Analysis of the viability of “land sparing” and “land sharing” strategies for commercial woodland expansion within Wales

Wiik, Emma; Pagella, Tim; Healey, John; Stephen, Bathgate; McKay, Helen; Jenkins, Tom

Published: 31/03/2020

Publisher's PDF, also known as Version of record

Climate Smart Woodlands in Wales

Final report

March 2020

Emma Wiik, Sue Hunter, Will Andrews, John Healey, Stephan Bathgate, Helen McKay, Tom Jenkins & Tim Pagella

Table of Contents

Acknowledgements

In addition to the acknowledgements given at the start of each section we would like to acknowledge and thank Professor Jon Moorby of Aberystwyth University who has overall responsibility for this project and who leads the overall Climate Smart Agriculture in Wales project of which this is a variation.

We also acknowledge the inputs of Drs Andy Smith and Prysor Williams of Bangor University who provided valuable information and access to contacts throughout the project.

We would like to specifically acknowledge the substantial contribution of Stephen Bathgate, Tom Jenkins and Dr Helen McKay of Forest Research whose work provided the basis for the first section of the report and its additional components.

We are very grateful to Fiona McFarlane, Erika Dawes and Fiona Hay of the Welsh Government who provided valuable steering throughout the course of the project, especially given the unusual set of difficulties encountered.

We are grateful to all the farmers and organisations that contributed their time.

Finally, we would like to acknowledge, with some sadness, the role of Dewi Jones of the Welsh Government, who was very active and enthusiastic about setting up this project at its initial conception in 2016, but who sadly passed away before the project began.

Introduction to the report

This report sets out the findings of the Climate Smart Woodland in Wales project that finished in March 2020. The phrase 'climate smart' denotes production systems that are best suited to respond to the challenges of climate change mitigation and adaptation for specific locations. This report explores what the 'climate smart' options are for two key forms of woodland. The first is the commercial forestry sector, which is likely to be the critical player in meeting future climate change-driven woodland creation targets in Wales. The second is agroforestry, which captures the various forms of system incorporating trees that can be integrated into farming systems, both to deliver benefits to the farm and a wider set of public goods. The report is divided into three sections:

The first section analyses the viability of "land sparing" and "land sharing" strategies for commercial woodland creation within Wales. This research is focused on identifying the opportunity space for productive woodland creation within agricultural land of moderate productivity classified as ALC3b, for both key conifer and broadleaf species to meet climate commitments. We also demonstrated the potential use of modern "app" technology to deliver decision-support for the planning of efficient target-driven woodland creation.

The second section provides an introduction to, and an overview of, agroforestry and discusses opportunities to expand agroforestry systems in Wales. It highlights both the costs and benefits associated with agroforestry (including climate change mitigation benefits) and discusses both how and where to increase agroforestry in Wales.

These two options represent potential adaptation or transformation pathways for agricultural systems in Wales to meet climate change mitigation commitments. Business as usual is no longer a viable option and tree planting, in some form, will be a significant component of any 'climate smart' solution.

The final section explores farmer attitudes to changes in tree cover; including some initial work exploring the role that decision support tools might play.

In developing these outputs, we have sought to be agnostic in relation to which tree-based option might be more or less appropriate in any particular context. The results suggest that there is a degree of overlap in many areas of Wales where both options may be suitable. At the same time, we acknowledge that barriers are also present that may restrict both. As such, this is not a set of proscriptive tools. Instead we wanted to create evidence that can feed into a decision-support framework by identifying areas that had significant potential for both options should the opportunity arise.

Section 1: Analysis of the viability of “land sparing” and “land sharing” strategies for commercial woodland expansion within Wales

March 2020

Emma Wiik, Tim Pagella, John Healey, Stephan Bathgate, Helen McKay & Tom Jenkins

Section 1: Key Messages:

- There is an estimated 551,277 ha of agricultural land classified, on the basis of its productive potential, as ALC grade 3b in Wales.
- It is estimated that the productivity of Sitka spruce established on ALC grade 3b land would be approximately 4 $m^3 ha^{-1} yr^{-1}$ higher on average than in existing forests in Wales, and 2 $m^3 ha^{-1} yr^{-1}$ greater than would be anticipated on ALC grade 4 land.
- The area of ALC 3b grade land suitable for the commercial growing of Sitka spruce in Wales is estimated as 531,975 ha, which is 96.5% of the total land area in this ALC category.
- Comparable figures for other tree species included in this study were:
    - Douglas fir 263,092 ha (47.7%);
    - Scots pine 544,274 ha (98.7%);
    - pedunculate oak 522,053 ha (94.7%);
    - silver birch 524,851 ha (95.2%); and
    - beech 344,971 ha (62.6%).
- ALC 3b is, therefore, a good proxy of suitability for some tree species (e.g. Sitka spruce, Scots pine and silver birch) but less so for species susceptible to very moist soils (e.g. Douglas fir).
- The viability of ALC 3b land for commercial investment in establishing woodlands for timber production is limited by a number of key constraints including, for economic and operational reasons, distance to the nearest accessible road and (rarely) steep slope angles. Other constraints are applied for reasons of environmental protection, e.g. no woodland establishment on deep peat or designated conservation sites, and restrictions on woodland establishment in riparian zones adjacent to water courses.
- Under these constraints the area of ALC 3b land available for woodland creation decreases.
    - Only 40,139 ha is excluded from new conifer woodland because it lies within a designated riparian zone.
    - If we factor in road access, then the area available is potentially more constrained: 37.8% of ALC3b land is more than 2000 m from an A road or motorway and 67.5% is more than 1000 m from an A road or motorway.
    - Distance from sawmills imposes an incremental cost rather than acting as a threshold constraint. The number of sawmills with the capacity to take large commercial volumes of timber across Wales has decreased greatly over the past 30 years. However, it can be anticipated that an increase in timber production will provide an incentive for commercial investment in new sawmill capacity.
- With the wide variation in physical and economic geography across Wales, ALC3b land occupies a large range of patch sizes and configurations (within a matrix of land in more and less productive land classifications). Most individual patches of ALC 3b grade are <1 ha, which is much smaller than the majority of existing commercial woodlands in Wales, thus restricting new commercial woodlands to land of this grade would significantly constrain the potential for conventional commercial investment. The fragmentation of these patches will also constrain the potential to establish *de novo* a woodland habitat network of high biodiversity value. Three potential scenarios can be envisaged of how this constraint will be overcome:
    a) transfer of larger land units (encompassing a wider range of ALC grades (e.g. grade 3a land of higher food production value or grade 4 land, which may have higher biodiversity or amenity value, from agriculture to forestry, e.g. through the sale of whole agricultural

land holdings (farms) to forestry investors. This may cause concerns of loss agricultural cultural values and sub-optimal use of land resources amongst the objectives of food production, wood production (and carbon sequestration) and biodiversity conservation.

