MIN:CENTIMIN) day 1	140340
TIME OFF (HR:MIN:CENTIMIN) day 1	170075
TIME ON (HR:MIN:CENTIMIN) day 2	75406
TIME OFF (HR:MIN:CENTIMIN) day 2	132436
TOTAL OBSERVED TIME (CENTIMIN)	50765

PLOT 3							
ACTIVITY	CODE	TOTAL TIME	NUMBER OF OCCURENCES	MIN	MAX	MEAN	STDEV
MOVE IN ROAD	A	1879	17	45	235	110.5	46.1
MOVE IN RIDE	B	1059	18	14	167	58.8	42.8
MOVE IN RACK	C	3715	119	6	135	31.2	22.4
MOVE IN WOOD	D	0	0	0	0	0.0	0.0
MOVE OUT WOOD	E	0	0	0	0	0.0	0.0
MOVE OUT RACK	F	4865	122	7	383	39.9	39.9
MOVE OUT RIDE	G	1319	15	18	188	87.9	50.5
MOVE OUT ROAD	H	2010	36	15	130	55.8	31.3
MOVE TO LOAD	J	0	0	0	0	0.0	0.0
MANOEUVRE IN WOOD	K	167	11	2	38	15.2	12.5
LOAD PRODUCT 1 (LOG 495CM)	L1	2811	69	14	123	40.7	17.1
LOAD PRODUCT 2 (LOG 315CM)	L2	2168	60	15	62	36.1	9.6
LOAD PRODUCT 3 (BAR 375CM)	L3	2495	72	12	79	34.7	11.5
LOAD PRODUCT 4 (BAR 254CM)	L4	1809	56	8	72	32.3	11.8
LOAD PRODUCT 5 (PULP 300CM)	L5	1738	44	17	70	39.5	14.4
LOAD PRODUCT 6 (STAKE 172CM)	L6	3253	74	20	76	44.0	12.6
UNLOAD PRODUCT 1 (LOG 495CM)	U1	1345	46	11	46	29.2	8.5
UNLOAD PRODUCT 2 (LOG 315CM)	U2	763	28	13	45	27.3	8.4
UNLOAD PRODUCT 3 (BAR 375CM)	U3	1029	35	13	46	29.4	8.5
UNLOAD PRODUCT 4 (BAR 254CM)	U4	319	13	13	35	24.5	7.0
UNLOAD PRODUCT 5 (PULP 300CM)	U5	658	21	17	72	31.3	11.5
UNLOAD PRODUCT 6 (STAKE 172CM)	U6	708	27	15	42	26.2	5.8
MOVE TO UNLOAD	A2	577	19	10	57	30.4	11.5
MANOEUVRE ON ROAD	A3	0	0	0	0	0.0	0.0
STACK	A5	913	52	5	68	17.6	11.4
STOW / UNSTOW GRAPPLE	A6	532	29	4	56	18.3	12.1
ADJUST LOAD	A8	2082	94	3	122	22.1	21.3
GRADE LOGS AT UNLOADING	A9	0	0	0	0	0.0	0.0
CLOCK READING	B1	0	0	0	0	0.0	0.0
GENERAL PREPARATION	B2	314	5	16	202	62.8	78.5
ON / OFF PROTECTIVE CLOTHING	B3	0	0	0	0	0.0	0.0
TO / FROM CAMP	B4	0	0	0	0	0.0	0.0
FETCH TOOLS	B6	0	0	0	0	0.0	0.0
AVOIDABLE DELAY	B7	0	0	0	0	0.0	0.0
UNAVOIDABLE DELAY	B8	712	12	8	144	59.3	43.7
REST AND PERSONAL	B9	875	2	140	735	437.5	420.7
WAIT OR TALK WORK STUDY	C1	1446	5	23	578	289.2	205.1
INSPECT	C2	353	25	3	53	14.1	12.5
COUNT / CHECK	C3	0	0	0	0	0.0	0.0
ASIDE BRASH	C4	148	9	5	25	16.4	7.1
START MACHINE	C5	154	4	20	53	38.5	16.6
MAINTENANCE	C6	408	2	8	400	204.0	277.2
REFUEL	C7	650	1	650	650	650.0	0.0
FIT / REMOVE CHAINS AND TRACKS	C8	14577	1	14577	14577	14577.0	0.0
DEBOG	C9	1821	4	35	1488	455.3	691.1
ASIDE PRODUCE TO TRAVEL	D1	0	0	0	0	0.0	0.0
ASIDE PRODUCE TO LOAD	D2	2721	84	3	186	32.4	25.9
MOVE HEADBOARD / BOLSTERS	D3	426	4	25	287	106.5	123.7
PREPARE STACKING AREA	D4	0	0	0	0	0.0	0.0
PREPARE ROUTE	D5	352	7	21	126	50.3	37.2
TRAVEL BETWEEN WORKSITES	D6	0	0	0	0	0.0	0.0
TRAVEL TO / FROM WORKSITE	D7	0	0	0	0	0.0	0.0
WET TIME	D8	0	0	0	0	0.0	0.0
UNPAID MEALBREAKS	D9	0	0	0	0	0.0	0.0
PERIOD NOT STUDIED (PNS)	F9	0	0	0	0	0.0	0.0
TOTAL CODE TIME (CENTIMIN)		63171					

TIME ON (HR:MIN:CENTIMIN) day 1	132655
TIME OFF (HR:MIN:CENTIMIN) day 1	170598
TIME ON (HR:MIN:CENTIMIN) day 2	81188
TIME OFF (HR:MIN:CENTIMIN) day 2	130208
TIME ON (HR:MIN:CENTIMIN) day 3	75738
TIME OFF (HR:MIN:CENTIMIN) day 3	95946
TOTAL OBSERVED TIME (CENTIMIN)	63171

PLOT 4							
ACTIVITY	CODE	TOTAL TIME	NUMBER OF OCCURENCES	MIN	MAX	MEAN	STDEV
MOVE IN ROAD	A	1461	12	40	392	121.8	91.4
MOVE IN RIDE	B	672	12	12	100	56.0	29.0
MOVE IN RACK	C	2404	74	8	111	32.5	20.2
MOVE IN WOOD	D	0	0	0	0	0.0	0.0
MOVE OUT WOOD	E	0	0	0	0	0.0	0.0
MOVE OUT RACK	F	2754	88	10	72	31.3	12.3
MOVE OUT RIDE	G	414	12	12	60	34.5	15.7
MOVE OUT ROAD	H	1665	25	11	150	66.6	43.4
MOVE TO LOAD	J	0	0	0	0	0.0	0.0
MANOEUVRE IN WOOD	K	32	2	7	25	16.0	12.7
LOAD PRODUCT 1 (LOG 495CM)	L1	3693	100	11	83	36.9	12.8
LOAD PRODUCT 2 (LOG 315CM)	L2	926	31	13	55	29.9	11.8
LOAD PRODUCT 3 (BAR 375CM)	L3	354	14	12	36	25.3	6.0
LOAD PRODUCT 4 (BAR 254CM)	L4	598	26	10	35	23.0	6.0
LOAD PRODUCT 5 (PULP 300CM)	L5	1494	46	11	78	32.5	14.7
LOAD PRODUCT 6 (STAKE 172CM)	L6	420	17	5	45	24.7	9.9
UNLOAD PRODUCT 1 (LOG 495CM)	U1	2268	78	11	49	29.1	6.6
UNLOAD PRODUCT 2 (LOG 315CM)	U2	435	16	12	45	27.2	7.8
UNLOAD PRODUCT 3 (BAR 375CM)	U3	142	6	15	38	23.7	9.8
UNLOAD PRODUCT 4 (BAR 254CM)	U4	176	6	15	40	29.3	8.6
UNLOAD PRODUCT 5 (PULP 300CM)	U5	553	20	10	43	27.7	8.0
UNLOAD PRODUCT 6 (STAKE 172CM)	U6	164	6	10	40	27.3	11.2
MOVE TO UNLOAD	A2	147	4	21	63	36.8	18.4
MANOEUVRE ON ROAD	A3	0	0	0	0	0.0	0.0
STACK	A5	383	22	5	70	17.4	15.2
STOW / UNSTOW GRAPPLE	A6	284	15	6	57	18.9	16.3
ADJUST LOAD	A8	309	26	3	35	11.9	8.2
GRADE LOGS AT UNLOADING	A9	0	0	0	0	0.0	0.0
CLOCK READING	B1	0	0	0	0	0.0	0.0
GENERAL PREPARATION	B2	160	2	15	145	80.0	91.9
ON / OFF PROTECTIVE CLOTHING	B3	0	0	0	0	0.0	0.0
TO / FROM CAMP	B4	0	0	0	0	0.0	0.0
FETCH TOOLS	B6	0	0	0	0	0.0	0.0
AVOIDABLE DELAY	B7	0	0	0	0	0.0	0.0
UNAVOIDABLE DELAY	B8	1174	4	8	1077	293.5	522.7
REST AND PERSONAL	B9	5556	1	5556	5556	5556.0	0.0
WAIT OR TALK WORK STUDY	C1	97	1	97	97	97.0	0.0
INSPECT	C2	117	5	4	91	23.4	37.9
COUNT / CHECK	C3	0	0	0	0	0.0	0.0
ASIDE BRASH	C4	36	3	10	16	12.0	3.5
START MACHINE	C5	22	1	22	22	22.0	0.0
MAINTENANCE	C6	0	0	0	0	0.0	0.0
REFUEL	C7	0	0	0	0	0.0	0.0
FIT / REMOVE CHAINS AND TRACKS	C8	0	0	0	0	0.0	0.0
DEBOG	C9	0	0	0	0	0.0	0.0
ASIDE PRODUCE TO TRAVEL	D1	60	4	8	27	15.0	8.3
ASIDE PRODUCE TO LOAD	D2	1253	48	6	75	26.1	12.1
MOVE HEADBOARD / BOLSTERS	D3	25	1	25	25	25.0	0.0
PREPARE STACKING AREA	D4	50	2	15	35	25.0	14.1
PREPARE ROUTE	D5	310	5	30	85	62.0	21.6
TRAVEL BETWEEN WORKSITES	D6	0	0	0	0	0.0	0.0
TRAVEL TO / FROM WORKSITE	D7	0	0	0	0	0.0	0.0
WET TIME	D8	0	0	0	0	0.0	0.0
UNPAID MEALBREAKS	D9	0	0	0	0	0.0	0.0
PERIOD NOT STUDIED (PNS)	F9	0	0	0	0	0.0	0.0
TOTAL CODE TIME (CENTIMIN)		30608					

TOTAL CODE TIME (CENTIMIN) 30608 appears above as the table's final row.

TIME ON (HR:MIN:CENTIMIN)	090638
TIME OFF (HR:MIN:CENTIMIN)	141246
TOTAL OBSERVED TIME (CENTIMIN)	30608

PLOT 5							
ACTIVITY	CODE	TOTAL TIME	NUMBER OF OCCURENCES	MIN	MAX	MEAN	STDEV
MOVE IN ROAD	A	4034	15	25	445	268.9	165.2
MOVE IN RIDE	B	640	12	10	97	53.3	24.8
MOVE IN RACK	C	3464	122	8	87	28.4	17.3
MOVE IN WOOD	D	0	0	0	0	0.0	0.0
MOVE OUT WOOD	E	0	0	0	0	0.0	0.0
MOVE OUT RACK	F	3479	117	5	119	29.7	19.5
MOVE OUT RIDE	G	367	11	21	53	33.4	11.5
MOVE OUT ROAD	H	5300	23	10	557	230.4	248.4
MOVE TO LOAD	J	0	0	0	0	0.0	0.0
MANOEUVRE IN WOOD	K	50	3	7	28	16.7	10.6
LOAD PRODUCT 1 (LOG 495CM)	L1	2490	71	9	69	35.1	11.4
LOAD PRODUCT 2 (LOG 315CM)	L2	1725	54	8	59	31.9	11.9
LOAD PRODUCT 3 (BAR 375CM)	L3	428	16	12	40	26.8	7.2
LOAD PRODUCT 4 (BAR 254CM)	L4	1219	46	12	54	26.5	10.2
LOAD PRODUCT 5 (PULP 300CM)	L5	1986	68	9	72	29.2	11.9
LOAD PRODUCT 6 (STAKE 172CM)	L6	1291	42	10	64	30.7	13.6
UNLOAD PRODUCT 1 (LOG 495CM)	U1	1457	49	8	58	29.7	7.8
UNLOAD PRODUCT 2 (LOG 315CM)	U2	781	24	21	55	32.5	8.4
UNLOAD PRODUCT 3 (BAR 375CM)	U3	307	10	16	44	30.7	7.3
UNLOAD PRODUCT 4 (BAR 254CM)	U4	353	13	14	40	27.2	7.3
UNLOAD PRODUCT 5 (PULP 300CM)	U5	771	28	20	36	27.5	4.2
UNLOAD PRODUCT 6 (STAKE 172CM)	U6	350	11	21	52	31.8	8.0
MOVE TO UNLOAD	A2	96	5	15	21	19.2	2.5
MANOEUVRE ON ROAD	A3	0	0	0	0	0.0	0.0
STACK	A5	707	45	4	62	15.7	10.0
STOW / UNSTOW GRAPPLE	A6	380	22	3	35	17.3	8.1
ADJUST LOAD	A8	524	47	3	55	11.1	9.3
GRADE LOGS AT UNLOADING	A9	0	0	0	0	0.0	0.0
CLOCK READING	B1	0	0	0	0	0.0	0.0
GENERAL PREPARATION	B2	1106	3	78	793	368.7	375.8
ON / OFF PROTECTIVE CLOTHING	B3	0	0	0	0	0.0	0.0
TO / FROM CAMP	B4	0	0	0	0	0.0	0.0
FETCH TOOLS	B6	0	0	0	0	0.0	0.0
AVOIDABLE DELAY	B7	0	0	0	0	0.0	0.0
UNAVOIDABLE DELAY	B8	46	1	46	46	46.0	0.0
REST AND PERSONAL	B9	3851	3	55	3688	1283.7	2082.4
WAIT OR TALK WORK STUDY	C1	60	1	60	60	60.0	
INSPECT	C2	76	7	5	20	10.9	6.2
COUNT / CHECK	C3	0	0	0	0	0.0	0.0
ASIDE BRASH	C4	49	2	16	33	24.5	12.0
START MACHINE	C5	52	2	22	30	26.0	5.7
MAINTENANCE	C6	0	0	0	0	0.0	0.0
REFUEL	C7	0	0	0	0	0.0	0.0
FIT / REMOVE CHAINS AND TRACKS	C8	0	0	0	0	0.0	0.0
DEBOG	C9	0	0	0	0	0.0	0.0
ASIDE PRODUCE TO TRAVEL	D1	46	3	13	18	15.3	2.5
ASIDE PRODUCE TO LOAD	D2	2868	108	6	80	26.6	13.3
MOVE HEADBOARD / BOLSTERS	D3	20	1	20	20	20.0	0.0
PREPARE STACKING AREA	D4	0	0	0	0	0.0	0.0
PREPARE ROUTE	D5	832	11	7	168	75.6	57.8
TRAVEL BETWEEN WORKSITES	D6	0	0	0	0	0.0	0.0
TRAVEL TO / FROM WORKSITE	D7	0	0	0	0	0.0	0.0
WET TIME	D8	0	0	0	0	0.0	0.0
UNPAID MEALBREAKS	D9	0	0	0	0	0.0	0.0
PERIOD NOT STUDIED (PNS)	F9	0	0	0	0	0.0	0.0
TOTAL CODE TIME (CENTIMIN)		41205					

TIME ON (HR:MIN:CENTIMIN) 081670
TIME OFF (HR:MIN:CENTIMIN) 150875
TOTAL OBSERVED TIME (CENTIMIN) 41205

PLOT 6							
ACTIVITY	CODE	TOTAL TIME	NUMBER OF OCCURENCES	MIN	MAX	MEAN	STDEV
MOVE IN ROAD	A	4894	21	13	522	233.0	202.3
MOVE IN RIDE	B	792	16	18	96	49.5	23.7
MOVE IN RACK	C	2767	91	7	182	30.4	24.4
MOVE IN WOOD	D	0	0	0	0	0.0	0.0
MOVE OUT WOOD	E	0	0	0	0	0.0	0.0
MOVE OUT RACK	F	3020	101	7	160	29.9	24.1
MOVE OUT RIDE	G	906	17	22	103	53.3	23.5
MOVE OUT ROAD	H	7314	38	10	695	192.5	265.3
MOVE TO LOAD	J	0	0	0	0	0.0	0.0
MANOEUVRE IN WOOD	K	34	2	11	23	17.0	8.5
LOAD PRODUCT 1 (LOG 495CM)	L1	3915	108	13	75	36.3	11.7
LOAD PRODUCT 2 (LOG 315CM)	L2	1516	45	15	77	33.7	12.3
LOAD PRODUCT 3 (BAR 375CM)	L3	445	16	17	53	27.8	9.2
LOAD PRODUCT 4 (BAR 254CM)	L4	1026	39	8	60	26.3	10.5
LOAD PRODUCT 5 (PULP 300CM)	L5	1424	43	10	62	33.1	13.2
LOAD PRODUCT 6 (STAKE 172CM)	L6	1119	37	11	69	30.2	13.4
UNLOAD PRODUCT 1 (LOG 495CM)	U1	2393	83	10	50	28.8	6.9
UNLOAD PRODUCT 2 (LOG 315CM)	U2	781	27	17	46	28.9	7.3
UNLOAD PRODUCT 3 (BAR 375CM)	U3	299	9	19	56	33.2	11.4
UNLOAD PRODUCT 4 (BAR 254CM)	U4	388	12	20	64	32.3	12.5
UNLOAD PRODUCT 5 (PULP 300CM)	U5	526	19	17	40	27.7	6.9
UNLOAD PRODUCT 6 (STAKE 172CM)	U6	268	9	21	47	29.8	9.2
MOVE TO UNLOAD	A2	205	8	17	47	25.6	9.4
MANOEUVRE ON ROAD	A3	0	0	0	0	0.0	0.0
STACK	A5	480	35	3	35	13.7	6.2
STOW / UNSTOW GRAPPLE	A6	416	24	7	40	17.3	8.3
ADJUST LOAD	A8	947	52	3	71	18.2	14.2
GRADE LOGS AT UNLOADING	A9	0	0	0	0	0.0	0.0
CLOCK READING	B1	0	0	0	0	0.0	0.0
GENERAL PREPARATION	B2	0	0	0	0	0.0	0.0
ON / OFF PROTECTIVE CLOTHING	B3	0	0	0	0	0.0	0.0
TO / FROM CAMP	B4	0	0	0	0	0.0	0.0
FETCH TOOLS	B6	0	0	0	0	0.0	0.0
AVOIDABLE DELAY	B7	0	0	0	0	0.0	0.0
UNAVOIDABLE DELAY	B8	867	14	21	120	61.9	31.1
REST AND PERSONAL	B9	5028	2	140	4888	2514.0	3357.3
WAIT OR TALK WORK STUDY	C1	441	2	127	314	220.5	132.2
INSPECT	C2	140	13	3	27	10.8	8.7
COUNT / CHECK	C3	0	0	0	0	0.0	0.0
ASIDE BRASH	C4	27	1	27	27	27.0	0.0
START MACHINE	C5	29	2	3	26	14.5	16.3
MAINTENANCE	C6	0	0	0	0	0.0	0.0
REFUEL	C7	520	1	520	520	520.0	0.0
FIT / REMOVE CHAINS AND TRACKS	C8	0	0	0	0	0.0	0.0
DEBOG	C9	0	0	0	0	0.0	0.0
ASIDE PRODUCE TO TRAVEL	D1	139	7	5	43	19.9	14.8
ASIDE PRODUCE TO LOAD	D2	3025	116	5	62	26.1	12.3
MOVE HEADBOARD / BOLSTERS	D3	0	0	0	0	0.0	0.0
PREPARE STACKING AREA	D4	148	3	28	90	49.3	35.2
PREPARE ROUTE	D5	193	6	8	59	32.2	22.2
TRAVEL BETWEEN WORKSITES	D6	0	0	0	0	0.0	0.0
TRAVEL TO / FROM WORKSITE	D7	0	0	0	0	0.0	0.0
WET TIME	D8	0	0	0	0	0.0	0.0
UNPAID MEALBREAKS	D9	0	0	0	0	0.0	0.0
PERIOD NOT STUDIED (PNS)	F9	0	0	0	0	0.0	0.0
TOTAL CODE TIME (CENTIMIN)		46432					