b) a switch of focus for timber producing forestry towards smaller forest blocks within continuing agricultural land holdings as part of a strategy towards diversification of income streams for farm holdings. Such smaller and more isolated woodland patches may also have advantages for reducing risk of tree pathogen infection (Roberts et al. 2020). They also have good potential to capitalise on and enhance existing social capital in the farming sector, through co-operative management, e.g. as promoted by Coed Cymru.

c) a greater focus of new woodland establishment on land that is adjacent/near to existing woodlands. The high potential for this is evidenced by the finding that approximately 278,562 ha (50.5%) of ALC grade 3b land in Wales lies within 500 m of existing established woodland. Use of this land has potential economic benefits because of the potential to share infrastructure, such as forest roads, and to increase connectivity for woodland habitats (of benefit to biodiversity but potential cost for biosecurity).

- The evidence of the high proportion of ALC3b land that is suitable and unconstrained for commercial conifer production forestry provides the opportunity to spare large areas of existing woodland and newly established woodland to be managed primarily for biodiversity, public amenity and other benefits, e.g. through establishment and management of native broadleaved species. There is growing international evidence that this is a more efficient method of combining production and conservation objectives at a landscape scale (e.g. Phalan et al. 2011; Edwards et al. 2014), than the recently conventional land sharing approach in the UK (in which a compromise is sought trading-off these two objectives in every woodland).
- There is increasingly robust evidence (e.g. Forster et al. submitted) that conifer commercial production forestry achieves the greatest climate change mitigation benefit of any option for new woodlands in environments such as those in Wales. This is largely due to the net carbon sequestration benefits of wood use through the value chain. As a result, commercial forestry investment and achievement of Welsh Government carbon emissions reduction targets represents a “win-win” strategy. However, some carbon accounting methods applied to woodlands (such as the Woodland Carbon Code) are restricted to the carbon stocks within the trees of standing woodland. Tree growth rates (e.g. as captured in the index “yield class” are traditionally measured in terms of wood volume. Because alternative commercial tree species differ significantly in their wood density (and thus carbon density). Thus, for a given area of land there can be a different optimal tree species to select if the objective is maximum rate of carbon sequestration compared with maximum rate of timber volume production (yield class). Thus, for all ALC grade 3b land in Wales (ignoring constraints), for the eight conifer species tested in this study, following ranking[1] to resolve ties, Sitka spruce is the optimal species for 63% of the area by yield class, and for 60% by carbon sequestration (at 45 years); whereas the denser-wooded Douglas fir is the optimal species for 1% of the area by yield class and for 29% by carbon sequestration (at 45 years).
- There is growing evidence of the benefits of establishing a woodland resource comprising a mixture of tree species rather than a single-species monoculture. However, most commercial foresters consider that intimate species mixtures impose significantly greater

[1] In order of preference: Douglas fir > Sitka spruce > Scots pine > western hemlock (then arbitrary for the lesser species)

management costs than monocultures. There is a major unanswered question about what spatial scale of tree mixture (from individual trees up to a patchwork of large monoculture blocks of individual species of several square kilometres each represents the optimal compromise between low-cost efficiency of commercial operations and species mixture benefits, e.g. to increase resilience against tree diseases (Roberts et al. 2020). A priority for future research will be to calculate the distribution of sizes of the patches of ALC 3b land that are optimal (by timber volume growth or carbon sequestration) for the establishment of each individual tree species, and their spatial configuration, to assess this mosaic as a model for a commercially viable mixed tree species landscape of resilient new woodland in Wales.

Section 1: Acknowledgements:

Activity in this work package was supported by research outputs supplied by Forest Research. We gratefully acknowledge their help in the development of this work package. A copy of their final report is included here as an appendix. We acknowledge the support of the Supercomputing Wales project, which is part-funded by the European Regional Development Fund (ERDF) via Welsh Government.

1.0 Introduction

This work package aims to provide evidence to support the Welsh Government in its ambition to reduce Wales' net greenhouse gas (GHG) emissions through expansion of woodland cover and improvements in the management and utilisation of existing woodland. Specifically, this work package is interested in the potential for expansion of woodlands managed for commercial timber production, which are likely to be dominated by conifer species. This climate change mitigation measure has been outlined in a number of important Welsh policy documents, and outputs from this project will provide key evidence to enable this strategy to be refined and implemented.

The objective to expand woodland cover was initially reported in the Climate Change Strategy for Wales (2010), which identified the need to create 100,000 ha of new woodland between 2010 and 2030 to offset GHG emissions. This was a key recommendation of the Land Use and Climate Change Group, which was set up by the then Minister for Rural Affairs. The recommendation was accepted by the Welsh Government in 2010 as a climate change commitment.

The Environment (Wales) Act (2016) sets out the current climate change commitments for Wales, including the need to reduce GHG emissions to at least 80% lower than the baseline by 2050.

This research project is also directly relevant to, and informed by, the Welsh Government's strategy for Woodland and Trees – "Woodland for Wales". In addition, there is widespread recognition of the need to move towards more 'climate smart' woodlands in a range of important Welsh policy documents. These include:

- The Welsh Government Rural Communities – Rural Development Programme 2014-2020, which explicitly states the need to utilise woodland more effectively to meet climate change targets. This programme states the key role that the Welsh Government sees woodlands playing in producing a range of public goods, including a strong emphasis on their role in increasing climate stability and providing resilience against climate change.
- The Well-being of Future Generations (Wales) Act (2015) sets out an agenda for managing the natural resources of Wales in such a way as to provide improved well-being to current and future generations. The act sets out the need to balance (and potentially reprioritise) the delivery of ecosystem services from natural systems.
- The State of Natural Resources Report (SoNaRR, 2016) reviewed the current threats to woodlands in Wales and sets out the well-being benefits of woodland expansion (with particular reference to the agenda set out in the Well-being of Future Generations Act).

1.1 The conifer afforestation agenda in Wales

In July 2017, the Climate Change, Environment and Rural Affairs Committee of the Welsh Assembly published 'Branching out: a new ambition for woodland policies', which sets out a series of relevant recommendations including the need to urgently address the barriers to woodland creation. This document includes a recommendation to review the Glastir Woodland Creation Opportunities Map with an aim to make it more user-friendly for a range of different user groups, and to link it to the land use planning system. This research seeks to directly address this need.

The Welsh Government has aspirations for significant additional tree cover to deliver climate change commitments. The woodland sector is being increasingly asked to contribute to a broader portfolio of ecosystem services including, but not limited to, a need to intensify timber production (to ensure its economic viability, and the health of the whole wood product value chain in Wales) and to increase the use of forest products to substitute for energy-intensive non-renewables. Meeting these targets will require multiple approaches, including the adaptation of farming systems (through increased areas of agroforestry integrated into pastoral systems) as well as potentially the transformation of existing agricultural land use systems to new woodland.

It is likely that any land cover change will result in trade-offs. The aspiration for this project was to identify "areas for woodland establishment" identifying where commercial woodlands (generally conifer softwood plantations) will bring maximum benefit to Wales. These "areas for woodland establishment" will indicate areas of Wales best suited for woodland creation. This will contribute towards the provision of evidence needed for policy makers, in the longer term, to decide that there could be a presumption in favour of woodland creation.

This will include, as a first step, quantification of the potential area for future woodland establishment for land cover transformation and/or farm system adaptation in the form of woodland creation. Woodland creation in this context includes both the integration of small-scale agroforestry and farm woodlands that provide green infrastructure enhancing the sustainability of farming systems, and the establishment of native broadleaf woodlands primarily for biodiversity and other environmental benefits alongside the creation of large-scale commercial conifer plantations that have the potential to deliver significant quantities of wood into the product value chain. The aim of this Work Package was to spatially identify areas where new conifer woodlands will deliver significant carbon benefits.

1.2 Brexit

The departure of the UK from the European Union (Brexit) has the potential to significantly increase the exposure of Welsh upland farmers to economic risks. Given the emphasis on sheep, beef and dairy production for the majority of farms in Wales, it is reasonable to assume the impacts will be felt at least as strongly in Wales as in the rest of the UK. Indeed, for sheep meat the impacts may be proportionately greater given the relatively large proportion of sheep meat production in Wales (Brexit and our Land consultation, 2019). Under many of the scenarios envisaged after Brexit (depending on what trading arrangements are established) there is likely to be a shift in agricultural practice; including the potential for more marginal systems to 'fall out' of agriculture thereby creating an opportunity for other land use systems. One method for identifying the more marginal systems is through the Agricultural Land Classification dataset; specifically, for land categorised as grade 3B and above (see following section). The vast majority of existing conifer woodlands in Wales are restricted to land that is poorer quality than ALC grade 3b, which is unclassified or classified as ALC 4 or 5 (fig. 3).

1.3 Agricultural Land Classification

The Agricultural Land Classification (ALC) dataset uses soil and site information to determine a grade (from 1 to 5) that can be used to assess the productivity of land. The ALC dataset was designed specifically to identify the potential of land to achieve agricultural objectives based on standard soil and site information (MAFF, 1988; Hallett et al., 2017). The system classifies land into one of 5 grades ranging from ALC grade 1, excellent quality agricultural land, with no or very minor limitations, to ALC grade 5, very poor-quality agricultural land with severe limitations which restrict use to permanent pasture or rough grazing with the exception of occasional pioneer forage crops. ALC Grade 3 represents the more marginal agricultural land. This category is further sub-divided into two sub-grades, 3a and 3b.

Subgrade 3a: Good quality agricultural land	Land capable of consistently producing moderate to high yields of a narrow range of arable crops, especially cereals, or moderate yields of a wide range of crops including cereals, grass, oilseed rape, potatoes, sugar beet and the less demanding horticultural crops.
Subgrade 3b: Moderate quality agricultural land	Land capable of producing moderate yields of a narrow range of crops, principally cereals and grass or lower yields of a wider range of crops or high yields of grass which can be grazed or harvested over most of the year.

A new Welsh Agricultural Land Classification (ALC), for use at a policy level to help plan and administer appropriate national agricultural support mechanisms was developed in 2017 (Hallett et al., 2017). This significantly refined the outputs from the original ALC datasets (as the modelling moved to a 50-m resolution). This new output 'extended' the area of land classified as 3b to approximately 26.5% of the total land area of Wales

ALC Grade 3b land has been identified as a category where the potential for conversion to forestry is more likely than grade 1, 2 or 3a land because its lower productivity makes agriculture less economically beneficial. Much, but not all, of the grade 4 and 5 land in Wales that is suitable for production forestry under current environmental guidelines, has already been converted to woodland. However, the full potential of ALC grade 3b land in Wales for commercial forestry is unclear and filling this evidence gap is the primary purpose of the present project. The particular approach adopted was to explore the degree to which the ALC dataset aligned with forestry yield modelling, i.e. what is the forestry production potential of the ALC grade 3b land that is marginal for future economic agriculture?

1.4 Area Statements

Since the 2016 Environment (Wales) Act, Wales has been divided into six areas (hereafter 'places') tasked to design coherent plans for sustainable natural resource management within the themes of public goods, resilience, and 'place-based' thinking. The new legislative framework provided an opportunity to rethink the way natural resources are managed and used. In principle Area Statements will help coordinate work with natural resources, including the forestry sector, with the specific aim of building resilience for Welsh ecosystems.