TIME ON (HR:MIN:CENTIMIN)	082523
TIME OFF (HR:MIN:CENTIMIN)	160955
TOTAL OBSERVED TIME (CENTIMIN)	46432

PLOT 7							
ACTIVITY	CODE	TOTAL TIME	NUMBER OF OCCURENCES	MIN	MAX	MEAN	STDEV
MOVE IN ROAD	A	2766	45	11	131	61.5	25.0
MOVE IN RIDE	B	2736	43	14	135	63.6	19.3
MOVE IN RACK	C	10782	242	7	237	44.6	45.0
MOVE IN WOOD	D	0	0	0	0	0.0	0.0
MOVE OUT WOOD	E	0	0	0	0	0.0	0.0
MOVE OUT RACK	F	11089	228	4	269	48.6	52.9
MOVE OUT RIDE	G	3293	41	26	110	80.3	17.0
MOVE OUT ROAD	H	4086	44	21	150	92.9	26.6
MOVE TO LOAD	J	0	0	0	0	0.0	0.0
MANOEUVRE IN WOOD	K	968	39	3	88	24.8	21.3
LOAD PRODUCT 1 (LOG 495CM)	L1	16021	525	9	68	30.5	10.3
LOAD PRODUCT 2 (LOG 315CM)	L2	3369	107	8	112	31.5	13.4
LOAD PRODUCT 3 (BAR 375CM)	L3	2520	79	8	75	31.9	14.1
LOAD PRODUCT 4 (BAR 254CM)	L4	2422	83	10	64	29.2	11.2
LOAD PRODUCT 5 (PULP 300CM)	L5	1458	51	13	58	28.6	11.1
LOAD PRODUCT 6 (STAKE 172CM)	L6	3518	102	11	63	34.5	12.3
UNLOAD PRODUCT 1 (LOG 495CM)	U1	9851	352	7	58	28.0	7.2
UNLOAD PRODUCT 2 (LOG 315CM)	U2	1647	63	3	58	26.1	10.0
UNLOAD PRODUCT 3 (BAR 375CM)	U3	976	32	12	115	30.5	17.2
UNLOAD PRODUCT 4 (BAR 254CM)	U4	702	29	13	36	24.2	6.1
UNLOAD PRODUCT 5 (PULP 300CM)	U5	799	30	9	42	26.6	7.7
UNLOAD PRODUCT 6 (STAKE 172CM)	U6	1213	45	13	63	27.0	8.7
MOVE TO UNLOAD	A2	2197	55	10	80	39.9	20.1
MANOEUVRE ON ROAD	A3	34	2	16	18	17.0	1.4
STACK	A5	1916	111	3	90	17.3	15.3
STOW / UNSTOW GRAPPLE	A6	1308	100	3	57	13.1	8.3
ADJUST LOAD	A8	2097	152	1	106	13.8	11.9
GRADE LOGS AT UNLOADING	A9	0	0	0	0	0.0	0.0
CLOCK READING	B1	0	0	0	0	0.0	0.0
GENERAL PREPARATION	B2	0	0	0	0	0.0	0.0
ON / OFF PROTECTIVE CLOTHING	B3	0	0	0	0	0.0	0.0
TO / FROM CAMP	B4	0	0	0	0	0.0	0.0
FETCH TOOLS	B6	0	0	0	0	0.0	0.0
AVOIDABLE DELAY	B7	1705	2	165	1540	852.5	972.3
UNAVOIDABLE DELAY	B8	1283	19	8	190	67.5	52.8
REST AND PERSONAL	B9	8434	8	5	3260	1054.3	1245.7
WAIT OR TALK WORK STUDY	C1	3161	5	74	2176	632.2	882.2
INSPECT	C2	721	42	2	108	17.2	20.6
COUNT / CHECK	C3	0	0	0	0	0.0	0.0
ASIDE BRASH	C4	272	17	5	33	16.0	7.6
START MACHINE	C5	260	7	18	65	37.1	18.9
MAINTENANCE	C6	4107	12	10	2009	342.3	543.3
REFUEL	C7	1253	3	206	570	417.7	189.1
FIT / REMOVE CHAINS AND TRACKS	C8	0	0	0	0	0.0	0.0
DEBOG	C9	0	0	0	0	0.0	0.0
ASIDE PRODUCE TO TRAVEL	D1	516	22	6	42	23.5	9.9
ASIDE PRODUCE TO LOAD	D2	5381	201	8	77	26.8	13.0
MOVE HEADBOARD / BOLSTERS	D3	0	0	0	0	0.0	0.0
PREPARE STACKING AREA	D4	54	2	13	41	27.0	19.8
PREPARE ROUTE	D5	7542	81	3	409	93.1	85.7
TRAVEL BETWEEN WORKSITES	D6	0	0	0	0	0.0	0.0
TRAVEL TO / FROM WORKSITE	D7	0	0	0	0	0.0	0.0
WET TIME	D8	0	0	0	0	0.0	0.0
UNPAID MEALBREAKS	D9	0	0	0	0	0.0	0.0
PERIOD NOT STUDIED (PNS)	F9	0	0	0	0	0.0	0.0
TOTAL CODE TIME (CENTIMIN)		122457					

TIME ON (HR:MIN:CENTIMIN) day 1	141198
TIME OFF (HR:MIN:CENTIMIN) day 1	172125
TIME ON (HR:MIN:CENTIMIN) day 2	80221
TIME OFF (HR:MIN:CENTIMIN) day 2	163946
TIME ON (HR:MIN:CENTIMIN) day 3	75626
TIME OFF (HR:MIN:CENTIMIN) day 3	163431
TOTAL OBSERVED TIME (CENTIMIN)	122457

PLOT 8							
ACTIVITY	CODE	TOTAL TIME	NUMBER OF OCCURENCES	MIN	MAX	MEAN	STDEV
MOVE IN ROAD	A	659	9	50	152	73.2	35.6
MOVE IN RIDE	B	1988	9	91	275	220.9	53.9
MOVE IN RACK	C	2859	60	10	194	47.7	37.5
MOVE IN WOOD	D	0	0	0	0	0.0	0.0
MOVE OUT WOOD	E	0	0	0	0	0.0	0.0
MOVE OUT RACK	F	2554	76	7	122	33.6	24.3
MOVE OUT RIDE	G	2394	12	12	310	199.5	134.6
MOVE OUT ROAD	H	832	25	7	103	33.3	17.8
MOVE TO LOAD	J	0	0	0	0	0.0	0.0
MANOEUVRE IN WOOD	K	110	10	3	35	11.0	9.5
LOAD PRODUCT 1 (LOG 495CM)	L1	2834	84	13	70	33.7	10.6
LOAD PRODUCT 2 (LOG 315CM)	L2	605	22	10	51	27.5	9.8
LOAD PRODUCT 3 (BAR 375CM)	L3	105	3	27	40	35.0	7.0
LOAD PRODUCT 4 (BAR 254CM)	L4	190	5	26	65	38.0	17.1
LOAD PRODUCT 5 (PULP 300CM)	L5	1579	52	10	74	30.4	13.1
LOAD PRODUCT 6 (STAKE 172CM)	L6	41	2	16	25	20.5	6.4
UNLOAD PRODUCT 1 (LOG 495CM)	U1	1799	65	12	45	27.7	7.7
UNLOAD PRODUCT 2 (LOG 315CM)	U2	486	15	10	52	32.4	10.8
UNLOAD PRODUCT 3 (BAR 375CM)	U3	80	3	21	32	26.7	5.5
UNLOAD PRODUCT 4 (BAR 254CM)	U4	90	4	18	27	22.5	3.7
UNLOAD PRODUCT 5 (PULP 300CM)	U5	445	17	15	37	26.2	7.0
UNLOAD PRODUCT 6 (STAKE 172CM)	U6	26	1	26	26	26.0	0.0
MOVE TO UNLOAD	A2	0	0	0	0	0.0	0.0
MANOEUVRE ON ROAD	A3	0	0	0	0	0.0	0.0
STACK	A5	461	27	1	41	17.1	10.7
STOW / UNSTOW GRAPPLE	A6	360	25	3	27	14.4	5.4
ADJUST LOAD	A8	635	36	2	80	17.6	16.8
GRADE LOGS AT UNLOADING	A9	0	0	0	0	0.0	0.0
CLOCK READING	B1	0	0	0	0	0.0	0.0
GENERAL PREPARATION	B2	0	0	0	0	0.0	0.0
ON / OFF PROTECTIVE CLOTHING	B3	0	0	0	0	0.0	0.0
TO / FROM CAMP	B4	0	0	0	0	0.0	0.0
FETCH TOOLS	B6	0	0	0	0	0.0	0.0
AVOIDABLE DELAY	B7	0	0	0	0	0.0	0.0
UNAVOIDABLE DELAY	B8	55	1	55	55	55.0	0.0
REST AND PERSONAL	B9	4822	1	4822	4822	4822.0	0.0
WAIT OR TALK WORK STUDY	C1	292	2	100	192	146.0	65.1
INSPECT	C2	143	9	5	34	15.9	10.6
COUNT / CHECK	C3	0	0	0	0	0.0	0.0
ASIDE BRASH	C4	41	1	41	41	41.0	0.0
START MACHINE	C5	18	1	18	18	18.0	0.0
MAINTENANCE	C6	0	0	0	0	0.0	0.0
REFUEL	C7	554	1	554	554	554.0	0.0
FIT / REMOVE CHAINS AND TRACKS	C8	0	0	0	0	0.0	0.0
DEBOG	C9	0	0	0	0	0.0	0.0
ASIDE PRODUCE TO TRAVEL	D1	115	4	12	51	28.8	17.0
ASIDE PRODUCE TO LOAD	D2	3236	134	3	56	24.1	10.3
MOVE HEADBOARD / BOLSTERS	D3	69	1	69	69	69.0	0.0
PREPARE STACKING AREA	D4	23	1	23	23	23.0	0.0
PREPARE ROUTE	D5	605	7	10	304	86.4	111.1
TRAVEL BETWEEN WORKSITES	D6	0	0	0	0	0.0	0.0
TRAVEL TO / FROM WORKSITE	D7	0	0	0	0	0.0	0.0
WET TIME	D8	0	0	0	0	0.0	0.0
UNPAID MEALBREAKS	D9	0	0	0	0	0.0	0.0
PERIOD NOT STUDIED (PNS)	F9	0	0	0	0	0.0	0.0
TOTAL CODE TIME (CENTIMIN)		31105					

TIME ON (HR:MIN:CENTIMIN)	082866
TIME OFF (HR:MIN:CENTIMIN)	133971
TOTAL OBSERVED TIME (CENTIMIN)	31105

APPENDIX 25: Forwarder Distance Summary

FORWARDER DISTANCE (m)			Total	N	Min	Max	Mean	Stdev
PLOT 1	MOVE IN ROAD	A	1030	12	25	105	85.8	21.4
	MOVE IN RIDE	B	490	17	2	45	28.8	18.1
	MOVE IN RACK	C	1028	85	1	90	12.1	16.5
	MOVE IN WOOD	D	0	0	0	0	0.0	0.0
	MOVE OUT WOOD	E	0	0	0	0	0.0	0.0
	MOVE OUT RACK	F	1065	95	1	70	11.2	13.2
	MOVE OUT RIDE	G	504	17	4	45	29.6	16.8
	MOVE OUT ROAD	H	1157	23	5	90	50.3	36.9
	MOVE TO LOAD	J	0	0	0	0	0.0	0.0
	MOVE TO UNLOAD	A2	62	6	2	30	10.3	10.1
PLOT 2	MOVE IN ROAD	A	1205	17	10	105	70.9	28.4
	MOVE IN RIDE	B	519	18	2	100	28.8	27.2
	MOVE IN RACK	C	1086	96	2	85	11.3	13.7
	MOVE IN WOOD	D	0	0	0	0	0.0	0.0
	MOVE OUT WOOD	E	0	0	0	0	0.0	0.0
	MOVE OUT RACK	F	1044	102	2	50	10.2	9.3
	MOVE OUT RIDE	G	579	20	5	110	29.0	28.0
	MOVE OUT ROAD	H	1370	32	2	100	42.8	33.4
	MOVE TO LOAD	J	0	0	0	0	0.0	0.0
	MOVE TO UNLOAD	A2	165	14	5	20	11.8	5.0
PLOT 3	MOVE IN ROAD	A	845	17	0	130	49.7	31.0
	MOVE IN RIDE	B	416	18	5	80	23.1	23.7
	MOVE IN RACK	C	985	119	1	55	8.3	10.3
	MOVE IN WOOD	D	0	0	0	0	0.0	0.0
	MOVE OUT WOOD	E	0	0	0	0	0.0	0.0
	MOVE OUT RACK	F	1004	122	2	80	8.2	9.3
	MOVE OUT RIDE	G	482	15	10	80	32.1	26.8
	MOVE OUT ROAD	H	1100	36	5	70	30.6	17.8
	MOVE TO LOAD	J	0	0	0	0	0.0	0.0
	MOVE TO UNLOAD	A2	293	19	3	35	15.4	8.5
PLOT 4	MOVE IN ROAD	A	1050	12	20	300	87.5	73.6
	MOVE IN RIDE	B	79	12	2	8	6.6	1.9
	MOVE IN RACK	C	923	74	1	50	12.5	10.7
	MOVE IN WOOD	D	0	0	0	0	0.0	0.0
	MOVE OUT WOOD	E	0	0	0	0	0.0	0.0
	MOVE OUT RACK	F	1027	88	1	40	11.7	7.7
	MOVE OUT RIDE	G	86	12	2	10	7.2	1.9
	MOVE OUT ROAD	H	1020	25	10	110	40.8	28.4
	MOVE TO LOAD	J	0	0	0	0	0.0	0.0
	MOVE TO UNLOAD	A2	90	4	10	40	22.5	15.0
PLOT 5	MOVE IN ROAD	A	4305	15	10	505	287.0	214.2
	MOVE IN RIDE	B	75	12	2	8	6.3	1.7
	MOVE IN RACK	C	750	122	1	30	6.1	5.1
	MOVE IN WOOD	D	0	0	0	0	0.0	0.0
	MOVE OUT WOOD	E	0	0	0	0	0.0	0.0
	MOVE OUT RACK	F	818	117	1	30	7.0	5.2
	MOVE OUT RIDE	G	76	11	4	8	6.9	1.0
	MOVE OUT ROAD	H	4460	23	5	480	193.9	225.7
	MOVE TO LOAD	J	0	0	0	0	0.0	0.0
	MOVE TO UNLOAD	A2	50	5	5	15	10.0	3.5
PLOT 6	MOVE IN ROAD	A	5279	21	4	600	251.4	253.3
	MOVE IN RIDE	B	240	16	10	30	15.0	7.7
	MOVE IN RACK	C	743	91	1	60	8.2	9.4
	MOVE IN WOOD	D	0	0	0	0	0.0	0.0
	MOVE OUT WOOD	E	0	0	0	0	0.0	0.0
	MOVE OUT RACK	F	924	101	1	65	9.1	10.5
	MOVE OUT RIDE	G	252	17	5	30	14.8	7.8
	MOVE OUT ROAD	H	5691	38	1	570	149.8	229.5
	MOVE TO LOAD	J	0	0	0	0	0.0	0.0
	MOVE TO UNLOAD	A2	90	8	5	20	11.3	6.4
PLOT 7	MOVE IN ROAD	A	1647	45	4	80	36.6	21.4
	MOVE IN RIDE	B	985	43	2	25	22.9	5.8
	MOVE IN RACK	C	3078	242	1	100	12.7	16.5
	MOVE IN WOOD	D	0	0	0	0	0.0	0.0
	MOVE OUT WOOD	E	0	0	0	0	0.0	0.0
	MOVE OUT RACK	F	3084	228	1	120	13.5	19.9
	MOVE OUT RIDE	G	980	41	5	25	23.9	4.1
	MOVE OUT ROAD	H	3110	44	10	95	70.7	24.1
	MOVE TO LOAD	J	0	0	0	0	0.0	0.0
	MOVE TO UNLOAD	A2	1431	55	4	70	26.0	18.6
PLOT 8	MOVE IN ROAD	A	420	9	5	140	46.7	37.9
	MOVE IN RIDE	B	890	9	10	110	98.9	33.3
	MOVE IN RACK	C	890	60	2	70	14.8	13.6
	MOVE IN WOOD	D	0	0	0	0	0.0	0.0
	MOVE OUT WOOD	E	0	0	0	0	0.0	0.0
	MOVE OUT RACK	F	847	76	1	45	11.1	10.1
	MOVE OUT RIDE	G	877	12	2	110	73.1	50.2
	MOVE OUT ROAD	H	470	25	5	100	18.8	17.7
	MOVE TO LOAD	J	0	0	0	0	0.0	0.0
	MOVE TO UNLOAD	A2	0	0	0	0	0.0	0.0

APPENDIX 26: Forwarder Speed Summary

FORWARDER SPEED (m/s)			N	Min	Max	Mean	Stdev
PLOT 1	MOVE IN ROAD	A	12	0.36	1.42	1.07	0.27
	MOVE IN RIDE	B	17	0.04	1.29	0.63	0.36
	MOVE IN RACK	C	85	0.14	1.23	0.45	0.22
	MOVE IN WOOD	D	0	0.00	0.00	0.00	0.00
	MOVE OUT WOOD	E	0	0.00	0.00	0.00	0.00
	MOVE OUT RACK	F	95	0.05	1.46	0.41	0.24
	MOVE OUT RIDE	G	17	0.06	1.07	0.54	0.25
	MOVE OUT ROAD	H	23	0.38	1.54	0.90	0.28
	MOVE TO LOAD	J	0	0.00	0.00	0.00	0.00
	MOVE TO UNLOAD	A2	6	0.17	2.27	0.80	0.77
PLOT 2	MOVE IN ROAD	A	17	0.26	1.52	0.91	0.35
	MOVE IN RIDE	B	18	0.05	1.22	0.62	0.29
	MOVE IN RACK	C	96	0.19	1.67	0.52	0.24
	MOVE IN WOOD	D	0	0.00	0.00	0.00	0.00
	MOVE OUT WOOD	E	0	0.00	0.00	0.00	0.00
	MOVE OUT RACK	F	102	0.07	1.39	0.47	0.19
	MOVE OUT RIDE	G	20	0.19	1.59	0.60	0.29
	MOVE OUT ROAD	H	32	0.13	2.22	0.98	0.36
	MOVE TO LOAD	J	0	0.00	0.00	0.00	0.00
	MOVE TO UNLOAD	A2	14	0.49	1.33	0.84	0.23
PLOT 3	MOVE IN ROAD	A	17	0.19	1.33	0.80	0.27
	MOVE IN RIDE	B	18	0.16	1.07	0.59	0.25
	MOVE IN RACK	C	119	0.09	1.83	0.40	0.23
	MOVE IN WOOD	D	0	0.00	0.00	0.00	0.00
	MOVE OUT WOOD	E	0	0.00	0.00	0.00	0.00
	MOVE OUT RACK	F	122	0.08	1.96	0.37	0.22
	MOVE OUT RIDE	G	15	0.21	0.93	0.58	0.24
	MOVE OUT ROAD	H	36	0.09	1.46	0.95	0.30
	MOVE TO LOAD	J	0	0.00	0.00	0.00	0.00
	MOVE TO UNLOAD	A2	19	0.29	2.01	0.86	0.38
PLOT 4	MOVE IN ROAD	A	12	0.61	1.94	1.19	0.40
	MOVE IN RIDE	B	12	0.11	0.46	0.25	0.13
	MOVE IN RACK	C	74	0.09	1.67	0.62	0.32
	MOVE IN WOOD	D	0	0.00	0.00	0.00	0.00
	MOVE OUT WOOD	E	0	0.00	0.00	0.00	0.00
	MOVE OUT RACK	F	88	0.06	1.59	0.62	0.31
	MOVE OUT RIDE	G	12	0.22	1.11	0.43	0.29
	MOVE OUT ROAD	H	25	0.40	1.80	1.06	0.39
	MOVE TO LOAD	J	0	0.00	0.00	0.00	0.00
	MOVE TO UNLOAD	A2	4	0.48	1.79	1.03	0.56
PLOT 5	MOVE IN ROAD	A	15	0.20	2.17	1.50	0.65
	MOVE IN RIDE	B	12	0.12	0.83	0.25	0.20
	MOVE IN RACK	C	122	0.11	1.09	0.37	0.16
	MOVE IN WOOD	D	0	0.00	0.00	0.00	0.00
	MOVE OUT WOOD	E	0	0.00	0.00	0.00	0.00
	MOVE OUT RACK	F	117	0.16	1.00	0.40	0.16
	MOVE OUT RIDE	G	11	0.24	0.53	0.37	0.11
	MOVE OUT ROAD	H	23	0.22	1.57	1.06	0.40
	MOVE TO LOAD	J	0	0.00	0.00	0.00	0.00
	MOVE TO UNLOAD	A2	5	0.44	1.25	0.88	0.32
PLOT 6	MOVE IN ROAD	A	21	0.26	2.12	1.36	0.65
	MOVE IN RIDE	B	16	0.21	1.00	0.55	0.22
	MOVE IN RACK	C	91	0.06	1.00	0.43	0.19
	MOVE IN WOOD	D	0	0.00	0.00	0.00	0.00
	MOVE OUT WOOD	E	0	0.00	0.00	0.00	0.00
	MOVE OUT RACK	F	101	0.13	1.32	0.48	0.23
	MOVE OUT RIDE	G	17	0.11	0.81	0.50	0.19
	MOVE OUT ROAD	H	38	0.15	1.50	0.87	0.44
	MOVE TO LOAD	J	0	0.00	0.00	0.00	0.00
	MOVE TO UNLOAD	A2	8	0.31	1.45	0.74	0.40
PLOT 7	MOVE IN ROAD	A	45	0.14	1.52	0.95	0.35
	MOVE IN RIDE	B	43	0.17	1.19	0.63	0.20
	MOVE IN RACK	C	242	0.07	2.08	0.44	0.25
	MOVE IN WOOD	D	0	0.00	0.00	0.00	0.00
	MOVE OUT WOOD	E	0	0.00	0.00	0.00	0.00
	MOVE OUT RACK	F	228	0.07	1.14	0.40	0.19
	MOVE OUT RIDE	G	41	0.30	0.83	0.51	0.09
	MOVE OUT ROAD	H	44	0.64	1.65	1.24	0.25
	MOVE TO LOAD	J	0	0.00	0.00	0.00	0.00
	MOVE TO UNLOAD	A2	55	0.32	2.12	1.03	0.44
PLOT 8	MOVE IN ROAD	A	9	0.14	1.54	1.02	0.46
	MOVE IN RIDE	B	9	0.18	0.94	0.71	0.21
	MOVE IN RACK	C	60	0.18	1.67	0.53	0.25
	MOVE IN WOOD	D	0	0.00	0.00	0.00	0.00
	MOVE OUT WOOD	E	0	0.00	0.00	0.00	0.00
	MOVE OUT RACK	F	76	0.11	1.17	0.54	0.23
	MOVE OUT RIDE	G	12	0.18	0.69	0.58	0.14
	MOVE OUT ROAD	H	25	0.36	1.62	0.93	0.32
	MOVE TO LOAD	J	0	0.00	0.00	0.00	0.00
	MOVE TO UNLOAD	A2	0	0.00	0.00	0.00	0.00