One of the goals of the work to develop Area Statements is to provide evidence to inform the setting of priorities for each locality. As such, we have incorporated the Area Statement regions into this

modelling to explicitly explore the potential for woodland creation to become a substantial component of the land use plan within each of the regions, and to assess the potential contribution of each region to the national woodland creation targets.

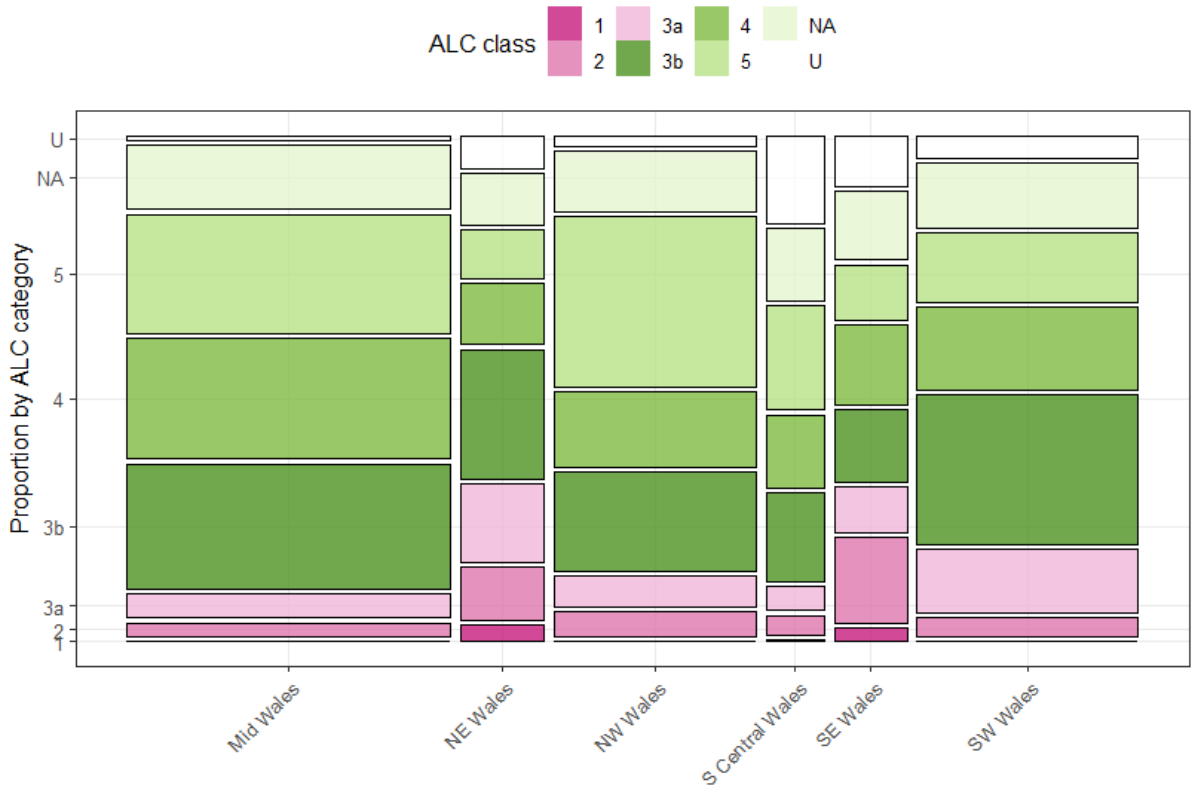

Figure 1: Distribution of ALC classes across Area Statement regions.

The balance in area between ALC grade 3b and 4 land is remarkably similar across the Area Statement regions, offering similar opportunity landscapes for woodland creation (fig. 1). For example, all regions could in theory satisfy their woodland creation targets by using only grade 3b and 4 land.

At present, the distribution of woodland area is surprisingly even across the six terrestrial regions (fig. 2). If the target to establish new woodland was made equally evenly amongst the regions (and proportionally), under Welsh national targets of 100 000 ha (and 60 000 ha) respectively, each region would aim for: Mid Wales, 33,612 ha (20,167 ha); NE Wales, 8,575 ha (5,145 ha}); NW Wales 21,132 ha (12,679 ha); S Central Wales, 6,058 ha (3,635 ha); SE Wales, 7,492 ha (4,495 ha); SW Wales, 23,132 ha (13,879 ha).