APPENDIX 27: Forwarder load cycle summary

LOAD	FRAME TREE PLOT 1			PRODUCT 111	112	113	114	127	115
1	Number of grapple loads	38	Number of grapple loads	19	0	0	9	0	10
	Mean grapple volume (m3)	0.29	Mean pieces per grapple load	1.6	0.0	0.0	1.6	0.0	2.7
	Std. Deviation (m3)	0.24	st. deviation	0.6	0.0	0.0	0.5	0.0	1.7
	Minimum	0.02	min	1	0	0	1	0	1
	Maximum	0.89	max	3	0	0	2	0	5
	Load Volume (m3)	10.86	sum	31	0	0	14	0	27
2	Number of grapple loads	18	Number of grapple loads	0	8	0	0	10	0
	Mean grapple volume (m3)	0.28	Mean pieces per grapple load	0.0	2.4	0.0	0.0	1.9	0.0
	Std. Deviation (m3)	0.16	st. deviation	0.0	0.7	0.0	0.0	1.3	0.0
	Minimum	0.10	min	0	1	0	0	1	0
	Maximum	0.50	max	0	3	0	0	4	0
	Load Volume (m3)	5.01	sum	0	19	0	0	19	0
3	Number of grapple loads	40	Number of grapple loads	21	0	0	8	0	11
	Mean grapple volume (m3)	0.26	Mean pieces per grapple load	1.4	0.0	0.0	1.4	0.0	2.8
	Std. Deviation (m3)	0.21	st. deviation	0.5	0.0	0.0	0.7	0.0	1.8
	Minimum	0.02	min	1	0	0	1	0	1
	Maximum	0.59	max	2	0	0	3	0	6
	Load Volume (m3)	10.42	sum	30	0	0	11	0	31
4	Number of grapple loads	25	Number of grapple loads	0	12	0	0	13	0
	Mean grapple volume (m3)	0.25	Mean pieces per grapple load	0.0	1.8	0.0	0.0	2.1	0.0
	Std. Deviation (m3)	0.10	st. deviation	0.0	0.6	0.0	0.0	0.9	0.0
	Minimum	0.10	min	0	1	0	0	1	0
	Maximum	0.50	max	0	3	0	0	3	0
	Load Volume (m3)	6.28	sum	0	22	0	0	27	0
5	Number of grapple loads	20	Number of grapple loads	11	0	0	5	0	4
	Mean grapple volume (m3)	0.30	Mean pieces per grapple load	1.5	0.0	0.0	2.0	0.0	3.0
	Std. Deviation (m3)	0.21	st. deviation	0.5	0.0	0.0	1.2	0.0	1.4
	Minimum	0.05	min	1	0	0	1	0	2
	Maximum	0.59	max	2	0	0	4	0	5
	Load Volume (m3)	6.08	sum	17	0	0	10	0	12
6	Number of grapple loads	17	Number of grapple loads	0	5	8	0	4	0
	Mean grapple volume (m3)	0.25	Mean pieces per grapple load	0	2.6	1.8	0	1.8	0
	Std. Deviation (m3)	0.17	st. deviation	0	0.9	1.2	0	1.0	0
	Minimum	0.10	min	0	2	1	0	1	0
	Maximum	0.67	max	0	4	4	0	3	0
	Load Volume (m3)	4.29	sum	0	13	14	0	7	0
7	Number of grapple loads	35	Number of grapple loads	15	0	0	8	0	12
	Mean grapple volume (m3)	0.25	Mean pieces per grapple load	1.7	0	0	1.5	0	2.1
	Std. Deviation (m3)	0.23	st. deviation	0.5	0	0	1.1	0	1.0
	Minimum	0.02	min	1	0	0	1	0	1
	Maximum	0.59	max	2	0	0	4	0	4
	Load Volume (m3)	8.89	sum	25	0	0	12	0	25
8	Number of grapple loads	23	Number of grapple loads	9	0	0	0	14	0
	Mean grapple volume (m3)	0.28	Mean pieces per grapple load	1.4	0	0	0	2.0	0
	Std. Deviation (m3)	0.17	st. deviation	0.5	0	0	0	1.0	0
	Minimum	0.10	min	1	0	0	0	1	0
	Maximum	0.59	max	2	0	0	0	4	0
	Load Volume (m3)	6.53	sum	13	0	0	0	28	0
9	Number of grapple loads	19	Number of grapple loads	5	14	0	0	0	0
	Mean grapple volume (m3)	0.32	Mean pieces per grapple load	1.4	1.7	0	0	0	0
	Std. Deviation (m3)	0.14	st. deviation	0.5	0.7	0	0	0	0
	Minimum	0.17	min	1	1	0	0	0	0
	Maximum	0.59	max	2	3	0	0	0	0
	Load Volume (m3)	6.08	sum	7	24	0	0	0	0
10	Number of grapple loads	23	Number of grapple loads	17	0	0	3	0	3
	Mean grapple volume (m3)	0.33	Mean pieces per grapple load	1.4	0	0	1.0	0	3.3
	Std. Deviation (m3)	0.20	st. deviation	0.5	0	0	0.0	0	1.2
	Minimum	0.05	min	1	0	0	1	0	2
	Maximum	0.59	max	2	0	0	1	0	4
	Load Volume (m3)	7.54	sum	24	0	0	3	0	10
11	Number of grapple loads	21	Number of grapple loads	14	0	0	4	0	3
	Mean grapple volume (m3)	0.33	Mean pieces per grapple load	1.5	0	0	1.5	0	5.0
	Std. Deviation (m3)	0.20	st. deviation	0.5	0	0	0.6	0	3.6
	Minimum	0.05	min	1	0	0	1	0	2
	Maximum	0.59	max	2	0	0	2	0	9
	Load Volume (m3)	7.01	sum	21	0	0	6	0	15
12	Number of grapple loads	19	Number of grapple loads	4	3	5	0	7	0
	Mean grapple volume (m3)	0.33	Mean pieces per grapple load	1.5	2.0	3.4	0	2.7	0
	Std. Deviation (m3)	0.16	st. deviation	0.6	0.0	1.1	0	2.1	0
	Minimum	0.10	min	1	2	2	0	1	0
	Maximum	0.59	max	2	2	5	0	6	0
	Load Volume (m3)	6.35	sum	6	6	17	0	19	0
TOTAL	Number of grapple loads	298	Number of grapple loads	115	42	13	37	48	43
	Mean grapple volume (m3)	0.29	Mean pieces per grapple load	1.5	2.0	2.4	2	2.1	3
	Std. Deviation (m3)	0.19	st. deviation	0.5	0.7	1.4	1	1.2	2
	Minimum	0.02	min	1	1	1	1	1	1
	Maximum	0.89	max	3	4	5	4	6	9
	Load Volume (m3)	85.35	sum	174	84	31	56	100	120

UNLOAD	FRAME TREE PLOT 1			PRODUCT					
				111	112	113	114	127	115
1	Number of grapple loads	18	Number of grapple loads	14	0	0	2	0	2
	Mean grapple volume (m3)	0.60	Mean pieces per grapple load	2.2	0.0	0.0	7.0	0.0	13.5
	Std. Deviation (m3)	0.19	st. deviation	0.6	0.0	0.0	1.4	0.0	6.4
	Minimum	0.20	min	1	0	0	6	0	9
	Maximum	0.89	max	3	0	0	8	0	18
	Load Volume (m3)	10.86	sum	31	0	0	14	0	27
2	Number of grapple loads	8	Number of grapple loads	0	5	0	0	3	0
	Mean grapple volume (m3)	0.63	Mean pieces per grapple load	0.0	3.8	0.0	0.0	6.3	0.0
	Std. Deviation (m3)	0.17	st. deviation	0.0	1.3	0.0	0.0	0.6	0.0
	Minimum	0.50	min	0	3	0	0	6	0
	Maximum	1.00	max	0	6	0	0	7	0
	Load Volume (m3)	5.01	sum	0	19	0	0	19	0
3	Number of grapple loads	19	Number of grapple loads	15	0	0	2	0	2
	Mean grapple volume (m3)	0.55	Mean pieces per grapple load	2.0	0.0	0.0	5.5	0.0	14.5
	Std. Deviation (m3)	0.15	st. deviation	0.4	0.0	0.0	3.5	0.0	2.1
	Minimum	0.24	min	1	0	0	3	0	13
	Maximum	0.89	max	3	0	0	8	0	16
	Load Volume (m3)	10.38	sum	30	0	0	11	0	29
4	Number of grapple loads	14	Number of grapple loads	0	8	0	0	6	0
	Mean grapple volume (m3)	0.45	Mean pieces per grapple load	0.0	2.8	0.0	0.0	4.5	0.0
	Std. Deviation (m3)	0.11	st. deviation	0.0	0.7	0.0	0.0	1.0	0.0
	Minimum	0.29	min	0	2	0	0	3	0
	Maximum	0.67	max	0	4	0	0	6	0
	Load Volume (m3)	6.28	sum	0	22	0	0	27	0
5	Number of grapple loads	12	Number of grapple loads	9	0	0	2	0	1
	Mean grapple volume (m3)	0.51	Mean pieces per grapple load	1.9	0.0	0.0	5.0	0.0	12.0
	Std. Deviation (m3)	0.18	st. deviation	0.6	0.0	0.0	1.4	0.0	0.0
	Minimum	0.27	min	1	0	0	4	0	12
	Maximum	0.89	max	3	0	0	6	0	12
	Load Volume (m3)	6.08	sum	17	0	0	10	0	12
6	Number of grapple loads	9	Number of grapple loads	0	4	3	0	2	0
	Mean grapple volume (m3)	0.48	Mean pieces per grapple load	0.0	3.3	4.7	0.0	3.5	0.0
	Std. Deviation (m3)	0.23	st. deviation	0.0	0.5	3.2	0.0	3.5	0.0
	Minimum	0.10	min	0	3	1	0	1	0
	Maximum	0.72	max	0	4	7	0	6	0
	Load Volume (m3)	4.29	sum	0	13	14	0	7	0
7	Number of grapple loads	16	Number of grapple loads	12	0	0	2	0	2
	Mean grapple volume (m3)	0.56	Mean pieces per grapple load	2.1	0.0	0.0	6.0	0.0	12.5
	Std. Deviation (m3)	0.14	st. deviation	0.3	0.0	0.0	1.4	0.0	2.1
	Minimum	0.25	min	2	0	0	5	0	11
	Maximum	0.89	max	3	0	0	7	0	14
	Load Volume (m3)	8.89	sum	25	0	0	12	0	25
8	Number of grapple loads	13	Number of grapple loads	7	0	0	0	6	0
	Mean grapple volume (m3)	0.50	Mean pieces per grapple load	1.9	0.0	0.0	0.0	4.7	0.0
	Std. Deviation (m3)	0.11	st. deviation	0.4	0.0	0.0	0.0	1.0	0.0
	Minimum	0.30	min	1	0	0	0	4	0
	Maximum	0.59	max	2	0	0	0	6	0
	Load Volume (m3)	6.53	sum	13	0	0	0	28	0
9	Number of grapple loads	10	Number of grapple loads	4	6	0	0	0	0
	Mean grapple volume (m3)	0.61	Mean pieces per grapple load	1.8	4.0	0.0	0.0	0.0	0.0
	Std. Deviation (m3)	0.16	st. deviation	0.5	0.9	0.0	0.0	0.0	0.0
	Minimum	0.30	min	1	3	0	0	0	0
	Maximum	0.84	max	2	5	0	0	0	0
	Load Volume (m3)	6.08	sum	7	24	0	0	0	0
10	Number of grapple loads	14	Number of grapple loads	12	0	0	1	0	1
	Mean grapple volume (m3)	0.54	Mean pieces per grapple load	2.0	0.0	0.0	3.0	0.0	10.0
	Std. Deviation (m3)	0.17	st. deviation	0.4	0.0	0.0	0.0	0.0	0.0
	Minimum	0.23	min	1	0	0	3	0	10
	Maximum	0.89	max	3	0	0	3	0	10
	Load Volume (m3)	7.54	sum	24	0	0	3	0	10
11	Number of grapple loads	12	Number of grapple loads	10	0	0	1	0	1
	Mean grapple volume (m3)	0.58	Mean pieces per grapple load	2.1	0.0	0.0	6.0	0.0	15.0
	Std. Deviation (m3)	0.17	st. deviation	0.6	0.0	0.0	0.0	0.0	0.0
	Minimum	0.30	min	1	0	0	6	0	15
	Maximum	0.89	max	3	0	0	6	0	15
	Load Volume (m3)	7.01	sum	21	0	0	6	0	15
12	Number of grapple loads	12	Number of grapple loads	3	2	4	0	3	0
	Mean grapple volume (m3)	0.53	Mean pieces per grapple load	2.0	3.0	4.3	0.0	6.3	0.0
	Std. Deviation (m3)	0.23	st. deviation	0.0	1.4	3.6	0.0	1.5	0.0
	Minimum	0.10	min	2	2	1	0	5	0
	Maximum	0.93	max	2	4	9	0	8	0
	Load Volume (m3)	6.35	sum	6	6	17	0	19	0
TOTAL	Number of grapple loads	157	Number of grapple loads	86	25	7	10	20	9
	Mean grapple volume (m3)	0.54	Mean pieces per grapple load	2.0	3.4	4.4	6	5.0	13
	Std. Deviation (m3)	0.17	st. deviation	0.5	1.0	3.2	2	1.6	3
	Minimum	0.10	min	1	2	1	3	1	9
	Maximum	1.00	max	3	6	9	8	8	18
	Load Volume (m3)	85.30	sum	174	84	31	56	100	118

LOAD	GROUP PLOT 2			PRODUCT 111	112	113	114	127	115
1	Number of grapple loads	18	Number of grapple loads	8	0	0	4	0	6
	Mean grapple volume (m3)	0.22	Mean pieces per grapple load	1.5	0.0	0.0	2.0	0.0	3.0
	Std. Deviation (m3)	0.18	st. deviation	0.5	0.0	0.0	0.8	0.0	3.2
	Minimum	0.02	min	1	0	0	1	0	1
	Maximum	0.51	max	2	0	0	3	0	8
	Load Volume (m3)	3.98	sum	12	0	0	8	0	18
2	Number of grapple loads	14	Number of grapple loads	1	5	4	0	4	0
	Mean grapple volume (m3)	0.22	Mean pieces per grapple load	1.0	1.8	1.8	0.0	2.8	0.0
	Std. Deviation (m3)	0.10	st. deviation	0.0	0.8	1.0	0.0	1.3	0.0
	Minimum	0.09	min	1	1	1	0	1	0
	Maximum	0.40	max	1	3	3	0	4	0
	Load Volume (m3)	3.10	sum	1	9	7	0	11	0
3	Number of grapple loads	32	Number of grapple loads	14	0	0	7	0	11
	Mean grapple volume (m3)	0.24	Mean pieces per grapple load	1.7	0.0	0.0	1.4	0.0	4.0
	Std. Deviation (m3)	0.20	st. deviation	0.5	0.0	0.0	0.8	0.0	2.4
	Minimum	0.02	min	1	0	0	1	0	1
	Maximum	0.51	max	2	0	0	3	0	8
	Load Volume (m3)	7.74	sum	24	0	0	10	0	44
4	Number of grapple loads	23	Number of grapple loads	3	0	13	0	7	0
	Mean grapple volume (m3)	0.22	Mean pieces per grapple load	1.7	0.0	1.8	0.0	2.4	0.0
	Std. Deviation (m3)	0.13	st. deviation	0.6	0.0	0.8	0.0	1.3	0.0
	Minimum	0.09	min	1	0	1	0	1	0
	Maximum	0.51	max	2	0	3	0	4	0
	Load Volume (m3)	5.00	sum	5	0	23	0	17	0
5	Number of grapple loads	17	Number of grapple loads	9	8	0	0	0	0
	Mean grapple volume (m3)	0.34	Mean pieces per grapple load	1.6	2.1	0.0	0.0	0.0	0.0
	Std. Deviation (m3)	0.12	st. deviation	0.5	0.6	0.0	0.0	0.0	0.0
	Minimum	0.13	min	1	1	0	0	0	0
	Maximum	0.51	max	2	3	0	0	0	0
	Load Volume (m3)	5.86	sum	14	17	0	0	0	0
6	Number of grapple loads	37	Number of grapple loads	13	0	0	11	0	13
	Mean grapple volume (m3)	0.22	Mean pieces per grapple load	2	0.0	0.0	2	0.0	5
	Std. Deviation (m3)	0.16	st. deviation	1	0.0	0.0	1	0.0	3
	Minimum	0.02	min	1	0	0	1	0	1
	Maximum	0.51	max	2	0	0	3	0	10
	Load Volume (m3)	8.03	sum	20	0	0	21	0	71
7	Number of grapple loads	19	Number of grapple loads	13	0	0	0	6	0
	Mean grapple volume (m3)	0.43	Mean pieces per grapple load	1.9	0	0	0.0	4	0.0
	Std. Deviation (m3)	0.14	st. deviation	0.3	0	0	0.0	2	0.0
	Minimum	0.09	min	1	0	0	0	1	0
	Maximum	0.52	max	2	0	0	0	6	0
	Load Volume (m3)	8.19	sum	25	0	0	0	21	0
8	Number of grapple loads	19	Number of grapple loads	0	7	12	0	0	0
	Mean grapple volume (m3)	0.31	Mean pieces per grapple load	0.0	2	3	0	0.0	0
	Std. Deviation (m3)	0.12	st. deviation	0.0	1	1	0	0.0	0
	Minimum	0.13	min	0	1	2	0	0	0
	Maximum	0.49	max	0	3	5	0	0	0
	Load Volume (m3)	5.91	sum	0	14	41	0	0	0
9	Number of grapple loads	13	Number of grapple loads	5	7	0	1	0	0
	Mean grapple volume (m3)	0.27	Mean pieces per grapple load	1.4	1.7	0	1	0	0
	Std. Deviation (m3)	0.14	st. deviation	0.5	0.8	0	0	0	0
	Minimum	0.07	min	1	1	0	1	0	0
	Maximum	0.51	max	2	3	0	1	0	0
	Load Volume (m3)	3.47	sum	7	12	0	1	0	0
10	Number of grapple loads	10	Number of grapple loads	2	3	1	1	2	1
	Mean grapple volume (m3)	0.34	Mean pieces per grapple load	1.0	3	2	5.0	6	5.0
	Std. Deviation (m3)	0.17	st. deviation	0.0	2	0	0.0	0	0.0
	Minimum	0.11	min	1	1	2	5	6	5
	Maximum	0.54	max	1	4	2	5	6	5
	Load Volume (m3)	3.39	sum	2	9	2	5	12	5
11	Number of grapple loads	19	Number of grapple loads	11	2	0	3	0	3
	Mean grapple volume (m3)	0.28	Mean pieces per grapple load	1.5	1	0	2.0	0	3.7
	Std. Deviation (m3)	0.18	st. deviation	0.5	0	0	1.0	0	2.1
	Minimum	0.04	min	1	1	0	1	0	2
	Maximum	0.51	max	2	1	0	3	0	6
	Load Volume (m3)	5.24	sum	17	2	0	6	0	11
12	Number of grapple loads	18	Number of grapple loads	0	7	5	0	6	0
	Mean grapple volume (m3)	0.22	Mean pieces per grapple load	0.0	1.9	1.8	0	2.5	0
	Std. Deviation (m3)	0.08	st. deviation	0.0	0.7	0.4	0	1.0	0
	Minimum	0.09	min	0	1	1	0	1	0
	Maximum	0.40	max	0	3	2	0	4	0
	Load Volume (m3)	3.92	sum	0	13	9	0	15	0
13	Number of grapple loads	18	Number of grapple loads	6	3	2	2	5	0
	Mean grapple volume (m3)	0.27	Mean pieces per grapple load	1.5	2	2	2.0	3	0.0
	Std. Deviation (m3)	0.17	st. deviation	0.5	1	1	1.4	2	0.0
	Minimum	0.07	min	1	1	1	1	1	0
	Maximum	0.60	max	2	3	2	3	7	0
	Load Volume (m3)	4.87	sum	9	6	3	4	14	0
14	Number of grapple loads	30	Number of grapple loads	20	0	0	6	0	4
	Mean grapple volume (m3)	0.28	Mean pieces per grapple load	1.4	0	0	2.2	0	5.5
	Std. Deviation (m3)	0.16	st. deviation	0.5	0	0	1.6	0	2.4
	Minimum	0.06	min	1	0	0	1	0	3
	Maximum	0.51	max	2	0	0	5	0	8
	Load Volume (m3)	8.48	sum	28	0	0	13	0	22
15	Number of grapple loads	21	Number of grapple loads	5	8	4	0	4	0
	Mean grapple volume (m3)	0.32	Mean pieces per grapple load	1.6	2.0	2.8	0	4.5	0
	Std. Deviation (m3)	0.14	st. deviation	0.5	0.5	0.5	0	2.6	0
	Minimum	0.09	min	1	1	2	0	1	0
	Maximum	0.60	max	2	3	3	0	7	0
	Load Volume (m3)	6.82	sum	8	16	11	0	18	0
TOTAL	Number of grapple loads	308	Number of grapple loads	110	50	41	35	34	38
	Mean grapple volume (m3)	0.27	Mean pieces per grapple load	1.6	2.0	2.3	2	3.2	5
	Std. Deviation (m3)	0.16	st. deviation	0.5	0.8	1.1	1	1.9	3
	Minimum	0.02	min	1	1	1	1	1	1
	Maximum	0.60	max	2	4	5	5	7	10
	Load Volume (m3)	84.01	sum	172	98	96	68	108	171

UNLOAD	GROUP PLOT 2			PRODUCT 111	112	113	114	127	115
1	Number of grapple loads	7	Number of grapple loads	5	0	0	1	0	1
	Mean grapple volume (m3)	0.57	Mean pieces per grapple load	2.4	0.0	0.0	8.0	0.0	18.0
	Std. Deviation (m3)	0.14	st. deviation	0.5	0.0	0.0	0.0	0.0	0.0
	Minimum	0.39	min	2	0	0	8	0	18
	Maximum	0.77	max	3	0	0	8	0	18
	Load Volume (m3)	3.98	sum	12	0	0	8	0	18
2	Number of grapple loads	8	Number of grapple loads	1	3	2	0	2	0
	Mean grapple volume (m3)	0.39	Mean pieces per grapple load	1.0	3.0	3.5	0.0	5.5	0.0
	Std. Deviation (m3)	0.10	st. deviation	0.0	0.0	0.7	0.0	2.1	0.0
	Minimum	0.26	min	1	3	3	0	4	0
	Maximum	0.60	max	1	3	4	0	7	0
	Load Volume (m3)	3.10	sum	1	9	7	0	11	0
3	Number of grapple loads	14	Number of grapple loads	9	0	0	2	0	3
	Mean grapple volume (m3)	0.55	Mean pieces per grapple load	2.7	0.0	0.0	5.0	0.0	14.7
	Std. Deviation (m3)	0.22	st. deviation	0.5	0.0	0.0	4.2	0.0	3.5
	Minimum	0.13	min	2	0	0	2	0	11
	Maximum	0.77	max	3	0	0	8	0	18
	Load Volume (m3)	7.74	sum	24	0	0	10	0	44
4	Number of grapple loads	10	Number of grapple loads	3	0	4	0	3	0
	Mean grapple volume (m3)	0.50	Mean pieces per grapple load	1.7	0.0	5.8	0.0	5.7	0.0
	Std. Deviation (m3)	0.22	st. deviation	0.6	0.0	2.5	0.0	3.5	0.0
	Minimum	0.17	min	1	0	3	0	2	0
	Maximum	0.88	max	2	0	9	0	9	0
	Load Volume (m3)	5.00	sum	5	0	23	0	17	0
5	Number of grapple loads	10	Number of grapple loads	6	4	0	0	0	0
	Mean grapple volume (m3)	0.59	Mean pieces per grapple load	2.3	4.3	0.0	0.0	0.0	0.0
	Std. Deviation (m3)	0.11	st. deviation	0.5	0.5	0.0	0.0	0.0	0.0
	Minimum	0.51	min	2	4	0	0	0	0
	Maximum	0.77	max	3	5	0	0	0	0
	Load Volume (m3)	5.86	sum	14	17	0	0	0	0
6	Number of grapple loads	16	Number of grapple loads	8	0	0	3	0	5
	Mean grapple volume (m3)	0.50	Mean pieces per grapple load	3	0.0	0.0	7	0.0	14
	Std. Deviation (m3)	0.21	st. deviation	1	0.0	0.0	1	0.0	5
	Minimum	0.13	min	2	0	0	6	0	6
	Maximum	1.02	max	4	0	0	8	0	17
	Load Volume (m3)	8.03	sum	20	0	0	21	0	71
7	Number of grapple loads	12	Number of grapple loads	9	0	0	0	3	0
	Mean grapple volume (m3)	0.68	Mean pieces per grapple load	2.8	0	0	0.0	7	0.0
	Std. Deviation (m3)	0.22	st. deviation	1.0	0	0	0.0	1	0.0
	Minimum	0.26	min	1	0	0	0	6	0
	Maximum	1.02	max	4	0	0	0	8	0
	Load Volume (m3)	8.19	sum	25	0	0	0	21	0
8	Number of grapple loads	10	Number of grapple loads	0	4	6	0	0	0
	Mean grapple volume (m3)	0.59	Mean pieces per grapple load	0.0	4	7	0	0.0	0
	Std. Deviation (m3)	0.24	st. deviation	0.0	1	3	0	0.0	0
	Minimum	0.27	min	0	2	4	0	0	0
	Maximum	1.08	max	0	4	11	0	0	0
	Load Volume (m3)	5.91	sum	0	14	41	0	0	0
9	Number of grapple loads	8	Number of grapple loads	4	3	0	1	0	0
	Mean grapple volume (m3)	0.43	Mean pieces per grapple load	1.8	4.0	0	1	0	0
	Std. Deviation (m3)	0.18	st. deviation	0.5	0.0	0	0	0	0
	Minimum	0.07	min	1	4	0	1	0	0
	Maximum	0.54	max	2	4	0	1	0	0
	Load Volume (m3)	3.47	sum	7	12	0	1	0	0
10	Number of grapple loads	8	Number of grapple loads	1	2	1	1	2	1
	Mean grapple volume (m3)	0.42	Mean pieces per grapple load	2.0	5	2	5.0	6	5.0
	Std. Deviation (m3)	0.24	st. deviation	0.0	1	0	0.0	4	0.0
	Minimum	0.11	min	2	4	2	5	3	5
	Maximum	0.78	max	2	5	2	5	9	5
	Load Volume (m3)	3.39	sum	2	9	2	5	12	5
11	Number of grapple loads	10	Number of grapple loads	8	0	0	1	0	1
	Mean grapple volume (m3)	0.50	Mean pieces per grapple load	2.1	0	0	7.0	0	11.0
	Std. Deviation (m3)	0.13	st. deviation	0.4	0	0	0.0	0	0.0
	Minimum	0.24	min	2	0	0	7	0	11
	Maximum	0.77	max	3	0	0	7	0	11
	Load Volume (m3)	5.04	sum	17	0	0	7	0	11
12	Number of grapple loads	8	Number of grapple loads	0	3	2	0	3	0
	Mean grapple volume (m3)	0.49	Mean pieces per grapple load	0.0	4.3	4.5	0	5.0	0
	Std. Deviation (m3)	0.28	st. deviation	0.0	2.1	4.9	0	3.0	0
	Minimum	0.10	min	0	2	1	0	2	0
	Maximum	0.81	max	0	6	8	0	8	0
	Load Volume (m3)	3.92	sum	0	13	9	0	15	0
13	Number of grapple loads	11	Number of grapple loads	4	2	1	1	3	0
	Mean grapple volume (m3)	0.44	Mean pieces per grapple load	2.3	3	3	4.0	5	0.0
	Std. Deviation (m3)	0.26	st. deviation	1.0	3	0	0.0	4	0.0
	Minimum	0.09	min	1	1	3	4	1	0
	Maximum	0.78	max	3	5	3	4	9	0
	Load Volume (m3)	4.87	sum	9	6	3	4	14	0
14	Number of grapple loads	16	Number of grapple loads	12	0	0	2	0	2
	Mean grapple volume (m3)	0.53	Mean pieces per grapple load	2.3	0	0	6.5	0	11.0
	Std. Deviation (m3)	0.20	st. deviation	0.7	0	0	3.5	0	5.7
	Minimum	0.15	min	2	0	0	4	0	7
	Maximum	1.02	max	4	0	0	9	0	15
	Load Volume (m3)	8.48	sum	28	0	0	13	0	22
15	Number of grapple loads	12	Number of grapple loads	4	4	2	0	2	0
	Mean grapple volume (m3)	0.57	Mean pieces per grapple load	2.0	4.0	5.5	0	9.0	0
	Std. Deviation (m3)	0.20	st. deviation	0.0	1.8	3.5	0	1.4	0
	Minimum	0.27	min	2	2	3	0	8	0
	Maximum	0.86	max	2	6	8	0	10	0
	Load Volume (m3)	6.82	sum	8	16	11	0	18	0
TOTAL	Number of grapple loads	160	Number of grapple loads	74	25	18	12	18	13
	Mean grapple volume (m3)	0.52	Mean pieces per grapple load	2.3	3.8	5.3	6	6.0	13
	Std. Deviation (m3)	0.21	st. deviation	0.7	1.2	2.8	3	2.8	5
	Minimum	0.07	min	1	1	1	1	1	5
	Maximum	1.08	max	4	6	11	9	10	18
	Load Volume (m3)	83.80	sum	172	96	96	69	108	171

LOAD	LOW PLOT 3			PRODUCT 111	112	113	114	127	115
1	Number of grapple loads	33	Number of grapple loads	0	0	7	11	0	15
	Mean grapple volume (m3)	0.15	Mean pieces per grapple load	0.0	0.0	3.1	1.5	0.0	5.0
	Std. Deviation (m3)	0.10	st. deviation	0.0	0.0	0.4	0.7	0.0	2.9
	Minimum	0.02	min	0	0	3	1	0	1
	Maximum	0.38	max	0	0	4	3	0	12
	Load Volume (m3)	4.83	sum	0	0	22	17	0	75
2	Number of grapple loads	23	Number of grapple loads	11	12	0	0	0	0
	Mean grapple volume (m3)	0.30	Mean pieces per grapple load	1.5	1.8	0.0	0.0	0.0	0.0
	Std. Deviation (m3)	0.13	st. deviation	0.5	0.6	0.0	0.0	0.0	0.0
	Minimum	0.12	min	1	1	0	0	0	0
	Maximum	0.49	max	2	3	0	0	0	0
	Load Volume (m3)	6.84	sum	17	22	0	0	0	0
3	Number of grapple loads	20	Number of grapple loads	4	0	10	0	6	0
	Mean grapple volume (m3)	0.23	Mean pieces per grapple load	1.3	0.0	2.0	0.0	3.0	0.0
	Std. Deviation (m3)	0.10	st. deviation	0.5	0.0	0.8	0.0	1.3	0.0
	Minimum	0.08	min	1	0	1	0	1	0
	Maximum	0.49	max	2	0	3	0	4	0
	Load Volume (m3)	4.53	sum	5	0	20	0	18	0
4	Number of grapple loads	25	Number of grapple loads	6	7	0	5	0	7
	Mean grapple volume (m3)	0.16	Mean pieces per grapple load	1.2	1.4	0.0	1.0	0.0	4.1
	Std. Deviation (m3)	0.11	st. deviation	0.4	0.8	0.0	0.0	0.0	2.5
	Minimum	0.02	min	1	1	0	1	0	1
	Maximum	0.49	max	2	3	0	1	0	7
	Load Volume (m3)	3.88	sum	7	10	0	5	0	29
5	Number of grapple loads	9	Number of grapple loads	0	0	6	0	3	0
	Mean grapple volume (m3)	0.24	Mean pieces per grapple load	0.0	0.0	2.5	0.0	3.0	0.0
	Std. Deviation (m3)	0.09	st. deviation	0.0	0.0	1.0	0.0	1.0	0.0
	Minimum	0.10	min	0	0	1	0	2	0
	Maximum	0.38	max	0	0	4	0	4	0
	Load Volume (m3)	2.14	sum	0	0	15	0	9	0
6	Number of grapple loads	41	Number of grapple loads	0	0	11	14	0	16
	Mean grapple volume (m3)	0.16	Mean pieces per grapple load	0	0.0	2.5	2	0.0	6
	Std. Deviation (m3)	0.11	st. deviation	0	0.0	1.2	2	0.0	3
	Minimum	0.04	min	0	0	1	1	0	2
	Maximum	0.50	max	0	0	5	8	0	12
	Load Volume (m3)	6.67	sum	0	0	27	31	0	97
7	Number of grapple loads	33	Number of grapple loads	6	16	7	0	4	0
	Mean grapple volume (m3)	0.24	Mean pieces per grapple load	1.3	2	2	0.0	3	0.0
	Std. Deviation (m3)	0.11	st. deviation	0.5	1	1	0.0	2	0.0
	Minimum	0.08	min	1	1	1	0	1	0
	Maximum	0.49	max	2	4	3	0	5	0
	Load Volume (m3)	7.79	sum	8	29	14	0	12	0
8	Number of grapple loads	14	Number of grapple loads	8	0	0	0	6	0
	Mean grapple volume (m3)	0.34	Mean pieces per grapple load	1.5	0	0	0	3.8	0
	Std. Deviation (m3)	0.13	st. deviation	0.5	0	0	0	1.6	0
	Minimum	0.08	min	1	0	0	0	1	0
	Maximum	0.49	max	2	0	0	0	5	0
	Load Volume (m3)	4.69	sum	12	0	0	0	23	0
9	Number of grapple loads	30	Number of grapple loads	2	3	10	6	0	9
	Mean grapple volume (m3)	0.18	Mean pieces per grapple load	2.0	1.7	2	1	0	5
	Std. Deviation (m3)	0.14	st. deviation	0.0	0.6	1	1	0	3
	Minimum	0.04	min	2	1	1	1	0	2
	Maximum	0.49	max	2	2	5	2	0	11
	Load Volume (m3)	5.31	sum	4	5	24	8	0	42
10	Number of grapple loads	14	Number of grapple loads	6	5	0	0	3	0
	Mean grapple volume (m3)	0.25	Mean pieces per grapple load	1.3	2	0	0.0	2	0.0
	Std. Deviation (m3)	0.14	st. deviation	0.5	1	0	0.0	1	0.0
	Minimum	0.08	min	1	1	0	0	1	0
	Maximum	0.49	max	2	4	0	0	3	0
	Load Volume (m3)	3.56	sum	8	10	0	0	5	0
11	Number of grapple loads	23	Number of grapple loads	4	0	5	7	0	7
	Mean grapple volume (m3)	0.15	Mean pieces per grapple load	1.3	0	2	1.3	0	5.1
	Std. Deviation (m3)	0.10	st. deviation	0.5	0	0	0.8	0	2.9
	Minimum	0.02	min	1	0	2	1	0	1
	Maximum	0.49	max	2	0	2	3	0	9
	Load Volume (m3)	3.53	sum	5	0	10	9	0	36
12	Number of grapple loads	23	Number of grapple loads	8	9	2	0	4	0
	Mean grapple volume (m3)	0.22	Mean pieces per grapple load	1.0	1.9	1.5	0	2.3	0
	Std. Deviation (m3)	0.09	st. deviation	0.0	0.8	0.7	0	1.9	0
	Minimum	0.08	min	1	1	1	0	1	0
	Maximum	0.39	max	1	3	2	0	5	0
	Load Volume (m3)	5.02	sum	8	17	3	0	9	0
13	Number of grapple loads	35	Number of grapple loads	0	0	12	9	0	14
	Mean grapple volume (m3)	0.17	Mean pieces per grapple load	0.0	0	3	2.1	0	4.8
	Std. Deviation (m3)	0.12	st. deviation	0.0	0	1	1.2	0	3.0
	Minimum	0.02	min	0	0	1	1	0	1
	Maximum	0.48	max	0	0	5	4	0	10
	Load Volume (m3)	6.02	sum	0	0	35	19	0	67
14	Number of grapple loads	30	Number of grapple loads	13	8	0	0	9	0
	Mean grapple volume (m3)	0.28	Mean pieces per grapple load	1.4	2	0	0.0	3	0.0
	Std. Deviation (m3)	0.13	st. deviation	0.5	1	0	0.0	2	0.0
	Minimum	0.08	min	1	1	0	0	1	0
	Maximum	0.49	max	2	4	0	0	6	0
	Load Volume (m3)	8.51	sum	18	16	0	0	28	0
15	Number of grapple loads	22	Number of grapple loads	1	0	2	4	9	6
	Mean grapple volume (m3)	0.17	Mean pieces per grapple load	1.0	0.0	2.5	3	2.6	3
	Std. Deviation (m3)	0.11	st. deviation	0.0	0.0	2.1	1	1.2	2
	Minimum	0.02	min	1	0	1	2	1	1
	Maximum	0.39	max	1	0	4	5	5	7
	Load Volume (m3)	3.70	sum	1	0	5	13	23	17
TOTAL	Number of grapple loads	375	Number of grapple loads	69	60	72	56	44	74
	Mean grapple volume (m3)	0.21	Mean pieces per grapple load	1.3	1.8	2.4	2	2.9	5
	Std. Deviation (m3)	0.12	st. deviation	0.5	0.8	1.1	1	1.5	3
	Minimum	0.02	min	1	1	1	1	1	1
	Maximum	0.50	max	2	4	5	8	6	12
	Load Volume (m3)	77.03	sum	93	109	175	102	127	363

UNLOAD	LOW PLOT 3			PRODUCT 111	112	113	114	127	115
1	Number of grapple loads	11	Number of grapple loads	0	0	4	2	0	5
	Mean grapple volume (m3)	0.44	Mean pieces per grapple load	0.0	0.0	5.5	8.5	0.0	15.0
	Std. Deviation (m3)	0.13	st. deviation	0.0	0.0	1.3	0.7	0.0	1.9
	Minimum	0.26	min	0	0	4	8	0	12
	Maximum	0.67	max	0	0	7	9	0	17
	Load Volume (m3)	4.83	sum	0	0	22	17	0	75
2	Number of grapple loads	14	Number of grapple loads	9	5	0	0	0	0
	Mean grapple volume (m3)	0.49	Mean pieces per grapple load	1.9	4.4	0.0	0.0	0.0	0.0
	Std. Deviation (m3)	0.11	st. deviation	0.3	1.1	0.0	0.0	0.0	0.0
	Minimum	0.24	min	1	3	0	0	0	0
	Maximum	0.74	max	2	6	0	0	0	0
	Load Volume (m3)	6.84	sum	17	22	0	0	0	0
3	Number of grapple loads	11	Number of grapple loads	3	0	5	0	3	0
	Mean grapple volume (m3)	0.41	Mean pieces per grapple load	1.7	0.0	4.0	0.0	6.0	0.0
	Std. Deviation (m3)	0.19	st. deviation	0.6	0.0	2.0	0.0	3.5	0.0
	Minimum	0.15	min	1	0	2	0	2	0
	Maximum	0.62	max	2	0	6	0	8	0
	Load Volume (m3)	4.53	sum	5	0	20	0	18	0
4	Number of grapple loads	10	Number of grapple loads	3	4	0	1	0	2
	Mean grapple volume (m3)	0.39	Mean pieces per grapple load	2.3	2.5	0.0	5.0	0.0	14.5
	Std. Deviation (m3)	0.20	st. deviation	0.6	1.9	0.0	0.0	0.0	0.7
	Minimum	0.12	min	2	1	0	5	0	14
	Maximum	0.73	max	3	5	0	5	0	15
	Load Volume (m3)	3.88	sum	7	10	0	5	0	29
5	Number of grapple loads	5	Number of grapple loads	0	0	3	0	2	0
	Mean grapple volume (m3)	0.43	Mean pieces per grapple load	0.0	0.0	5.0	0.0	4.5	0.0
	Std. Deviation (m3)	0.19	st. deviation	0.0	0.0	1.7	0.0	3.5	0.0
	Minimum	0.15	min	0	0	3	0	2	0
	Maximum	0.58	max	0	0	6	0	7	0
	Load Volume (m3)	2.14	sum	0	0	15	0	9	0
6	Number of grapple loads	16	Number of grapple loads	0	0	6	4	0	6
	Mean grapple volume (m3)	0.41	Mean pieces per grapple load	0	0.0	4.3	8	0.0	16
	Std. Deviation (m3)	0.18	st. deviation	0	0.0	2.9	2	0.0	2
	Minimum	0.10	min	0	0	1	5	0	14
	Maximum	0.77	max	0	0	8	10	0	20
	Load Volume (m3)	6.57	sum	0	0	26	31	0	97
7	Number of grapple loads	17	Number of grapple loads	4	7	4	0	2	0
	Mean grapple volume (m3)	0.46	Mean pieces per grapple load	2.0	4	4	0.0	6	0.0
	Std. Deviation (m3)	0.21	st. deviation	0.0	2	3	0.0	6	0.0
	Minimum	0.10	min	2	2	1	0	2	0
	Maximum	0.77	max	2	6	7	0	10	0
	Load Volume (m3)	7.79	sum	8	29	14	0	12	0
8	Number of grapple loads	10	Number of grapple loads	6	0	0	0	4	0
	Mean grapple volume (m3)	0.47	Mean pieces per grapple load	2.0	0	0	0	5.8	0
	Std. Deviation (m3)	0.17	st. deviation	0.6	0	0	0	2.6	0
	Minimum	0.15	min	1	0	0	0	2	0
	Maximum	0.73	max	3	0	0	0	8	0
	Load Volume (m3)	4.69	sum	12	0	0	0	23	0
9	Number of grapple loads	13	Number of grapple loads	2	2	4	1	0	4
	Mean grapple volume (m3)	0.41	Mean pieces per grapple load	2.0	2.5	6	8	0	11
	Std. Deviation (m3)	0.19	st. deviation	0.0	0.7	2	0	0	7
	Minimum	0.02	min	2	2	4	8	0	1
	Maximum	0.77	max	2	3	8	8	0	17
	Load Volume (m3)	5.31	sum	4	5	24	8	0	42
10	Number of grapple loads	8	Number of grapple loads	4	3	0	0	1	0
	Mean grapple volume (m3)	0.45	Mean pieces per grapple load	2.0	3	0	0.0	5	0.0
	Std. Deviation (m3)	0.17	st. deviation	0.8	2	0	0.0	0	0.0
	Minimum	0.24	min	1	2	0	0	5	0
	Maximum	0.73	max	3	5	0	0	5	0
	Load Volume (m3)	3.56	sum	8	10	0	0	5	0
11	Number of grapple loads	8	Number of grapple loads	2	0	2	1	0	3
	Mean grapple volume (m3)	0.44	Mean pieces per grapple load	2.5	0	5	9.0	0	12.0
	Std. Deviation (m3)	0.20	st. deviation	0.7	0	1	0.0	0	7.8
	Minimum	0.07	min	2	0	4	9	0	3
	Maximum	0.73	max	3	0	6	9	0	17
	Load Volume (m3)	3.53	sum	5	0	10	9	0	36
12	Number of grapple loads	9	Number of grapple loads	4	3	1	0	1	0
	Mean grapple volume (m3)	0.56	Mean pieces per grapple load	2.0	5.7	3.0	0	9.0	0
	Std. Deviation (m3)	0.24	st. deviation	0.8	2.3	0.0	0	0.0	0
	Minimum	0.24	min	1	3	3	0	9	0
	Maximum	0.86	max	3	7	3	0	9	0
	Load Volume (m3)	5.02	sum	8	17	3	0	9	0
13	Number of grapple loads	12	Number of grapple loads	0	0	5	2	0	5
	Mean grapple volume (m3)	0.50	Mean pieces per grapple load	0.0	0	7	9.5	0	13.4
	Std. Deviation (m3)	0.24	st. deviation	0.0	0	2	2.1	0	7.2
	Minimum	0.02	min	0	0	4	8	0	1
	Maximum	0.86	max	0	0	9	11	0	18
	Load Volume (m3)	6.02	sum	0	0	35	19	0	67
14	Number of grapple loads	16	Number of grapple loads	8	4	0	0	4	0
	Mean grapple volume (m3)	0.53	Mean pieces per grapple load	2.3	4	0	0.0	7	0.0
	Std. Deviation (m3)	0.13	st. deviation	0.5	1	0	0.0	2	0.0
	Minimum	0.25	min	2	2	0	0	5	0
	Maximum	0.77	max	3	5	0	0	10	0
	Load Volume (m3)	8.51	sum	18	16	0	0	28	0
15	Number of grapple loads	10	Number of grapple loads	1	0	1	2	4	2
	Mean grapple volume (m3)	0.37	Mean pieces per grapple load	1.0	0.0	5.0	7	5.8	9
	Std. Deviation (m3)	0.20	st. deviation	0.0	0.0	0.0	5	2.1	11
	Minimum	0.02	min	1	0	5	3	3	1
	Maximum	0.63	max	1	0	5	10	8	16
	Load Volume (m3)	3.70	sum	1	0	5	13	23	17
TOTAL	Number of grapple loads	170	Number of grapple loads	46	28	35	13	21	27
	Mean grapple volume (m3)	0.45	Mean pieces per grapple load	2.0	3.9	5.0	8	6.0	13
	Std. Deviation (m3)	0.18	st. deviation	0.5	1.7	2.2	2	2.6	5
	Minimum	0.02	min	1	1	1	3	2	1
	Maximum	0.86	max	3	7	9	11	10	20
	Load Volume (m3)	76.93	sum	93	109	174	102	127	363