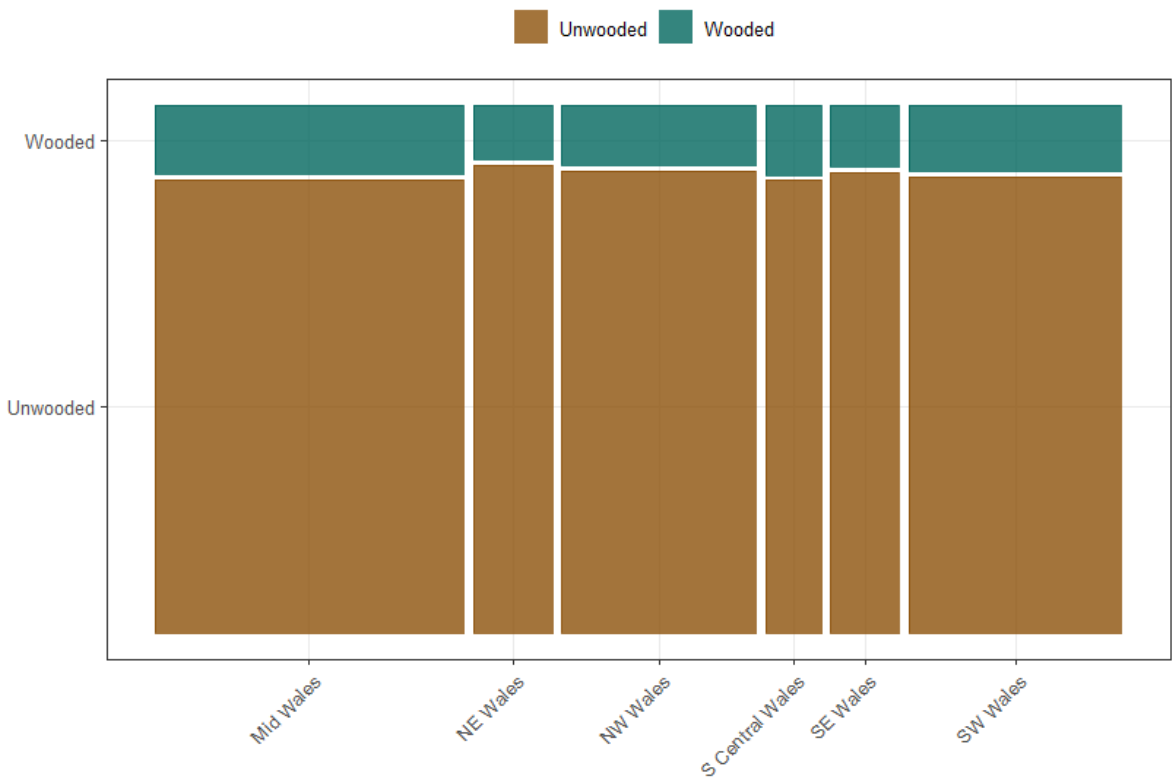

Figure 2: The distribution of land area between wooded and unwooded habitat across the six Area Statement regions.

1.5 Notes about current extent of conifer woodland in Wales

Key points:

- Currently the vast majority of commercial conifer plantation woodlands are on land that is highly likely to be of poorer quality than ALC grade 3b, being classified as ALC 4 or 5 or not classified in the agricultural land survey (fig. 3). It is not known how much of the land not-classified in this survey would be grade 3b or better, however knowledge of the history of conifer woodland creation in Wales indicates that it would be a very small proportion.
- Of the land that has been classified as grade 3b in the ALC survey of agricultural land only ca. 6,500 ha is covered by conifer woodland (fig. 3).
- The most common size class of individual current commercial conifer woodlands is 3-10 ha, though a majority are smaller than 3 ha (fig. 4). Nonetheless, woodlands > 3 ha in size account for the vast majority of the total area of this woodland type (fig. 4, 5).

The wide distribution of existing woodlands across Wales (fig. 5) already provides the nodes for dispersed nationwide provisioning of timber and other woodland ecosystem services, as well as an extensive woodland habitat network. There is huge potential to capitalise on existing local forestry infrastructure and wood value chain marketing, and to increase woodland connectivity, through strategic placement of new woodlands in each of the six Area Statement regions across Wales.

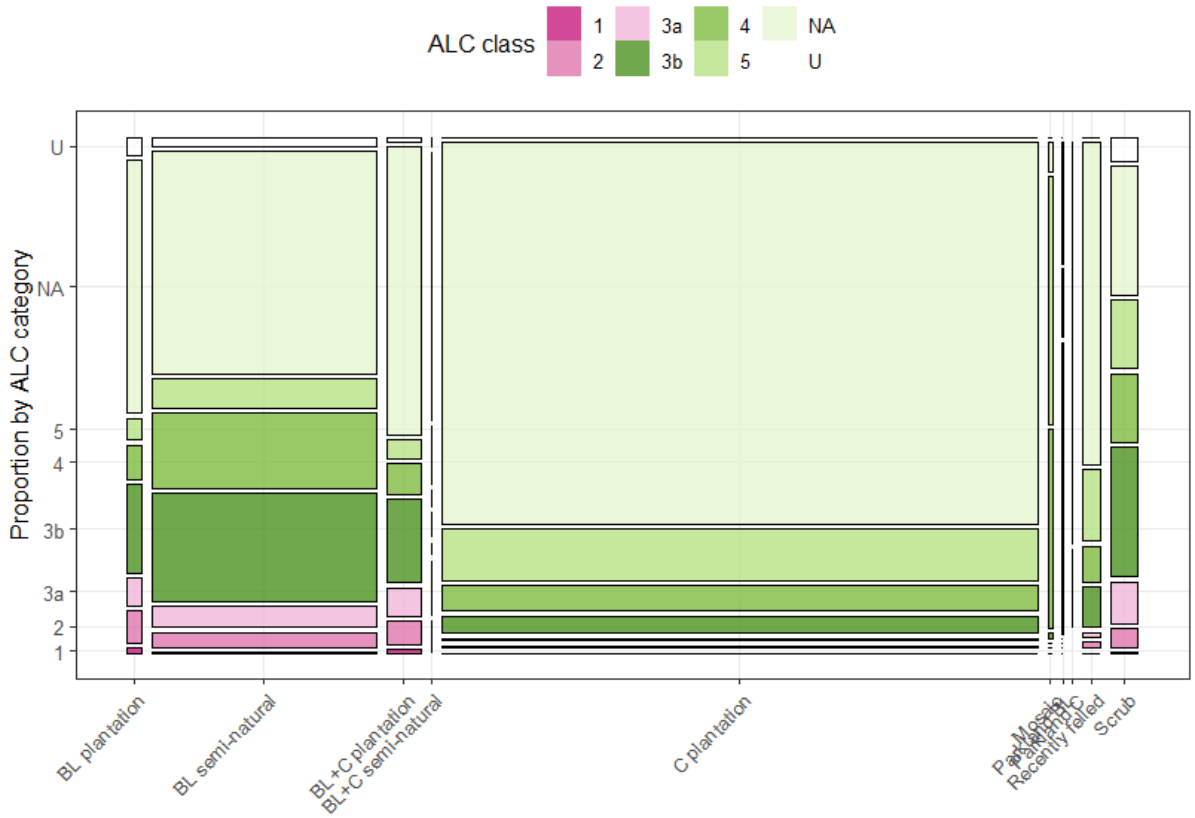

Figure 3: The distribution of woodland types across ALC categories in Wales, showing from left to right: broadleaved plantation woodlands; broadleaved semi-natural woodlands; broadleaved and conifer mixed plantation woodlands; broadleaved and conifer semi-natural woodlands; conifer plantation woodlands; mosaic woodlands; parkland broadleaved; parkland conifer; recently felled woodland; scrub woodland.