LOAD	FRAME PLOT 4			PRODUCT					
				111	112	113	114	127	115
1	Number of grapple loads	18	Number of grapple loads	14	0	0	4	0	0
	Mean grapple volume (m3)	0.41	Mean pieces per grapple load	1.6	0.0	0.0	1.0	0.0	0.0
	Std. Deviation (m3)	0.24	st. deviation	0.5	0.0	0.0	0.0	0.0	0.0
	Minimum	0.08	min	1	0	0	1	0	0
	Maximum	0.65	max	2	0	0	1	0	0
	Load Volume (m3)	7.47	sum	22	0	0	4	0	0
2	Number of grapple loads	18	Number of grapple loads	1	6	3	0	8	0
	Mean grapple volume (m3)	0.17	Mean pieces per grapple load	1.0	1.2	1.0	0.0	2.1	0.0
	Std. Deviation (m3)	0.07	st. deviation	0.0	0.4	0.0	0.0	0.8	0.0
	Minimum	0.08	min	1	1	1	0	1	0
	Maximum	0.32	max	1	2	1	0	3	0
	Load Volume (m3)	3.13	sum	1	7	3	0	17	0
3	Number of grapple loads	23	Number of grapple loads	17	0	0	3	0	3
	Mean grapple volume (m3)	0.43	Mean pieces per grapple load	1.7	0.0	0.0	1.3	0.0	1.3
	Std. Deviation (m3)	0.25	st. deviation	0.5	0.0	0.0	0.6	0.0	0.6
	Minimum	0.03	min	1	0	0	1	0	1
	Maximum	0.65	max	2	0	0	2	0	2
	Load Volume (m3)	9.85	sum	29	0	0	4	0	4
4	Number of grapple loads	18	Number of grapple loads	0	5	5	0	7	1
	Mean grapple volume (m3)	0.21	Mean pieces per grapple load	0.0	2.0	1.2	0.0	2.7	1.0
	Std. Deviation (m3)	0.13	st. deviation	0.0	0.7	0.4	0.0	1.5	0.0
	Minimum	0.03	min	0	1	1	0	1	1
	Maximum	0.48	max	0	3	2	0	5	1
	Load Volume (m3)	3.80	sum	0	10	6	0	19	1
5	Number of grapple loads	23	Number of grapple loads	16	0	0	4	0	3
	Mean grapple volume (m3)	0.34	Mean pieces per grapple load	1.4	0.0	0.0	1.0	0.0	1.0
	Std. Deviation (m3)	0.24	st. deviation	0.5	0.0	0.0	0.0	0.0	0.0
	Minimum	0.03	min	1	0	0	1	0	1
	Maximum	0.65	max	2	0	0	1	0	1
	Load Volume (m3)	7.87	sum	23	0	0	4	0	3
6	Number of grapple loads	17	Number of grapple loads	0	7	1	0	9	0
	Mean grapple volume (m3)	0.22	Mean pieces per grapple load	0	1.7	1.0	0	2.3	0
	Std. Deviation (m3)	0.11	st. deviation	0	0.5	0.0	0	1.6	0
	Minimum	0.08	min	0	1	1	0	1	0
	Maximum	0.40	max	0	2	1	0	5	0
	Load Volume (m3)	3.70	sum	0	12	1	0	21	0
7	Number of grapple loads	25	Number of grapple loads	18	0	0	3	0	4
	Mean grapple volume (m3)	0.40	Mean pieces per grapple load	1.6	0	0	1.3	0	1.3
	Std. Deviation (m3)	0.25	st. deviation	0.5	0	0	0.6	0	0.5
	Minimum	0.03	min	1	0	0	1	0	1
	Maximum	0.65	max	2	0	0	2	0	2
	Load Volume (m3)	9.88	sum	29	0	0	4	0	5
8	Number of grapple loads	21	Number of grapple loads	10	0	0	0	11	0
	Mean grapple volume (m3)	0.28	Mean pieces per grapple load	1.2	0	0	0	2.3	0
	Std. Deviation (m3)	0.17	st. deviation	0.4	0	0	0	1.6	0
	Minimum	0.08	min	1	0	0	0	1	0
	Maximum	0.65	max	2	0	0	0	5	0
	Load Volume (m3)	5.90	sum	12	0	0	0	25	0
9	Number of grapple loads	7	Number of grapple loads	0	5	1	0	1	0
	Mean grapple volume (m3)	0.49	Mean pieces per grapple load	0.0	3.6	4	0	2	0
	Std. Deviation (m3)	0.30	st. deviation	0.0	1.9	0	0	0	0
	Minimum	0.16	min	0	1	4	0	2	0
	Maximum	0.80	max	0	5	4	0	2	0
	Load Volume (m3)	3.46	sum	0	18	4	0	2	0
10	Number of grapple loads	39	Number of grapple loads	21	0	0	12	0	6
	Mean grapple volume (m3)	0.27	Mean pieces per grapple load	1.3	0	0	1.1	0	2.5
	Std. Deviation (m3)	0.21	st. deviation	0.5	0	0	0.3	0	1.9
	Minimum	0.03	min	1	0	0	1	0	1
	Maximum	0.65	max	2	0	0	2	0	6
	Load Volume (m3)	10.55	sum	28	0	0	13	0	15
11	Number of grapple loads	25	Number of grapple loads	3	8	4	0	10	0
	Mean grapple volume (m3)	0.23	Mean pieces per grapple load	1.0	2	1	0.0	3	0.0
	Std. Deviation (m3)	0.11	st. deviation	0.0	1	0	0.0	1	0.0
	Minimum	0.08	min	1	1	1	0	1	0
	Maximum	0.48	max	1	3	1	0	5	0
	Load Volume (m3)	5.72	sum	3	13	4	0	28	0
TOTAL	Number of grapple loads	234	Number of grapple loads	100	31	14	26	46	17
	Mean grapple volume (m3)	0.30	Mean pieces per grapple load	1.5	1.9	1.3	1	2.4	2
	Std. Deviation (m3)	0.21	st. deviation	0.5	1.2	0.8	0	1.3	1
	Minimum	0.03	min	1	1	1	1	1	1
	Maximum	0.80	max	2	5	4	2	5	6
	Load Volume (m3)	71.34	sum	147	60	18	29	112	28

UNLOAD	FRAME PLOT 4			PRODUCT 111	112	113	114	127	115
1	Number of grapple loads	13	Number of grapple loads	12	0	0	1	0	0
	Mean grapple volume (m3)	0.57	Mean pieces per grapple load	1.8	0.0	0.0	4.0	0.0	0.0
	Std. Deviation (m3)	0.14	st. deviation	0.4	0.0	0.0	0.0	0.0	0.0
	Minimum	0.32	min	1	0	0	4	0	0
	Maximum	0.65	max	2	0	0	4	0	0
	Load Volume (m3)	7.47	sum	22	0	0	4	0	0
2	Number of grapple loads	5	Number of grapple loads	0	2	1	0	2	0
	Mean grapple volume (m3)	0.56	Mean pieces per grapple load	0.0	3.5	3.0	0.0	8.5	0.0
	Std. Deviation (m3)	0.24	st. deviation	0.0	2.1	0.0	0.0	2.1	0.0
	Minimum	0.32	min	0	2	3	0	7	0
	Maximum	0.80	max	0	5	3	0	10	0
	Load Volume (m3)	2.80	sum	0	7	3	0	17	0
3	Number of grapple loads	16	Number of grapple loads	14	0	0	1	0	1
	Mean grapple volume (m3)	0.64	Mean pieces per grapple load	2.1	0.0	0.0	4.0	0.0	4.0
	Std. Deviation (m3)	0.20	st. deviation	0.4	0.0	0.0	0.0	0.0	0.0
	Minimum	0.11	min	2	0	0	4	0	4
	Maximum	0.97	max	3	0	0	4	0	4
	Load Volume (m3)	10.18	sum	30	0	0	4	0	4
4	Number of grapple loads	9	Number of grapple loads	0	3	1	0	4	1
	Mean grapple volume (m3)	0.42	Mean pieces per grapple load	0.0	3.3	6.0	0.0	4.8	1.0
	Std. Deviation (m3)	0.23	st. deviation	0.0	1.2	0.0	0.0	2.5	0.0
	Minimum	0.03	min	0	2	6	0	1	1
	Maximum	0.66	max	0	4	6	0	6	1
	Load Volume (m3)	3.80	sum	0	10	6	0	19	1
5	Number of grapple loads	14	Number of grapple loads	12	0	0	1	0	1
	Mean grapple volume (m3)	0.56	Mean pieces per grapple load	1.9	0.0	0.0	4.0	0.0	3.0
	Std. Deviation (m3)	0.18	st. deviation	0.3	0.0	0.0	0.0	0.0	0.0
	Minimum	0.08	min	1	0	0	4	0	3
	Maximum	0.65	max	2	0	0	4	0	3
	Load Volume (m3)	7.87	sum	23	0	0	4	0	3
6	Number of grapple loads	7	Number of grapple loads	0	3	1	0	3	0
	Mean grapple volume (m3)	0.53	Mean pieces per grapple load	0	4.0	1.0	0	7.0	0
	Std. Deviation (m3)	0.27	st. deviation	0	2.0	0.0	0	1.0	0
	Minimum	0.11	min	0	2	1	0	6	0
	Maximum	0.96	max	0	6	1	0	8	0
	Load Volume (m3)	3.70	sum	0	12	1	0	21	0
7	Number of grapple loads	16	Number of grapple loads	14	0	0	1	0	1
	Mean grapple volume (m3)	0.62	Mean pieces per grapple load	2.1	0	0	4.0	0	5.0
	Std. Deviation (m3)	0.21	st. deviation	0.5	0	0	0.0	0	0.0
	Minimum	0.14	min	1	0	0	4	0	5
	Maximum	0.97	max	3	0	0	4	0	5
	Load Volume (m3)	9.88	sum	29	0	0	4	0	5
8	Number of grapple loads	12	Number of grapple loads	8	0	0	0	4	0
	Mean grapple volume (m3)	0.49	Mean pieces per grapple load	1.5	0	0	0	6.3	0
	Std. Deviation (m3)	0.21	st. deviation	0.5	0	0	0	3.8	0
	Minimum	0.08	min	1	0	0	0	1	0
	Maximum	0.80	max	2	0	0	0	10	0
	Load Volume (m3)	5.90	sum	12	0	0	0	25	0
9	Number of grapple loads	7	Number of grapple loads	0	4	1	0	2	0
	Mean grapple volume (m3)	0.49	Mean pieces per grapple load	0.0	4.5	4	0	1	0
	Std. Deviation (m3)	0.31	st. deviation	0.0	0.6	0	0	0	0
	Minimum	0.08	min	0	4	4	0	1	0
	Maximum	0.80	max	0	5	4	0	1	0
	Load Volume (m3)	3.46	sum	0	18	4	0	2	0
10	Number of grapple loads	20	Number of grapple loads	16	0	0	2	0	2
	Mean grapple volume (m3)	0.53	Mean pieces per grapple load	1.8	0	0	6.5	0	7.5
	Std. Deviation (m3)	0.20	st. deviation	0.6	0	0	0.7	0	6.4
	Minimum	0.08	min	1	0	0	6	0	3
	Maximum	0.97	max	3	0	0	7	0	12
	Load Volume (m3)	10.55	sum	28	0	0	13	0	15
11	Number of grapple loads	13	Number of grapple loads	2	4	2	0	5	0
	Mean grapple volume (m3)	0.44	Mean pieces per grapple load	1.5	3	2	0.0	6	0.0
	Std. Deviation (m3)	0.24	st. deviation	0.7	2	1	0.0	3	0.0
	Minimum	0.08	min	1	1	1	0	1	0
	Maximum	0.80	max	2	5	3	0	7	0
	Load Volume (m3)	5.72	sum	3	13	4	0	28	0
TOTAL	Number of grapple loads	132	Number of grapple loads	78	16	6	6	20	6
	Mean grapple volume (m3)	0.54	Mean pieces per grapple load	1.9	3.8	3.0	5	5.6	5
	Std. Deviation (m3)	0.22	st. deviation	0.5	1.5	1.9	1	2.9	4
	Minimum	0.03	min	1	1	1	4	1	1
	Maximum	0.97	max	3	6	6	7	10	12
	Load Volume (m3)	71.34	sum	147	60	18	29	112	28

LOAD	LOW PLOT 5			PRODUCT 111	112	113	114	127	115
1	Number of grapple loads	36	Number of grapple loads	12	15	0	5	0	4
	Mean grapple volume (m3)	0.26	Mean pieces per grapple load	1.4	1.8	0.0	1.8	0.0	1.8
	Std. Deviation (m3)	0.17	st. deviation	0.5	0.9	0.0	1.1	0.0	1.0
	Minimum	0.02	min	1	1	0	1	0	1
	Maximum	0.56	max	2	3	0	3	0	3
	Load Volume (m3)	9.48	sum	17	27	0	9	0	7
2	Number of grapple loads	30	Number of grapple loads	5	0	4	0	21	0
	Mean grapple volume (m3)	0.26	Mean pieces per grapple load	1.8	0.0	2.3	0.0	2.3	0.0
	Std. Deviation (m3)	0.16	st. deviation	0.4	0.0	1.5	0.0	1.3	0.0
	Minimum	0.09	min	1	0	1	0	1	0
	Maximum	0.56	max	2	0	4	0	5	0
	Load Volume (m3)	7.67	sum	9	0	9	0	48	0
3	Number of grapple loads	43	Number of grapple loads	9	6	0	14	0	14
	Mean grapple volume (m3)	0.21	Mean pieces per grapple load	1.7	2.5	0.0	1.6	0.0	2.9
	Std. Deviation (m3)	0.19	st. deviation	0.5	1.0	0.0	0.7	0.0	1.9
	Minimum	0.02	min	1	1	0	1	0	1
	Maximum	0.58	max	2	4	0	3	0	7
	Load Volume (m3)	8.95	sum	15	15	0	23	0	40
4	Number of grapple loads	29	Number of grapple loads	14	0	0	0	15	0
	Mean grapple volume (m3)	0.31	Mean pieces per grapple load	1.5	0.0	0.0	0.0	2.3	0.0
	Std. Deviation (m3)	0.17	st. deviation	0.5	0.0	0.0	0.0	1.4	0.0
	Minimum	0.09	min	1	0	0	0	1	0
	Maximum	0.56	max	2	0	0	0	5	0
	Load Volume (m3)	8.87	sum	21	0	0	0	34	0
5	Number of grapple loads	41	Number of grapple loads	0	22	0	8	0	11
	Mean grapple volume (m3)	0.22	Mean pieces per grapple load	0.0	2.0	0.0	2.1	0.0	4.4
	Std. Deviation (m3)	0.14	st. deviation	0.0	0.8	0.0	1.6	0.0	1.8
	Minimum	0.02	min	0	1	0	1	0	1
	Maximum	0.58	max	0	4	0	5	0	7
	Load Volume (m3)	8.86	sum	0	45	0	17	0	48
6	Number of grapple loads	35	Number of grapple loads	16	0	0	0	19	0
	Mean grapple volume (m3)	0.31	Mean pieces per grapple load	1	0.0	0.0	0	3.1	0
	Std. Deviation (m3)	0.13	st. deviation	0	0.0	0.0	0	1.5	0
	Minimum	0.09	min	1	0	0	0	1	0
	Maximum	0.56	max	2	0	0	0	6	0
	Load Volume (m3)	10.71	sum	20	0	0	0	58	0
7	Number of grapple loads	23	Number of grapple loads	10	6	0	0	7	0
	Mean grapple volume (m3)	0.38	Mean pieces per grapple load	1.6	2	0	0.0	4	0.0
	Std. Deviation (m3)	0.14	st. deviation	0.5	1	0	0.0	1	0.0
	Minimum	0.15	min	1	1	0	0	2	0
	Maximum	0.56	max	2	3	0	0	6	0
	Load Volume (m3)	8.74	sum	16	13	0	0	27	0
8	Number of grapple loads	44	Number of grapple loads	0	0	12	19	0	13
	Mean grapple volume (m3)	0.17	Mean pieces per grapple load	0.0	0	3	2	0.0	3
	Std. Deviation (m3)	0.16	st. deviation	0.0	0	2	1	0.0	2
	Minimum	0.02	min	0	0	1	1	0	1
	Maximum	0.71	max	0	0	7	3	0	9
	Load Volume (m3)	7.37	sum	0	0	41	30	0	45
9	Number of grapple loads	16	Number of grapple loads	5	5	0	0	6	0
	Mean grapple volume (m3)	0.35	Mean pieces per grapple load	1.2	2.4	0	0	4	0
	Std. Deviation (m3)	0.13	st. deviation	0.4	0.5	0	0	2	0
	Minimum	0.18	min	1	2	0	0	2	0
	Maximum	0.62	max	2	3	0	0	7	0
	Load Volume (m3)	5.54	sum	6	12	0	0	24	0
TOTAL	Number of grapple loads	297	Number of grapple loads	71	54	16	46	68	42
	Mean grapple volume (m3)	0.26	Mean pieces per grapple load	1.5	2	3	1.7	3	3.3
	Std. Deviation (m3)	0.17	st. deviation	0.5	1	2	1.0	2	2.0
	Minimum	0.02	min	1	1	1	1	1	1
	Maximum	0.71	max	2	4	7	5	7	9
	Load Volume (m3)	76.19	sum	104	112	50	79	191	140

UNLOAD	LOW PLOT 5			PRODUCT 111	112	113	114	127	115
1	Number of grapple loads	17	Number of grapple loads	8	6	0	2	0	1
	Mean grapple volume (m3)	0.56	Mean pieces per grapple load	2.1	4.5	0.0	4.5	0.0	7.0
	Std. Deviation (m3)	0.21	st. deviation	0.4	1.6	0.0	2.1	0.0	0.0
	Minimum	0.16	min	2	2	0	3	0	7
	Maximum	0.87	max	3	6	0	6	0	7
	Load Volume (m3)	9.48	sum	17	27	0	9	0	7
2	Number of grapple loads	16	Number of grapple loads	5	0	3	0	8	0
	Mean grapple volume (m3)	0.48	Mean pieces per grapple load	1.8	0.0	3.0	0.0	6.0	0.0
	Std. Deviation (m3)	0.20	st. deviation	0.8	0.0	1.0	0.0	2.0	0.0
	Minimum	0.20	min	1	0	2	0	3	0
	Maximum	0.84	max	3	0	4	0	8	0
	Load Volume (m3)	7.67	sum	9	0	9	0	48	0
3	Number of grapple loads	16	Number of grapple loads	7	3	0	3	0	3
	Mean grapple volume (m3)	0.56	Mean pieces per grapple load	2.1	5.0	0.0	7.7	0.0	13.3
	Std. Deviation (m3)	0.23	st. deviation	0.7	2.6	0.0	0.6	0.0	1.5
	Minimum	0.27	min	1	2	0	7	0	12
	Maximum	1.02	max	3	7	0	8	0	15
	Load Volume (m3)	8.95	sum	15	15	0	23	0	40
4	Number of grapple loads	15	Number of grapple loads	10	0	0	0	5	0
	Mean grapple volume (m3)	0.57	Mean pieces per grapple load	2.0	0.0	0.0	0.0	6.8	0.0
	Std. Deviation (m3)	0.20	st. deviation	0.8	0.0	0.0	0.0	1.6	0.0
	Minimum	0.28	min	1	0	0	0	4	0
	Maximum	0.84	max	3	0	0	0	8	0
	Load Volume (m3)	8.59	sum	20	0	0	0	34	0
5	Number of grapple loads	16	Number of grapple loads	0	9	0	3	0	4
	Mean grapple volume (m3)	0.59	Mean pieces per grapple load	0.0	5.4	0.0	5.7	0.0	12.0
	Std. Deviation (m3)	0.32	st. deviation	0.0	1.5	0.0	4.2	0.0	6.7
	Minimum	0.05	min	0	3	0	1	0	2
	Maximum	1.02	max	0	7	0	9	0	16
	Load Volume (m3)	9.44	sum	0	49	0	17	0	48
6	Number of grapple loads	15	Number of grapple loads	7	0	0	0	8	0
	Mean grapple volume (m3)	0.71	Mean pieces per grapple load	3	0.0	0.0	0	7.3	0
	Std. Deviation (m3)	0.22	st. deviation	1	0.0	0.0	0	2.5	0
	Minimum	0.35	min	2	0	0	0	4	0
	Maximum	1.12	max	4	0	0	0	11	0
	Load Volume (m3)	10.71	sum	20	0	0	0	58	0
7	Number of grapple loads	16	Number of grapple loads	9	3	0	0	4	0
	Mean grapple volume (m3)	0.55	Mean pieces per grapple load	1.8	4	0	0.0	7	0.0
	Std. Deviation (m3)	0.14	st. deviation	0.4	1	0	0.0	2	0.0
	Minimum	0.28	min	1	4	0	0	4	0
	Maximum	0.79	max	2	5	0	0	9	0
	Load Volume (m3)	8.74	sum	16	13	0	0	27	0
8	Number of grapple loads	15	Number of grapple loads	0	0	7	5	0	3
	Mean grapple volume (m3)	0.49	Mean pieces per grapple load	0.0	0	6	6	0.0	15
	Std. Deviation (m3)	0.28	st. deviation	0.0	0	3	4	0.0	0
	Minimum	0.07	min	0	0	1	1	0	15
	Maximum	1.02	max	0	0	10	10	0	15
	Load Volume (m3)	7.37	sum	0	0	41	30	0	45
9	Number of grapple loads	9	Number of grapple loads	3	3	0	0	3	0
	Mean grapple volume (m3)	0.62	Mean pieces per grapple load	2.0	4.0	0	0	8	0
	Std. Deviation (m3)	0.13	st. deviation	0.0	1.0	0	0	2	0
	Minimum	0.44	min	2	3	0	0	6	0
	Maximum	0.88	max	2	5	0	0	10	0
	Load Volume (m3)	5.54	sum	6	12	0	0	24	0
TOTAL	Number of grapple loads	135	Number of grapple loads	49	24	10	13	28	11
	Mean grapple volume (m3)	0.57	Mean pieces per grapple load	2.1	5	5	6.1	7	12.7
	Std. Deviation (m3)	0.23	st. deviation	0.7	2	3	3.2	2	4.4
	Minimum	0.05	min	1	2	1	1	3	2
	Maximum	1.12	max	4	7	10	10	11	16
	Load Volume (m3)	76.49	sum	103	116	50	79	191	140

LOAD	GROUP PLOT 6			PRODUCT 111	112	113	114	127	115
1	Number of grapple loads	28	Number of grapple loads	25	0	0	0	3	0
	Mean grapple volume (m3)	0.40	Mean pieces per grapple load	1.5	0.0	0.0	0.0	1.3	0.0
	Std. Deviation (m3)	0.17	st. deviation	0.5	0.0	0.0	0.0	0.6	0.0
	Minimum	0.09	min	1	0	0	0	1	0
	Maximum	0.57	max	2	0	0	0	2	0
	Load Volume (m3)	11.15	sum	38	0	0	0	4	0
2	Number of grapple loads	43	Number of grapple loads	17	0	0	12	0	14
	Mean grapple volume (m3)	0.26	Mean pieces per grapple load	1.8	0.0	0.0	1.8	0.0	3.0
	Std. Deviation (m3)	0.22	st. deviation	0.4	0.0	0.0	1.1	0.0	2.0
	Minimum	0.02	min	1	0	0	1	0	1
	Maximum	0.57	max	2	0	0	4	0	7
	Load Volume (m3)	11.02	sum	30	0	0	21	0	42
3	Number of grapple loads	23	Number of grapple loads	5	8	1	0	9	0
	Mean grapple volume (m3)	0.28	Mean pieces per grapple load	1.0	2.3	4.0	0.0	2.7	0.0
	Std. Deviation (m3)	0.11	st. deviation	0.0	0.9	0.0	0.0	1.2	0.0
	Minimum	0.09	min	1	1	4	0	1	0
	Maximum	0.44	max	1	3	4	0	5	0
	Load Volume (m3)	6.54	sum	5	18	4	0	24	0
4	Number of grapple loads	20	Number of grapple loads	6	5	3	2	3	1
	Mean grapple volume (m3)	0.39	Mean pieces per grapple load	1.7	3.4	4.0	2.0	3.0	4.0
	Std. Deviation (m3)	0.19	st. deviation	0.5	1.1	1.0	1.4	2.0	0.0
	Minimum	0.07	min	1	2	3	1	1	4
	Maximum	0.74	max	2	5	5	3	5	4
	Load Volume (m3)	7.72	sum	10	17	12	4	9	4
5	Number of grapple loads	34	Number of grapple loads	13	7	0	6	0	8
	Mean grapple volume (m3)	0.29	Mean pieces per grapple load	1.8	2.0	0.0	1.8	0.0	2.5
	Std. Deviation (m3)	0.23	st. deviation	0.6	1.0	0.0	1.0	0.0	1.2
	Minimum	0.02	min	1	1	0	1	0	1
	Maximum	0.85	max	3	4	0	3	0	4
	Load Volume (m3)	9.86	sum	23	14	0	11	0	20
6	Number of grapple loads	33	Number of grapple loads	15.0	7.0	0.0	7.0	0.0	4.0
	Mean grapple volume (m3)	0.33	Mean pieces per grapple load	2	2.1	0.0	2	0.0	4
	Std. Deviation (m3)	0.21	st. deviation	0	1.1	0.0	1	0.0	2
	Minimum	0.02	min	1	1.0	0.0	1	0.0	1
	Maximum	0.59	max	2	4.0	0.0	5	0.0	6
	Load Volume (m3)	10.95	sum	26	15	0	14	0	14
7	Number of grapple loads	24	Number of grapple loads	12	0	0	0	12	0
	Mean grapple volume (m3)	0.35	Mean pieces per grapple load	1.5	0	0	0.0	3	0.0
	Std. Deviation (m3)	0.17	st. deviation	0.5	0	0	0.0	2	0.0
	Minimum	0.09	min	1	0	0	0	1	0
	Maximum	0.69	max	2	0	0	0	8	0
	Load Volume (m3)	8.29	sum	18	0	0	0	37	0
8	Number of grapple loads	39	Number of grapple loads	15	2	0	12	0	10
	Mean grapple volume (m3)	0.24	Mean pieces per grapple load	1.5	4	0	2	0.0	3
	Std. Deviation (m3)	0.21	st. deviation	0.5	1	0	1	0.0	1
	Minimum	0.02	min	1	3	0	1	0	1
	Maximum	0.74	max	2	5	0	6	0	4
	Load Volume (m3)	9.54	sum	22	8	0	21	0	25
9	Number of grapple loads	26	Number of grapple loads	0	0	12	0	14	0
	Mean grapple volume (m3)	0.24	Mean pieces per grapple load	0.0	0.0	2	0	3	0
	Std. Deviation (m3)	0.17	st. deviation	0.0	0.0	2	0	1	0
	Minimum	0.09	min	0	0	1	0	1	0
	Maximum	0.71	max	0	0	7	0	5	0
	Load Volume (m3)	6.36	sum	0	0	29	0	40	0
10	Number of grapple loads	18	Number of grapple loads	0	16	0	0	2	0
	Mean grapple volume (m3)	0.36	Mean pieces per grapple load	0.0	2	0	0.0	6	0.0
	Std. Deviation (m3)	0.14	st. deviation	0.0	1	0	0.0	0	0.0
	Minimum	0.15	min	0	1	0	0	6	0
	Maximum	0.59	max	0	4	0	0	6	0
	Load Volume (m3)	6.48	sum	0	37	0	0	12	0
TOTAL	Number of grapple loads	288	Number of grapple loads	108	45	16	39	43	37
	Mean grapple volume (m3)	0.31	Mean pieces per grapple load	1.6	2	3	1.8	3	2.8
	Std. Deviation (m3)	0.20	st. deviation	0.5	1	2	1.2	2	1.6
	Minimum	0.02	min	1	1	1	1	1	1
	Maximum	0.85	max	3	5	7	6	8	7
	Load Volume (m3)	87.92	sum	172	109	45	71	126	105

UNLOAD	GROUP PLOT 6			PRODUCT					
				111	112	113	114	127	115
1	Number of grapple loads	20	Number of grapple loads	19	0	0	0	1	0
	Mean grapple volume (m3)	0.56	Mean pieces per grapple load	2.0	0.0	0.0	0.0	4.0	0.0
	Std. Deviation (m3)	0.11	st. deviation	0.3	0.0	0.0	0.0	0.0	0.0
	Minimum	0.28	min	1	0	0	0	4	0
	Maximum	0.85	max	3	0	0	0	4	0
	Load Volume (m3)	11.15	sum	38	0	0	0	4	0
2	Number of grapple loads	22	Number of grapple loads	16	0	0	3	0	3
	Mean grapple volume (m3)	0.50	Mean pieces per grapple load	1.9	0.0	0.0	7.0	0.0	14.0
	Std. Deviation (m3)	0.15	st. deviation	0.5	0.0	0.0	1.0	0.0	2.0
	Minimum	0.27	min	1	0	0	6	0	12
	Maximum	0.85	max	3	0	0	8	0	16
	Load Volume (m3)	11.02	sum	30	0	0	21	0	42
3	Number of grapple loads	16	Number of grapple loads	5	5	2	0	4	0
	Mean grapple volume (m3)	0.41	Mean pieces per grapple load	1.0	3.6	2.0	0.0	6.0	0.0
	Std. Deviation (m3)	0.17	st. deviation	0.0	0.5	0.0	0.0	2.2	0.0
	Minimum	0.20	min	1	3	2	0	3	0
	Maximum	0.69	max	1	4	2	0	8	0
	Load Volume (m3)	6.54	sum	5	18	4	0	24	0
4	Number of grapple loads	15	Number of grapple loads	5	4	3	1	1	1
	Mean grapple volume (m3)	0.51	Mean pieces per grapple load	2.0	4.3	4.0	4.0	9.0	4.0
	Std. Deviation (m3)	0.20	st. deviation	0.0	0.5	2.6	0.0	0.0	0.0
	Minimum	0.09	min	2	4	2	4	9	4
	Maximum	0.77	max	2	5	7	4	9	4
	Load Volume (m3)	7.72	sum	10	17	12	4	9	4
5	Number of grapple loads	16	Number of grapple loads	8	4	0	2	0	2
	Mean grapple volume (m3)	0.62	Mean pieces per grapple load	2.9	3.5	0.0	5.5	0.0	10.0
	Std. Deviation (m3)	0.30	st. deviation	0.8	1.3	0.0	0.7	0.0	8.5
	Minimum	0.09	min	2	2	0	5	0	4
	Maximum	1.14	max	4	5	0	6	0	16
	Load Volume (m3)	9.86	sum	23	14	0	11	0	20
6	Number of grapple loads	19	Number of grapple loads	12.0	3.0	0.0	3.0	0.0	1.0
	Mean grapple volume (m3)	0.58	Mean pieces per grapple load	2	5.0	0.0	5	0.0	14
	Std. Deviation (m3)	0.22	st. deviation	1	1.0	0.0	2	0.0	0
	Minimum	0.22	min	1	4.0	0.0	3	0.0	14
	Maximum	0.88	max	3	6	0	6	0	14
	Load Volume (m3)	10.95	sum	26	15	0	14	0	14
7	Number of grapple loads	15	Number of grapple loads	10	0	0	0	5	0
	Mean grapple volume (m3)	0.55	Mean pieces per grapple load	1.8	0	0	0.0	7	0.0
	Std. Deviation (m3)	0.17	st. deviation	0.6	0	0	0.0	1	0.0
	Minimum	0.28	min	1	0	0	0	6	0
	Maximum	0.85	max	3	0	0	0	9	0
	Load Volume (m3)	8.29	sum	18	0	0	0	37	0
8	Number of grapple loads	16	Number of grapple loads	8	3	0	3	0	2
	Mean grapple volume (m3)	0.60	Mean pieces per grapple load	2.8	3	0	7	0.0	13
	Std. Deviation (m3)	0.27	st. deviation	0.7	2	0	2	0.0	4
	Minimum	0.15	min	2	1	0	5	0	10
	Maximum	1.14	max	4	4	0	9	0	15
	Load Volume (m3)	9.54	sum	22	8	0	21	0	25
9	Number of grapple loads	10	Number of grapple loads	0	0	4	0	6	0
	Mean grapple volume (m3)	0.64	Mean pieces per grapple load	0.0	0.0	7	0	7	0
	Std. Deviation (m3)	0.20	st. deviation	0.0	0.0	2	0	2	0
	Minimum	0.40	min	0	0	4	0	5	0
	Maximum	0.91	max	0	0	9	0	10	0
	Load Volume (m3)	6.36	sum	0	0	29	0	40	0
10	Number of grapple loads	10	Number of grapple loads	0	8	0	0	2	0
	Mean grapple volume (m3)	0.65	Mean pieces per grapple load	0.0	5	0	0.0	6	0.0
	Std. Deviation (m3)	0.17	st. deviation	0.0	1	0	0.0	0	0.0
	Minimum	0.44	min	0	3	0	0	6	0
	Maximum	1.03	max	0	7	0	0	6	0
	Load Volume (m3)	6.48	sum	0	37	0	0	12	0
TOTAL	Number of grapple loads	159	Number of grapple loads	83	27	9	12	19	9
	Mean grapple volume (m3)	0.55	Mean pieces per grapple load	2.1	4	5	5.9	7	11.7
	Std. Deviation (m3)	0.20	st. deviation	0.7	1	3	1.7	2	4.7
	Minimum	0.09	min	1	1	2	3	3	4
	Maximum	1.14	max	4	7	9	9	10	16
	Load Volume (m3)	87.92	sum	172	109	45	71	126	105

LOAD	CLEARFELL PLOT 7			PRODUCT 111	112	113	114	127	115
1	Number of grapple loads	17	Number of grapple loads	17	0	0	0	0	0
	Mean grapple volume (m3)	0.35	Mean pieces per grapple load	1.1	0.0	0.0	0.0	0.0	0.0
	Std. Deviation (m3)	0.10	st. deviation	0.3	0.0	0.0	0.0	0.0	0.0
	Minimum	0.31	min	1	0	0	0	0	0
	Maximum	0.63	max	2	0	0	0	0	0
	Load Volume (m3)	5.96	sum	19	0	0	0	0	0
2	Number of grapple loads	33	Number of grapple loads	16	0	0	7	0	10
	Mean grapple volume (m3)	0.25	Mean pieces per grapple load	1.3	0.0	0.0	1.7	0.0	4.3
	Std. Deviation (m3)	0.19	st. deviation	0.5	0.0	0.0	1.0	0.0	2.1
	Minimum	0.04	min	1	0	0	1	0	2
	Maximum	0.63	max	2	0	0	3	0	8
	Load Volume (m3)	8.34	sum	21	0	0	12	0	43
3	Number of grapple loads	23	Number of grapple loads	17	0	0	0	6	0
	Mean grapple volume (m3)	0.34	Mean pieces per grapple load	1.2	0.0	0.0	0.0	2.7	0.0
	Std. Deviation (m3)	0.12	st. deviation	0.4	0.0	0.0	0.0	0.8	0.0
	Minimum	0.19	min	1	0	0	0	2	0
	Maximum	0.63	max	2	0	0	0	4	0
	Load Volume (m3)	7.79	sum	20	0	0	0	16	0
4	Number of grapple loads	24	Number of grapple loads	9	15	0	0	0	0
	Mean grapple volume (m3)	0.30	Mean pieces per grapple load	1.0	1.9	0.0	0.0	0.0	0.0
	Std. Deviation (m3)	0.10	st. deviation	0.0	0.9	0.0	0.0	0.0	0.0
	Minimum	0.15	min	1	1	0	0	0	0
	Maximum	0.45	max	1	3	0	0	0	0
	Load Volume (m3)	7.14	sum	9	29	0	0	0	0
5	Number of grapple loads	26	Number of grapple loads	16	0	10	0	0	0
	Mean grapple volume (m3)	0.32	Mean pieces per grapple load	1.2	0.0	2.5	0.0	0.0	0.0
	Std. Deviation (m3)	0.14	st. deviation	0.4	0.0	1.2	0.0	0.0	0.0
	Minimum	0.10	min	1	0	1	0	0	0
	Maximum	0.63	max	2	0	4	0	0	0
	Load Volume (m3)	8.44	sum	19	0	25	0	0	0
6	Number of grapple loads	29	Number of grapple loads	8	0	0	9	0	12
	Mean grapple volume (m3)	0.19	Mean pieces per grapple load	1	0.0	0.0	2	0.0	6
	Std. Deviation (m3)	0.10	st. deviation	0	0.0	0.0	1	0.0	3
	Minimum	0.02	min	1	0	0	1	0	1
	Maximum	0.34	max	1	0	0	5	0	9
	Load Volume (m3)	5.45	sum	8	0	0	22	0	67
7	Number of grapple loads	25	Number of grapple loads	19	0	0	0	6	0
	Mean grapple volume (m3)	0.32	Mean pieces per grapple load	1.1	0	0	0.0	3	0.0
	Std. Deviation (m3)	0.10	st. deviation	0.2	0	0	0.0	2	0.0
	Minimum	0.09	min	1	0	0	0	1	0
	Maximum	0.63	max	2	0	0	0	6	0
	Load Volume (m3)	7.98	sum	20	0	0	0	18	0
8	Number of grapple loads	30	Number of grapple loads	21	0	9	0	0	0
	Mean grapple volume (m3)	0.33	Mean pieces per grapple load	1.2	0	2	0	0.0	0
	Std. Deviation (m3)	0.16	st. deviation	0.4	0	1	0	0.0	0
	Minimum	0.10	min	1	0	1	0	0	0
	Maximum	0.63	max	2	0	4	0	0	0
	Load Volume (m3)	9.94	sum	26	0	18	0	0	0
9	Number of grapple loads	23	Number of grapple loads	10	13	0	0	0	0
	Mean grapple volume (m3)	0.35	Mean pieces per grapple load	1.4	1.8	0	0	0	0
	Std. Deviation (m3)	0.16	st. deviation	0.5	0.8	0	0	0	0
	Minimum	0.15	min	1	1	0	0	0	0
	Maximum	0.63	max	2	3	0	0	0	0
	Load Volume (m3)	7.97	sum	14	24	0	0	0	0
10	Number of grapple loads	22	Number of grapple loads	16	6	0	0	0	0
	Mean grapple volume (m3)	0.43	Mean pieces per grapple load	1.4	3	0	0.0	0	0.0
	Std. Deviation (m3)	0.15	st. deviation	0.5	1	0	0.0	0	0.0
	Minimum	0.30	min	1	2	0	0	0	0
	Maximum	0.63	max	2	3	0	0	0	0
	Load Volume (m3)	9.45	sum	23	15	0	0	0	0
11	Number of grapple loads	35	Number of grapple loads	13	0	0	8	0	14
	Mean grapple volume (m3)	0.24	Mean pieces per grapple load	1.2	0	0	2.9	0	6.1
	Std. Deviation (m3)	0.15	st. deviation	0.4	0	0	1.2	0	3.4
	Minimum	0.04	min	1	0	0	1	0	2
	Maximum	0.63	max	2	0	0	4	0	13
	Load Volume (m3)	8.42	sum	16	0	0	23	0	85
12	Number of grapple loads	21	Number of grapple loads	15	0	0	3	0	3
	Mean grapple volume (m3)	0.35	Mean pieces per grapple load	1.3	0.0	0.0	3	0.0	10
	Std. Deviation (m3)	0.17	st. deviation	0.5	0.0	0.0	2	0.0	2
	Minimum	0.07	min	1	0	0	1	0	8
	Maximum	0.63	max	2	0	0	5	0	12
	Load Volume (m3)	7.45	sum	20	0	0	8	0	29
13	Number of grapple loads	21	Number of grapple loads	8	6	0	0	7	0
	Mean grapple volume (m3)	0.29	Mean pieces per grapple load	1.3	2	0	0.0	2	0.0
	Std. Deviation (m3)	0.13	st. deviation	0.5	0	0	0.0	0	0.0
	Minimum	0.09	min	1	2	0	0	1	0
	Maximum	0.63	max	2	2	0	0	2	0
	Load Volume (m3)	6.06	sum	10	12	0	0	12	0