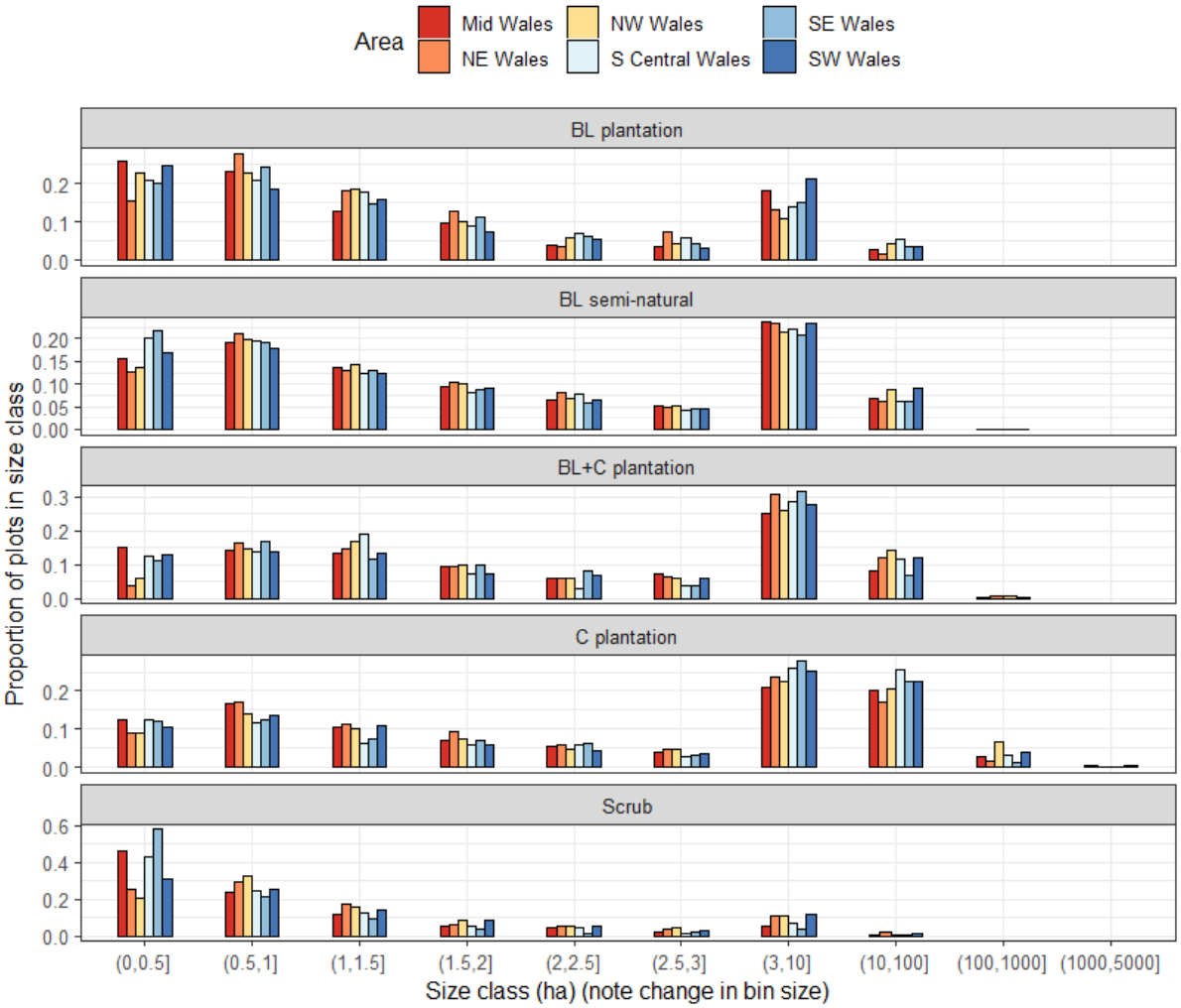

Figure 4: Distribution of woodland size classes across Area Statement regions, with the size classes shown as proportions to aid comparison between regions of vastly different sizes.