14	Number of grapple loads	33	Number of grapple loads	0	0	15	9	0	9
	Mean grapple volume (m3)	0.20	Mean pieces per grapple load	0.0	0	3	2.4	0	5.9
	Std. Deviation (m3)	0.10	st. deviation	0.0	0	1	1.4	0	2.0
	Minimum	0.07	min	0	0	1	1	0	4
	Maximum	0.40	max	0	0	4	4	0	10
	Load Volume (m3)	6.49	sum	0	0	39	22	0	53
15	Number of grapple loads	23	Number of grapple loads	15	8	0	0	0	0
	Mean grapple volume (m3)	0.39	Mean pieces per grapple load	1.4	2.0	0.0	0	0.0	0
	Std. Deviation (m3)	0.16	st. deviation	0.5	0.8	0.0	0	0.0	0
	Minimum	0.15	min	1	1	0	0	0	0
	Maximum	0.63	max	2	3	0	0	0	0
	Load Volume (m3)	8.97	sum	21	16	0	0	0	0
16	Number of grapple loads	27	Number of grapple loads	19	0	0	3	0	5
	Mean grapple volume (m3)	0.35	Mean pieces per grapple load	1.4	0	0	2.7	0	6.0
	Std. Deviation (m3)	0.19	st. deviation	0.5	0	0	1.5	0	3.1
	Minimum	0.06	min	1	0	0	1	0	3
	Maximum	0.63	max	2	0	0	4	0	11
	Load Volume (m3)	9.35	sum	26	0	0	8	0	30
17	Number of grapple loads	28	Number of grapple loads	21	0	7	0	0	0
	Mean grapple volume (m3)	0.32	Mean pieces per grapple load	1.1	0	2	0.0	0	0.0
	Std. Deviation (m3)	0.13	st. deviation	0.4	0	1	0.0	0	0.0
	Minimum	0.10	min	1	0	1	0	0	0
	Maximum	0.63	max	2	0	3	0	0	0
	Load Volume (m3)	8.92	sum	24	0	14	0	0	0
18	Number of grapple loads	23	Number of grapple loads	17	6	0	0	0	0
	Mean grapple volume (m3)	0.36	Mean pieces per grapple load	1.1	2.7	0.0	0	0.0	0
	Std. Deviation (m3)	0.11	st. deviation	0.3	0.8	0.0	0	0.0	0
	Minimum	0.15	min	1	1	0	0	0	0
	Maximum	0.63	max	2	3	0	0	0	0
	Load Volume (m3)	8.35	sum	19	16	0	0	0	0
19	Number of grapple loads	30	Number of grapple loads	18	0	0	6	0	6
	Mean grapple volume (m3)	0.29	Mean pieces per grapple load	1.2	0	0	2.0	0	6.5
	Std. Deviation (m3)	0.16	st. deviation	0.4	0	0	0.0	0	2.4
	Minimum	0.09	min	1	0	0	2	0	4
	Maximum	0.63	max	2	0	0	2	0	9
	Load Volume (m3)	8.56	sum	22	0	0	12	0	39
20	Number of grapple loads	21	Number of grapple loads	14	0	0	0	7	0
	Mean grapple volume (m3)	0.40	Mean pieces per grapple load	1.4	0	0	0.0	3	0.0
	Std. Deviation (m3)	0.19	st. deviation	0.5	0	0	0.0	2	0.0
	Minimum	0.09	min	1	0	0	0	1	0
	Maximum	0.66	max	2	0	0	0	7	0
	Load Volume (m3)	8.36	sum	20	0	0	0	22	0
21	Number of grapple loads	25	Number of grapple loads	17	0	8	0	0	0
	Mean grapple volume (m3)	0.34	Mean pieces per grapple load	1.2	0.0	2.5	0	0.0	0
	Std. Deviation (m3)	0.15	st. deviation	0.4	0.0	1.2	0	0.0	0
	Minimum	0.10	min	1	0	1	0	0	0
	Maximum	0.63	max	2	0	4	0	0	0
	Load Volume (m3)	8.57	sum	21	0	20	0	0	0
22	Number of grapple loads	23	Number of grapple loads	17	0	0	4	0	2
	Mean grapple volume (m3)	0.36	Mean pieces per grapple load	1.4	0	0	3.3	0	6.5
	Std. Deviation (m3)	0.18	st. deviation	0.5	0	0	2.1	0	0.7
	Minimum	0.07	min	1	0	0	1	0	6
	Maximum	0.63	max	2	0	0	5	0	7
	Load Volume (m3)	8.38	sum	23	0	0	13	0	13
23	Number of grapple loads	24	Number of grapple loads	17	7	0	0	0	0
	Mean grapple volume (m3)	0.37	Mean pieces per grapple load	1.2	2	0	0.0	0	0.0
	Std. Deviation (m3)	0.13	st. deviation	0.4	1	0	0.0	0	0.0
	Minimum	0.15	min	1	1	0	0	0	0
	Maximum	0.63	max	2	3	0	0	0	0
	Load Volume (m3)	8.97	sum	21	16	0	0	0	0
24	Number of grapple loads	36	Number of grapple loads	19	0	0	8	0	9
	Mean grapple volume (m3)	0.26	Mean pieces per grapple load	1.3	0.0	0.0	2	0.0	5
	Std. Deviation (m3)	0.18	st. deviation	0.5	0.0	0.0	1	0.0	2
	Minimum	0.02	min	1	0	0	1	0	1
	Maximum	0.63	max	2	0	0	3	0	8
	Load Volume (m3)	9.48	sum	24	0	0	15	0	43
25	Number of grapple loads	21	Number of grapple loads	13	0	0	0	8	0
	Mean grapple volume (m3)	0.37	Mean pieces per grapple load	1.4	0	0	0.0	3	0.0
	Std. Deviation (m3)	0.16	st. deviation	0.5	0	0	0.0	1	0.0
	Minimum	0.19	min	1	0	0	0	2	0
	Maximum	0.63	max	2	0	0	0	5	0
	Load Volume (m3)	7.82	sum	18	0	0	0	23	0
26	Number of grapple loads	26	Number of grapple loads	19	0	7	0	0	0
	Mean grapple volume (m3)	0.36	Mean pieces per grapple load	1.3	0	2	0.0	0	0.0
	Std. Deviation (m3)	0.17	st. deviation	0.5	0	1	0.0	0	0.0
	Minimum	0.10	min	1	0	1	0	0	0
	Maximum	0.63	max	2	0	3	0	0	0
	Load Volume (m3)	9.23	sum	25	0	14	0	0	0

27	Number of grapple loads	23	Number of grapple loads	12	6	0	3	0	2
	Mean grapple volume (m3)	0.31	Mean pieces per grapple load	1.2	2.5	0.0	2	0.0	3
	Std. Deviation (m3)	0.15	st. deviation	0.4	0.5	0.0	1	0.0	1
	Minimum	0.04	min	1	2	0	1	0	2
	Maximum	0.63	max	2	3	0	3	0	4
	Load Volume (m3)	7.10	sum	14	15	0	5	0	6
28	Number of grapple loads	16	Number of grapple loads	0	11	0	0	5	0
	Mean grapple volume (m3)	0.36	Mean pieces per grapple load	0.0	2	0	0.0	4	0.0
	Std. Deviation (m3)	0.17	st. deviation	0.0	1	0	0.0	2	0.0
	Minimum	0.09	min	0	1	0	0	1	0
	Maximum	0.66	max	0	4	0	0	7	0
	Load Volume (m3)	5.80	sum	0	25	0	0	22	0
29	Number of grapple loads	36	Number of grapple loads	17	0	0	8	0	11
	Mean grapple volume (m3)	0.25	Mean pieces per grapple load	1.3	0	0	1.5	0	5.5
	Std. Deviation (m3)	0.19	st. deviation	0.5	0	0	0.8	0	3.5
	Minimum	0.04	min	1	0	0	1	0	2
	Maximum	0.63	max	2	0	0	3	0	11
	Load Volume (m3)	9.02	sum	22	0	0	12	0	60
30	Number of grapple loads	23	Number of grapple loads	18	0	0	0	5	0
	Mean grapple volume (m3)	0.34	Mean pieces per grapple load	1.1	0.0	0.0	0	3.2	0
	Std. Deviation (m3)	0.12	st. deviation	0.3	0.0	0.0	0	1.8	0
	Minimum	0.09	min	1	0	0	0	1	0
	Maximum	0.63	max	2	0	0	0	5	0
	Load Volume (m3)	7.79	sum	20	0	0	0	16	0
31	Number of grapple loads	26	Number of grapple loads	9	8	9	0	0	0
	Mean grapple volume (m3)	0.33	Mean pieces per grapple load	1.4	2	2	0.0	0	0.0
	Std. Deviation (m3)	0.16	st. deviation	0.5	1	1	0.0	0	0.0
	Minimum	0.10	min	1	1	1	0	0	0
	Maximum	0.63	max	2	3	4	0	0	0
	Load Volume (m3)	8.64	sum	13	16	22	0	0	0
32	Number of grapple loads	29	Number of grapple loads	16	0	0	5	0	8
	Mean grapple volume (m3)	0.31	Mean pieces per grapple load	1.4	0	0	2.0	0	5.9
	Std. Deviation (m3)	0.20	st. deviation	0.5	0	0	0.0	0	2.2
	Minimum	0.06	min	1	0	0	2	0	3
	Maximum	0.63	max	2	0	0	2	0	8
	Load Volume (m3)	8.91	sum	23	0	0	10	0	47
33	Number of grapple loads	25	Number of grapple loads	8	10	7	0	0	0
	Mean grapple volume (m3)	0.33	Mean pieces per grapple load	1.5	1.9	2.4	0	0.0	0
	Std. Deviation (m3)	0.15	st. deviation	0.5	0.3	1.1	0	0.0	0
	Minimum	0.10	min	1	1	1	0	0	0
	Maximum	0.63	max	2	2	4	0	0	0
	Load Volume (m3)	8.28	sum	12	19	17	0	0	0
34	Number of grapple loads	31	Number of grapple loads	16	0	0	8	0	7
	Mean grapple volume (m3)	0.31	Mean pieces per grapple load	1.4	0	0	2.4	0	7.0
	Std. Deviation (m3)	0.19	st. deviation	0.5	0	0	1.3	0	2.6
	Minimum	0.06	min	1	0	0	1	0	3
	Maximum	0.63	max	2	0	0	4	0	11
	Load Volume (m3)	9.57	sum	23	0	0	19	0	49
35	Number of grapple loads	25	Number of grapple loads	22	3	0	0	0	0
	Mean grapple volume (m3)	0.41	Mean pieces per grapple load	1.4	1	0	0.0	0	0.0
	Std. Deviation (m3)	0.17	st. deviation	0.5	1	0	0.0	0	0.0
	Minimum	0.15	min	1	1	0	0	0	0
	Maximum	0.63	max	2	2	0	0	0	0
	Load Volume (m3)	10.33	sum	31	4	0	0	0	0
36	Number of grapple loads	11	Number of grapple loads	1	5	0	0	5	0
	Mean grapple volume (m3)	0.40	Mean pieces per grapple load	2.0	2.2	0.0	0	4.6	0
	Std. Deviation (m3)	0.27	st. deviation	0.0	2.2	0.0	0	2.5	0
	Minimum	0.09	min	2	1	0	0	1	0
	Maximum	0.89	max	2	6	0	0	8	0
	Load Volume (m3)	4.44	sum	2	11	0	0	23	0
37	Number of grapple loads	23	Number of grapple loads	15	2	0	2	0	4
	Mean grapple volume (m3)	0.27	Mean pieces per grapple load	1.0	2	0	2.5	0	5.8
	Std. Deviation (m3)	0.11	st. deviation	0.0	1	0	2.1	0	5.6
	Minimum	0.04	min	1	1	0	1	0	2
	Maximum	0.45	max	1	3	0	4	0	14
	Load Volume (m3)	6.14	sum	15	4	0	5	0	23
38	Number of grapple loads	10	Number of grapple loads	0	1	7	0	2	0
	Mean grapple volume (m3)	0.31	Mean pieces per grapple load	0.0	2	4	0.0	2	0.0
	Std. Deviation (m3)	0.17	st. deviation	0.0	0	2	0.0	0	0.0
	Minimum	0.10	min	0	2	1	0	2	0
	Maximum	0.59	max	0	2	6	0	2	0
	Load Volume (m3)	3.15	sum	0	2	25	0	4	0
TOTAL	Number of grapple loads	947	Number of grapple loads	525	107	79	83	51	102
	Mean grapple volume (m3)	0.32	Mean pieces per grapple load	1.3	2.1	2.5	2	3.1	6
	Std. Deviation (m3)	0.16	st. deviation	0.4	0.8	1.2	1	1.8	3
	Minimum	0.02	min	1	1	1	1	1	1
	Maximum	0.89	max	2	6	6	5	8	14
	Load Volume (m3)	301.02	sum	664	224	194	186	156	587

UNLOAD	CLEARFELL PLOT 7			PRODUCT					
				111	112	113	114	127	115
1	Number of grapple loads	10	Number of grapple loads	10	0	0	0	0	0
	Mean grapple volume (m3)	0.60	Mean pieces per grapple load	1.9	0.0	0.0	0.0	0.0	0.0
	Std. Deviation (m3)	0.10	st. deviation	0.3	0.0	0.0	0.0	0.0	0.0
	Minimum	0.31	min	1	0	0	0	0	0
	Maximum	0.63	max	2	0	0	0	0	0
	Load Volume (m3)	5.96	sum	19	0	0	0	0	0
2	Number of grapple loads	18	Number of grapple loads	11	0	0	2	0	5
	Mean grapple volume (m3)	0.46	Mean pieces per grapple load	1.9	0.0	0.0	6.0	0.0	8.6
	Std. Deviation (m3)	0.24	st. deviation	0.5	0.0	0.0	1.4	0.0	6.7
	Minimum	0.02	min	1	0	0	5	0	1
	Maximum	0.94	max	3	0	0	7	0	16
	Load Volume (m3)	8.34	sum	21	0	0	12	0	43
3	Number of grapple loads	13	Number of grapple loads	10	0	0	0	3	0
	Mean grapple volume (m3)	0.60	Mean pieces per grapple load	2.0	0.0	0.0	0.0	5.3	0.0
	Std. Deviation (m3)	0.14	st. deviation	0.5	0.0	0.0	0.0	0.6	0.0
	Minimum	0.31	min	1	0	0	0	5	0
	Maximum	0.94	max	3	0	0	0	6	0
	Load Volume (m3)	7.79	sum	20	0	0	0	16	0
4	Number of grapple loads	14	Number of grapple loads	5	9	0	0	0	0
	Mean grapple volume (m3)	0.51	Mean pieces per grapple load	1.8	3.2	0.0	0.0	0.0	0.0
	Std. Deviation (m3)	0.13	st. deviation	0.4	0.8	0.0	0.0	0.0	0.0
	Minimum	0.30	min	1	2	0	0	0	0
	Maximum	0.63	max	2	4	0	0	0	0
	Load Volume (m3)	7.14	sum	9	29	0	0	0	0
5	Number of grapple loads	15	Number of grapple loads	11	0	4	0	0	0
	Mean grapple volume (m3)	0.56	Mean pieces per grapple load	1.7	0.0	6.3	0.0	0.0	0.0
	Std. Deviation (m3)	0.13	st. deviation	0.5	0.0	0.5	0.0	0.0	0.0
	Minimum	0.31	min	1	0	6	0	0	0
	Maximum	0.69	max	2	0	7	0	0	0
	Load Volume (m3)	8.44	sum	19	0	25	0	0	0
6	Number of grapple loads	14	Number of grapple loads	5	0	0	4	0	5
	Mean grapple volume (m3)	0.39	Mean pieces per grapple load	2	0.0	0.0	6	0.0	13
	Std. Deviation (m3)	0.16	st. deviation	1	0.0	0.0	2	0.0	5
	Minimum	0.13	min	1	0	0	3	0	6
	Maximum	0.63	max	2	0	0	7	0	18
	Load Volume (m3)	5.45	sum	8	0	0	22	0	67
7	Number of grapple loads	16	Number of grapple loads	13	0	0	0	3	0
	Mean grapple volume (m3)	0.50	Mean pieces per grapple load	1.5	0	0	0.0	6	0.0
	Std. Deviation (m3)	0.15	st. deviation	0.5	0	0	0.0	1	0.0
	Minimum	0.31	min	1	0	0	0	5	0
	Maximum	0.66	max	2	0	0	0	7	0
	Load Volume (m3)	7.98	sum	20	0	0	0	18	0
8	Number of grapple loads	16	Number of grapple loads	13	0	3	0	0	0
	Mean grapple volume (m3)	0.62	Mean pieces per grapple load	2.0	0	6	0	0.0	0
	Std. Deviation (m3)	0.06	st. deviation	0.0	0	2	0	0.0	0
	Minimum	0.49	min	2	0	5	0	0	0
	Maximum	0.79	max	2	0	8	0	0	0
	Load Volume (m3)	9.94	sum	26	0	18	0	0	0
9	Number of grapple loads	13	Number of grapple loads	7	6	0	0	0	0
	Mean grapple volume (m3)	0.61	Mean pieces per grapple load	2.0	4.0	0	0	0	0
	Std. Deviation (m3)	0.18	st. deviation	0.6	1.3	0	0	0	0
	Minimum	0.31	min	1	3	0	0	0	0
	Maximum	0.94	max	3	6	0	0	0	0
	Load Volume (m3)	7.97	sum	14	24	0	0	0	0
10	Number of grapple loads	16	Number of grapple loads	12	4	0	0	0	0
	Mean grapple volume (m3)	0.59	Mean pieces per grapple load	1.9	4	0	0.0	0	0.0
	Std. Deviation (m3)	0.10	st. deviation	0.3	1	0	0.0	0	0.0
	Minimum	0.31	min	1	3	0	0	0	0
	Maximum	0.74	max	2	5	0	0	0	0
	Load Volume (m3)	9.45	sum	23	15	0	0	0	0
11	Number of grapple loads	18	Number of grapple loads	9	0	0	3	0	6
	Mean grapple volume (m3)	0.47	Mean pieces per grapple load	1.8	0	0	7.7	0	14.2
	Std. Deviation (m3)	0.17	st. deviation	0.4	0	0	0.6	0	6.1
	Minimum	0.04	min	1	0	0	7	0	2
	Maximum	0.63	max	2	0	0	8	0	18
	Load Volume (m3)	8.42	sum	16	0	0	23	0	85
12	Number of grapple loads	13	Number of grapple loads	10	0	0	1	0	2
	Mean grapple volume (m3)	0.57	Mean pieces per grapple load	2.0	0.0	0.0	8	0.0	15
	Std. Deviation (m3)	0.19	st. deviation	0.5	0.0	0.0	0	0.0	11
	Minimum	0.15	min	1	0	0	8	0	7
	Maximum	0.94	max	3	0	0	8	0	22
	Load Volume (m3)	7.45	sum	20	0	0	8	0	29
13	Number of grapple loads	11	Number of grapple loads	5	3	0	0	3	0
	Mean grapple volume (m3)	0.55	Mean pieces per grapple load	2.0	4	0	0.0	4	0.0
	Std. Deviation (m3)	0.24	st. deviation	0.7	2	0	0.0	2	0.0
	Minimum	0.28	min	1	2	0	0	3	0
	Maximum	0.94	max	3	6	0	0	6	0
	Load Volume (m3)	6.06	sum	10	12	0	0	12	0