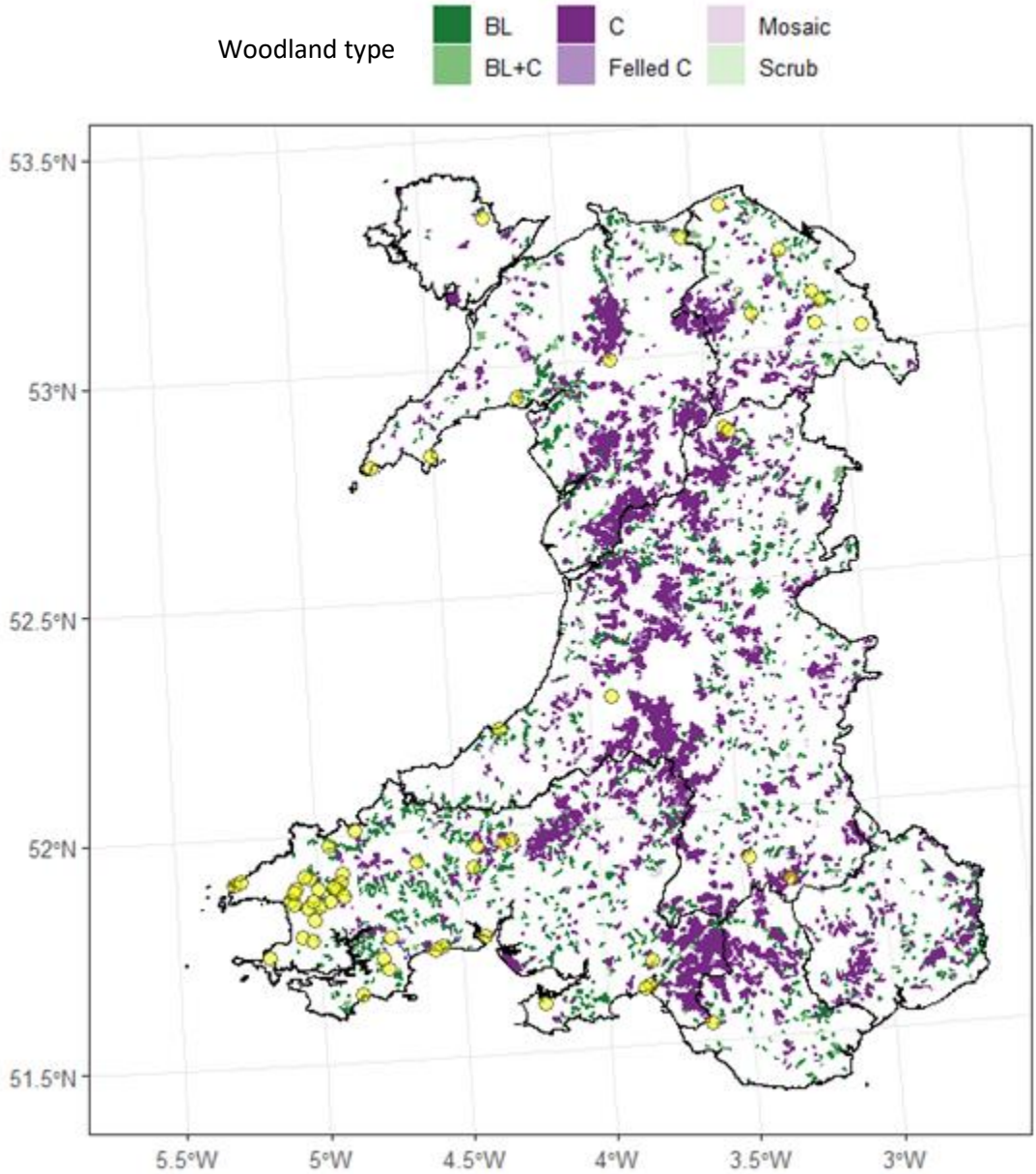

Figure 5: The distribution of large (> 10 ha) woodland areas in Wales. Yellow circles indicate scrubland, showing the concentration of large scrub patches in SW Wales. If all scrub patches were allowed to regenerate or be planted to woodland, SW Wales would reach 18%, and 30%, respectively, of its hypothetical woodland creation target as per the 100,000 ha and 60,000 ha scenarios, respectively.

1.6 Main aims of the climate smart woodlands project

The objective of this work package was to identify and quantify potential 'woodland establishment areas' where woodland creation would both meet environmental requirements and be a feasible option for commercial production woodlands (given elimination of certain barriers and provision of adequate incentives). This activity was focused on agricultural land in grade 3B, using the updated Agricultural Land Classification maps. This was achieved by identifying areas where new woodland establishment will be feasible for the commercial forestry sector, e.g. transport access for harvesting. This activity was guided by the Glastir Woodland Creation Opportunities Map.

2.0 Methods

2.1 Yield Class

Yield class is an index measure of forest productivity based on the maximum mean annual increment (MAI) of cumulative timber volume achieved by a given tree species growing on a given site and managed according to a specified prescription (Matthews et al., 2016). It is measured in units of cubic metres per hectare per year. The evaluation of tree species suitability in this study was based upon yield class values from the Ecological Site Classification (ESC) decision support system (DSS) which derives estimates of yield class for tree species based upon climate and soil factors (Pyatt et al., 2001). Yield class estimates and assumptions around management are integrated with existing carbon sequestration models (Jenkins et al., 2018). The linkage of climate data and Forest Research models of forest productivity and biomass is described in Ray et al. (2014). For the purposes of this study, however, estimates are based upon the assumption of baseline climate growth.

2.1.1 The potential for afforestation on ALC grade 3b land

The assessment of ALC grade 3b land suitable for afforestation was undertaken using ESC, which uses four climatic variables and two soil variables to determine the growth potential of a given tree species (Pyatt et al., 2001).

To assess site warmth during the growing season ESC uses the mean yearly accumulated temperature (AT5), defined as day degrees above 5 ° Celsius, from a 30-year period (1961-1990). Continentality is a measure of distance from sea related to Conrad's continentality index (Conrad, 1946). Detailed Aspect Method Scoring (DAMS) (Quine & White, 1993) describes the wind exposure of a site based on prevailing wind and topography. Moisture Deficit is an index based upon the estimated difference between precipitation and evaporation during the growing season. At present the outputs from ESC are largely predicated on evidence that accumulated temperature is the primary limiting factor to tree growth in Great Britain. Soil moisture and nutrient regimes are modelled for soil types in the Forestry Commission soil classification system (Pyatt, 1982) and mapped to national scale data.

Given the variability of soil conditions, in practice it is recommended that, prior to applying any results, a detailed site assessment is made following ESC methods and a site-specific prescription drawn up.

ESC data have been previously downscaled from coarse-resolution climate datasets to 250-m-resolution using environmental lapse rates to account for topographic variation in temperature.

As outlined above, the DAMS system developed by Forest Research (Quine & White, 1993) gives an indication of wind exposure for a site. Higher values indicate more exposed sites. As a rule of thumb, sites above DAMS 16 are exposed, those below 12 are sheltered and those in between are moderately exposed – however each tree species has different tolerances to this variable. DAMS score thresholds were adjusted up by 2 units to check the sensitivity of variation in exposure limits within the modelled outputs. For Sitka spruce and Douglas fir on ALC grade 3b land the effect of this change was marginal, but it was decided to base the analysis on a 2-unit modified DAMS score because:

- There is evidence from NRW sub-compartment databases that trees in Wales grow to higher levels of exposure/elevation (DAMS) than in Scotland.

- Ecological Site Classification places equal weighting on AT5 and DAMS, but it appears that AT5 is the dominant factor governing growth.
- Should future analysis be extended to ALC grade 4 land, these sites will show a stronger response to changes to DAMS. By including this score adjustment at this stage, it future-proofs the conclusions of this report if they need to be viewed alongside a subsequent study of ALC grade 4.

2.2 ALC data

ALC data were cleaned prior to use. Geometry errors were corrected using GRASS (Geographic Resources Analysis Support System) and QGIS software packages. Corrected errors included, for example, overlapping polygons (which inflate the area associated with an ALC class because it is counted twice).

The ALC data were also found to include areas that are presently settlements (e.g. villages) and lakes. Given the limited time available to edit base data for this study, changes were confined to removing spatial errors. It is therefore important to note, from cursory exploration of the outputs, that the area of ALC grade 3b land actually available for forestry will occasionally be less than the area of the mapping unit displayed.