14	Number of grapple loads	12	Number of grapple loads	0	0	6	3	0	3
	Mean grapple volume (m3)	0.54	Mean pieces per grapple load	0.0	0	7	7.3	0	17.7
	Std. Deviation (m3)	0.20	st. deviation	0.0	0	2	0.6	0	2.1
	Minimum	0.30	min	0	0	3	7	0	16
	Maximum	0.89	max	0	0	9	8	0	20
	Load Volume (m3)	6.49	sum	0	0	39	22	0	53
15	Number of grapple loads	15	Number of grapple loads	11	4	0	0	0	0
	Mean grapple volume (m3)	0.60	Mean pieces per grapple load	1.9	4.0	0.0	0	0.0	0
	Std. Deviation (m3)	0.14	st. deviation	0.3	1.6	0.0	0	0.0	0
	Minimum	0.30	min	1	2	0	0	0	0
	Maximum	0.89	max	2	6	0	0	0	0
	Load Volume (m3)	8.97	sum	21	16	0	0	0	0
16	Number of grapple loads	16	Number of grapple loads	13	0	0	1	0	2
	Mean grapple volume (m3)	0.58	Mean pieces per grapple load	2.0	0	0	8.0	0	15.0
	Std. Deviation (m3)	0.16	st. deviation	0.4	0	0	0.0	0	4.2
	Minimum	0.26	min	1	0	0	8	0	12
	Maximum	0.94	max	3	0	0	8	0	18
	Load Volume (m3)	9.35	sum	26	0	0	8	0	30
17	Number of grapple loads	16	Number of grapple loads	13	0	3	0	0	0
	Mean grapple volume (m3)	0.56	Mean pieces per grapple load	1.8	0	5	0.0	0	0.0
	Std. Deviation (m3)	0.12	st. deviation	0.4	0	1	0.0	0	0.0
	Minimum	0.31	min	1	0	4	0	0	0
	Maximum	0.63	max	2	0	5	0	0	0
	Load Volume (m3)	8.92	sum	24	0	14	0	0	0
18	Number of grapple loads	15	Number of grapple loads	11	4	0	0	0	0
	Mean grapple volume (m3)	0.56	Mean pieces per grapple load	1.7	4.0	0.0	0	0.0	0
	Std. Deviation (m3)	0.16	st. deviation	0.5	1.4	0.0	0	0.0	0
	Minimum	0.31	min	1	3	0	0	0	0
	Maximum	0.89	max	2	6	0	0	0	0
	Load Volume (m3)	8.35	sum	19	16	0	0	0	0
19	Number of grapple loads	16	Number of grapple loads	11	0	0	2	0	3
	Mean grapple volume (m3)	0.54	Mean pieces per grapple load	2.0	0	0	6.0	0	13.0
	Std. Deviation (m3)	0.19	st. deviation	0.4	0	0	1.4	0	4.4
	Minimum	0.17	min	1	0	0	5	0	8
	Maximum	0.94	max	3	0	0	7	0	16
	Load Volume (m3)	8.56	sum	22	0	0	12	0	39
20	Number of grapple loads	16	Number of grapple loads	12	0	0	0	4	0
	Mean grapple volume (m3)	0.52	Mean pieces per grapple load	1.7	0	0	0.0	6	0.0
	Std. Deviation (m3)	0.17	st. deviation	0.5	0	0	0.0	2	0.0
	Minimum	0.28	min	1	0	0	0	3	0
	Maximum	0.76	max	2	0	0	0	8	0
	Load Volume (m3)	8.36	sum	20	0	0	0	22	0
21	Number of grapple loads	15	Number of grapple loads	12	0	3	0	0	0
	Mean grapple volume (m3)	0.57	Mean pieces per grapple load	1.8	0.0	6.7	0	0.0	0
	Std. Deviation (m3)	0.14	st. deviation	0.5	0.0	0.6	0	0.0	0
	Minimum	0.31	min	1	0	6	0	0	0
	Maximum	0.69	max	2	0	7	0	0	0
	Load Volume (m3)	8.57	sum	21	0	20	0	0	0
22	Number of grapple loads	16	Number of grapple loads	13	0	0	2	0	1
	Mean grapple volume (m3)	0.52	Mean pieces per grapple load	1.8	0	0	6.5	0	13.0
	Std. Deviation (m3)	0.15	st. deviation	0.4	0	0	0.7	0	0.0
	Minimum	0.28	min	1	0	0	6	0	13
	Maximum	0.63	max	2	0	0	7	0	13
	Load Volume (m3)	8.38	sum	23	0	0	13	0	13
23	Number of grapple loads	17	Number of grapple loads	12	5	0	0	0	0
	Mean grapple volume (m3)	0.53	Mean pieces per grapple load	1.8	3	0	0.0	0	0.0
	Std. Deviation (m3)	0.21	st. deviation	0.6	2	0	0.0	0	0.0
	Minimum	0.15	min	1	1	0	0	0	0
	Maximum	0.94	max	3	6	0	0	0	0
	Load Volume (m3)	8.97	sum	21	16	0	0	0	0
24	Number of grapple loads	16	Number of grapple loads	11	0	0	2	0	3
	Mean grapple volume (m3)	0.59	Mean pieces per grapple load	2.2	0.0	0.0	8	0.0	14
	Std. Deviation (m3)	0.22	st. deviation	0.6	0.0	0.0	2	0.0	1
	Minimum	0.30	min	1	0	0	6	0	14
	Maximum	0.94	max	3	0	0	9	0	15
	Load Volume (m3)	9.48	sum	24	0	0	15	0	43
25	Number of grapple loads	15	Number of grapple loads	10	0	0	0	5	0
	Mean grapple volume (m3)	0.52	Mean pieces per grapple load	1.8	0	0	0.0	5	0.0
	Std. Deviation (m3)	0.15	st. deviation	0.4	0	0	0.0	2	0.0
	Minimum	0.19	min	1	0	0	0	2	0
	Maximum	0.63	max	2	0	0	0	6	0
	Load Volume (m3)	7.82	sum	18	0	0	0	23	0
26	Number of grapple loads	16	Number of grapple loads	13	0	3	0	0	0
	Mean grapple volume (m3)	0.58	Mean pieces per grapple load	1.9	0	5	0.0	0	0.0
	Std. Deviation (m3)	0.16	st. deviation	0.5	0	1	0.0	0	0.0
	Minimum	0.31	min	1	0	4	0	0	0
	Maximum	0.94	max	3	0	6	0	0	0
	Load Volume (m3)	9.23	sum	25	0	14	0	0	0

27	Number of grapple loads	13	Number of grapple loads	7	4	0	1	0	1
	Mean grapple volume (m3)	0.55	Mean pieces per grapple load	2.0	3.8	0.0	5	0.0	6
	Std. Deviation (m3)	0.16	st. deviation	0.0	1.0	0.0	0	0.0	0
	Minimum	0.13	min	2	3	0	5	0	6
	Maximum	0.74	max	2	5	0	5	0	6
	Load Volume (m3)	7.10	sum	14	15	0	5	0	6
28	Number of grapple loads	11	Number of grapple loads	0	7	0	0	4	0
	Mean grapple volume (m3)	0.53	Mean pieces per grapple load	0.0	4	0	0.0	6	0.0
	Std. Deviation (m3)	0.19	st. deviation	0.0	1	0	0.0	3	0.0
	Minimum	0.09	min	0	2	0	0	1	0
	Maximum	0.74	max	0	5	0	0	7	0
	Load Volume (m3)	5.80	sum	0	25	0	0	22	0
29	Number of grapple loads	17	Number of grapple loads	10	0	0	2	0	5
	Mean grapple volume (m3)	0.53	Mean pieces per grapple load	2.2	0	0	6.0	0	12.0
	Std. Deviation (m3)	0.24	st. deviation	0.4	0	0	0.0	0	8.5
	Minimum	0.02	min	2	0	0	6	0	1
	Maximum	0.94	max	3	0	0	6	0	20
	Load Volume (m3)	9.02	sum	22	0	0	12	0	60
30	Number of grapple loads	13	Number of grapple loads	10	0	0	0	3	0
	Mean grapple volume (m3)	0.60	Mean pieces per grapple load	2.0	0.0	0.0	0	5.3	0
	Std. Deviation (m3)	0.19	st. deviation	0.7	0.0	0.0	0	0.6	0
	Minimum	0.31	min	1	0	0	0	5	0
	Maximum	0.94	max	3	0	0	0	6	0
	Load Volume (m3)	7.79	sum	20	0	0	0	16	0
31	Number of grapple loads	14	Number of grapple loads	7	4	3	0	0	0
	Mean grapple volume (m3)	0.62	Mean pieces per grapple load	1.9	4	7	0.0	0	0.0
	Std. Deviation (m3)	0.17	st. deviation	0.4	2	2	0.0	0	0.0
	Minimum	0.30	min	1	2	6	0	0	0
	Maximum	0.89	max	2	6	9	0	0	0
	Load Volume (m3)	8.64	sum	13	16	22	0	0	0
32	Number of grapple loads	17	Number of grapple loads	12	0	0	2	0	3
	Mean grapple volume (m3)	0.52	Mean pieces per grapple load	1.9	0	0	5.0	0	15.7
	Std. Deviation (m3)	0.17	st. deviation	0.3	0	0	5.7	0	2.3
	Minimum	0.07	min	1	0	0	1	0	13
	Maximum	0.63	max	2	0	0	9	0	17
	Load Volume (m3)	8.91	sum	23	0	0	10	0	47
33	Number of grapple loads	16	Number of grapple loads	7	6	3	0	0	0
	Mean grapple volume (m3)	0.52	Mean pieces per grapple load	1.7	3.2	5.7	0	0.0	0
	Std. Deviation (m3)	0.18	st. deviation	0.5	1.3	2.5	0	0.0	0
	Minimum	0.15	min	1	1	3	0	0	0
	Maximum	0.79	max	2	4	8	0	0	0
	Load Volume (m3)	8.28	sum	12	19	17	0	0	0
34	Number of grapple loads	19	Number of grapple loads	12	0	0	3	0	4
	Mean grapple volume (m3)	0.50	Mean pieces per grapple load	1.9	0	0	6.3	0	12.3
	Std. Deviation (m3)	0.18	st. deviation	0.3	0	0	3.2	0	5.0
	Minimum	0.11	min	1	0	0	4	0	5
	Maximum	0.68	max	2	0	0	10	0	16
	Load Volume (m3)	9.57	sum	23	0	0	19	0	49
35	Number of grapple loads	17	Number of grapple loads	15	2	0	0	0	0
	Mean grapple volume (m3)	0.61	Mean pieces per grapple load	2.1	2	0	0.0	0	0.0
	Std. Deviation (m3)	0.24	st. deviation	0.7	1	0	0.0	0	0.0
	Minimum	0.15	min	1	1	0	0	0	0
	Maximum	0.94	max	3	3	0	0	0	0
	Load Volume (m3)	10.33	sum	31	4	0	0	0	0
36	Number of grapple loads	8	Number of grapple loads	1	3	0	0	4	0
	Mean grapple volume (m3)	0.55	Mean pieces per grapple load	2.0	3.7	0.0	0	5.8	0
	Std. Deviation (m3)	0.19	st. deviation	0.0	1.2	0.0	0	2.6	0
	Minimum	0.19	min	2	3	0	0	2	0
	Maximum	0.76	max	2	5	0	0	8	0
	Load Volume (m3)	4.44	sum	2	11	0	0	23	0
37	Number of grapple loads	12	Number of grapple loads	8	1	0	1	0	2
	Mean grapple volume (m3)	0.51	Mean pieces per grapple load	1.9	4	0	5.0	0	11.5
	Std. Deviation (m3)	0.18	st. deviation	0.4	0	0	0.0	0	7.8
	Minimum	0.13	min	1	4	0	5	0	6
	Maximum	0.63	max	2	4	0	5	0	17
	Load Volume (m3)	6.14	sum	15	4	0	5	0	23
38	Number of grapple loads	6	Number of grapple loads	0	1	4	0	1	0
	Mean grapple volume (m3)	0.52	Mean pieces per grapple load	0.0	2	6	0.0	4	0.0
	Std. Deviation (m3)	0.33	st. deviation	0.0	0	4	0.0	0	0.0
	Minimum	0.20	min	0	2	2	0	4	0
	Maximum	0.99	max	0	2	10	0	4	0
	Load Volume (m3)	3.15	sum	0	2	25	0	4	0
TOTAL	Number of grapple loads	551	Number of grapple loads	352	63	32	29	30	45
	Mean grapple volume (m3)	0.55	Mean pieces per grapple load	1.9	3.6	6.1	6	5.2	13
	Std. Deviation (m3)	0.18	st. deviation	0.5	1.3	2.0	2	1.8	6
	Minimum	0.02	min	1	1	2	1	1	1
	Maximum	0.99	max	3	6	10	10	8	22
	Load Volume (m3)	301.02	sum	664	224	194	186	156	587

LOAD	CREAMING PLOT 8			PRODUCT 111	112	113	114	127	115
1	Number of grapple loads	22	Number of grapple loads	12	4	0	0	6	0
	Mean grapple volume (m3)	0.32	Mean pieces per grapple load	1.2	1.3	0.0	0.0	2.2	0.0
	Std. Deviation (m3)	0.16	st. deviation	0.4	0.5	0.0	0.0	1.0	0.0
	Minimum	0.08	min	1	1	0	0	1	0
	Maximum	0.71	max	2	2	0	0	3	0
	Load Volume (m3)	6.93	sum	14	5	0	0	13	0
2	Number of grapple loads	26	Number of grapple loads	17	0	0	0	9	0
	Mean grapple volume (m3)	0.38	Mean pieces per grapple load	1.4	0.0	0.0	0.0	2.4	0.0
	Std. Deviation (m3)	0.20	st. deviation	0.5	0.0	0.0	0.0	1.4	0.0
	Minimum	0.08	min	1	0	0	0	1	0
	Maximum	0.71	max	2	0	0	0	5	0
	Load Volume (m3)	9.95	sum	23	0	0	0	22	0
3	Number of grapple loads	26	Number of grapple loads	12	4	0	0	10	0
	Mean grapple volume (m3)	0.37	Mean pieces per grapple load	1.7	1.5	0.0	0.0	1.8	0.0
	Std. Deviation (m3)	0.25	st. deviation	0.5	0.6	0.0	0.0	1.2	0.0
	Minimum	0.08	min	1	1	0	0	1	0
	Maximum	0.71	max	2	2	0	0	5	0
	Load Volume (m3)	9.65	sum	20	6	0	0	18	0
4	Number of grapple loads	17	Number of grapple loads	8	7	0	0	2	0
	Mean grapple volume (m3)	0.43	Mean pieces per grapple load	1.5	2.1	0.0	0.0	2.5	0.0
	Std. Deviation (m3)	0.20	st. deviation	0.5	0.9	0.0	0.0	2.1	0.0
	Minimum	0.08	min	1	1	0	0	1	0
	Maximum	0.71	max	2	3	0	0	4	0
	Load Volume (m3)	7.38	sum	12	15	0	0	5	0
5	Number of grapple loads	23	Number of grapple loads	11	2	0	0	10	0
	Mean grapple volume (m3)	0.40	Mean pieces per grapple load	1.7	2.5	0.0	0.0	1.8	0.0
	Std. Deviation (m3)	0.27	st. deviation	0.5	0.7	0.0	0.0	1.5	0.0
	Minimum	0.08	min	1	2	0	0	1	0
	Maximum	0.71	max	2	3	0	0	6	0
	Load Volume (m3)	9.11	sum	19	5	0	0	18	0
6	Number of grapple loads	19	Number of grapple loads	10	3	0	0	6	0
	Mean grapple volume (m3)	0.37	Mean pieces per grapple load	1	1.3	0.0	0	2.7	0
	Std. Deviation (m3)	0.20	st. deviation	1	0.6	0.0	0	1.5	0
	Minimum	0.08	min	1	1	0	0	1	0
	Maximum	0.71	max	2	2	0	0	5	0
	Load Volume (m3)	7.00	sum	14	4	0	0	16	0
7	Number of grapple loads	25	Number of grapple loads	14	2	0	0	9	0
	Mean grapple volume (m3)	0.43	Mean pieces per grapple load	1.6	3	0	0.0	2	0.0
	Std. Deviation (m3)	0.25	st. deviation	0.5	1	0	0.0	1	0.0
	Minimum	0.08	min	1	2	0	0	1	0
	Maximum	0.73	max	2	4	0	0	5	0
	Load Volume (m3)	10.87	sum	23	6	0	0	20	0
8	Number of grapple loads	10	Number of grapple loads	0	0	3	5	0	2
	Mean grapple volume (m3)	0.34	Mean pieces per grapple load	0.0	0	4	5	0.0	5
	Std. Deviation (m3)	0.23	st. deviation	0.0	0	2	3	0.0	3
	Minimum	0.07	min	0	0	1	1	0	3
	Maximum	0.61	max	0	0	5	7	0	7
	Load Volume (m3)	3.43	sum	0	0	11	23	0	10
TOTAL	Number of grapple loads	168	Number of grapple loads	84	22	3	5	52	2
	Mean grapple volume (m3)	0.38	Mean pieces per grapple load	1.5	1.9	4	5	2	5
	Std. Deviation (m3)	0.22	st. deviation	0.5	0.9	2	3	1	3
	Minimum	0.07	min	1	1	1	1	1	3
	Maximum	0.73	max	2	4	5	7	6	7
	Load Volume (m3)	64.33	sum	125	41	11	23	112	10

UNLOAD	CREAMING PLOT 8			PRODUCT 111	112	113	114	127	115
1	Number of grapple loads	13	Number of grapple loads	9	2	0	0	2	0
	Mean grapple volume (m3)	0.53	Mean pieces per grapple load	1.6	2.5	0.0	0.0	6.5	0.0
	Std. Deviation (m3)	0.17	st. deviation	0.5	0.7	0.0	0.0	2.1	0.0
	Minimum	0.35	min	1	2	0	0	5	0
	Maximum	0.71	max	2	3	0	0	8	0
	Load Volume (m3)	6.93	sum	14	5	0	0	13	0
2	Number of grapple loads	16	Number of grapple loads	12	0	0	0	4	0
	Mean grapple volume (m3)	0.62	Mean pieces per grapple load	1.9	0.0	0.0	0.0	5.5	0.0
	Std. Deviation (m3)	0.14	st. deviation	0.3	0.0	0.0	0.0	1.3	0.0
	Minimum	0.33	min	1	0	0	0	4	0
	Maximum	0.71	max	2	0	0	0	7	0
	Load Volume (m3)	9.95	sum	23	0	0	0	22	0
3	Number of grapple loads	16	Number of grapple loads	11	2	0	0	3	0
	Mean grapple volume (m3)	0.60	Mean pieces per grapple load	1.8	3.0	0.0	0.0	6.0	0.0
	Std. Deviation (m3)	0.23	st. deviation	0.6	0.0	0.0	0.0	4.4	0.0
	Minimum	0.08	min	1	3	0	0	1	0
	Maximum	1.06	max	3	3	0	0	9	0
	Load Volume (m3)	9.65	sum	20	6	0	0	18	0
4	Number of grapple loads	12	Number of grapple loads	6	5	0	0	1	0
	Mean grapple volume (m3)	0.61	Mean pieces per grapple load	2.0	3.0	0.0	0.0	5.0	0.0
	Std. Deviation (m3)	0.15	st. deviation	0.0	1.0	0.0	0.0	0.0	0.0
	Minimum	0.36	min	2	2	0	0	5	0
	Maximum	0.73	max	2	4	0	0	5	0
	Load Volume (m3)	7.38	sum	12	15	0	0	5	0
5	Number of grapple loads	14	Number of grapple loads	10	2	0	0	2	0
	Mean grapple volume (m3)	0.65	Mean pieces per grapple load	1.9	2.5	0.0	0.0	9.0	0.0
	Std. Deviation (m3)	0.23	st. deviation	0.6	2.1	0.0	0.0	2.8	0.0
	Minimum	0.18	min	1	1	0	0	7	0
	Maximum	1.06	max	3	4	0	0	11	0
	Load Volume (m3)	9.11	sum	19	5	0	0	18	0
6	Number of grapple loads	11	Number of grapple loads	7.0	2.0	0.0	0.0	2.0	0.0
	Mean grapple volume (m3)	0.64	Mean pieces per grapple load	2	2.0	0.0	0	8.0	0
	Std. Deviation (m3)	0.16	st. deviation	0	1.4	0.0	0	1.4	0
	Minimum	0.18	min	2	1.0	0.0	0	7.0	0
	Maximum	0.75	max	2	3	0	0	9	0
	Load Volume (m3)	7.00	sum	14	4	0	0	16	0
7	Number of grapple loads	15	Number of grapple loads	10	2	0	0	3	0
	Mean grapple volume (m3)	0.72	Mean pieces per grapple load	2.3	3	0	0.0	7	0.0
	Std. Deviation (m3)	0.21	st. deviation	0.5	1	0	0.0	2	0.0
	Minimum	0.36	min	2	2	0	0	5	0
	Maximum	1.06	max	3	4	0	0	8	0
	Load Volume (m3)	10.87	sum	23	6	0	0	20	0
8	Number of grapple loads	8	Number of grapple loads	0	0	3	4	0	1
	Mean grapple volume (m3)	0.43	Mean pieces per grapple load	0.0	0	4	6	0.0	10
	Std. Deviation (m3)	0.20	st. deviation	0.0	0	2	2	0.0	0
	Minimum	0.12	min	0	0	1	3	0	10
	Maximum	0.61	max	0	0	5	7	0	10
	Load Volume (m3)	3.43	sum	0	0	11	23	0	10
TOTAL	Number of grapple loads	105	Number of grapple loads	65	15	3	4	17	1
	Mean grapple volume (m3)	0.61	Mean pieces per grapple load	1.9	2.7	4	6	7	10
	Std. Deviation (m3)	0.20	st. deviation	0.5	1.0	2	2	2	
	Minimum	0.08	min	1	1	1	3	1	10
	Maximum	1.06	max	3	4	5	7	11	10
	Load Volume (m3)	64.33	sum	125	41	11	23	112	10

APPENDIX 28: Harvester per-tree time consumption