The ALC 3b grade land was characterised according to the soil moisture and soil nutrient regimes which underpin ESC.

2.3 Access mapping

2.3.1 Topographic data

Based upon a 50-m digital elevation model (DEM), maximum values were selected where they might impose working constraints on a site. These were:

Slope in degrees (maximum)

Elevation (mean)

Topographic roughness index (maximum)

2.3.2 Riparian zones

The extent of riparian zones within ALC grade 3b land was studied with Ordnance Survey rivers data from the open rivers and Zoomstack products. The latter included more accurate representation of larger water features.

From the Forests and Water guidelines within the current UK Forestry Standard (UKFS), the upper recommended buffer widths for watercourses were applied to water features derived from the Ordnance Survey data. A 20-m buffer was therefore applied to watercourses with a channel more than 2 m wide and along the edge of lakes, reservoirs, large ponds and wetlands, whilst a 10-m buffer was applied to smaller streams. Note that these buffers only consider riparian zonation for the purposes of forest establishment, not the necessary buffer widths required for chemical stores, water supplies and other specialised considerations.

Since harvesting operations in riparian areas can affect water quality the impact of implementing riparian zone restrictions is to reduce the harvestable area within a management unit. However, riparian zones may provide forest managers with dedicated areas for growing alternative species to address other UKFS guidelines, for example increasing species diversity within management areas.

Riparian zones within ALC grade 3b land include features such as lakes which were not flagged as unplantable in the original data provided for this study. As a consequence, the dataset could be improved by using the ALC grade 3b data in conjunction with the Ordnance Survey rivers data, to remove unplantable features from the combined dataset.

2.3.3 Proximity to roads

Roads were buffered to 500, 1000 and 2000 m to provide an index of proximity to the existing public road infrastructure. Results were calculated separately for motorways/A roads and B roads. These data were rasterised at 100 m for integration with the main dataset.

The desk-based analysis of proximity to roads did not consider topographic constraints that might in practice limit connectivity, for example since the data were calculated 'as the crow flies' there will be circumstances where a hill, settlement, lake or other feature would obstruct a direct road connection. It was assumed, based upon previous timber transport route definitions, that A roads are preferable to B roads for timber transport.

2.3.4 Proximity to existing woodland

The proximity of ALC grade 3b land to existing mature woodlands was determined using National Forest Inventory data (2020). Two woodland categories were considered separately, coniferous woodland and mixed/broadleaved woodland, both with a minimum size of 5 ha.

Because considerations around the proximity of existing woodland include the potential to utilise existing transport infrastructure, buffers of 500, 1000 and 2000 m were applied for consistency with the roads' analysis. The final product was rasterised at 100-m cell resolution and integrated with the main dataset.

2.4 Constraint mapping

A layer of constraints to woodland creation was generated for all ALC land classes. Data processing was undertaken using the R programming language, using code developed for the Woodland Planting App (see section 7.4). The principle adopted for the analysis was to rely as much as possible on openly available data. To this end, we relied heavily on the products supplied by the Welsh Government data portal 'lle'[2]. All data described below can be assumed to derive from lle if no other data source is made explicit.

Constraint layers were informed by the Glastir Woodland Creation Opportunities Map. Constraints fell into the following categories: lakes (GB Lakes Inventory); urban areas (ALC urban layer); existing woodland (Phase I habitat surveys); conservation areas, specifically: Sites of Special Scientific Interest (SSSI); existing (not candidate) Special Areas of Conservation (SAC); local and national nature reserves (L/N|NR); RAMSAR sites; Special Protection Areas (SPA); biospheric reserves. Nitrate-

[2] http://lle.gov.wales/home

Vulnerable Zones (NVZ), national parks, areas of outstanding natural beauty (AONB), and acid-sensitive areas (Nisbet & Evans 2014; Forestry Commission, 2014) were assumed to not preclude woodland creation.

The constraints layer was subtracted from the Forest Research-developed product for ALC 3b land to obtain realistic estimates of the woodland creation opportunities. This was computed for polygons of the priority conifer species with the highest Yield Class.

Data that were assessed, and considered to have potential for future research, but could not be used for this analysis were as follows. For road access, 5000 regularly spaced points across Wales were generated, and their distance to the nearest tertiary or higher-order road (as the crow flies) was computed based on the Open Streetmaps product. For this analysis all tertiary or higher-order roads were presumed permissible for timber lorries. An example of this layer is given in Fig. xxx which shows the constraints layer as used for this report, and with a minimum distance to tertiary road of 5 km. A slope raster was generated from 5-m DEM data from Ordnance Survey, with possibilities to generate a restriction layer for any slope the user chooses. This layer is used in the app described in section 7.4.

The R code, and any appropriately licensed data, will be made openly available at the end of the project.

2.5 Plant Trees App

Methods used to create a Plant Trees App followed those outlined for the constraints layer (instructions for the app, and the link, are in section 7.4). The app was created using RShiny and the R version of 'leaflet'.

The draft version of the app is available here: https://rstudio.bangor.ac.uk/content/3

Instructions for use are included in Appendix 7.4

The FR polygon product used for tree species mapping was sizeable, which, combined with the default processing of data sets by RShiny, has led to slow loading of the initial map view. This is also why the app is currently limited to the North Wales area statement region of the FR product. With future development, it would be possible to speed the app up considerably by working together with Forest Research to explore: 1) integrating the FR outputs by calculating species yield class on the fly, on a site by site basis using a webservice, where the url is parameterised according to the site of interest (e.g. by adding grid reference and site soil properties to query string); 2) using PostGIS that allows spatial indexing more efficiently; 3) loading data initially as a raster, which is faster to process than a polygon file.

Large estates layer: Polygons of large estates were acquired from Who Owns England[3], with the following attributions (verbatim from the website 31.03.2020):

- **Anglian Water**: GIS data supplied following Environmental Information Request, August 2016. Released with licensing stipulation that "You are free to use it for your own purposes, including any non-commercial research you are doing, and for the purposes of news reporting." It is reproduced here for the purposes of news reporting. Also see blog post. No other water companies have yet released GIS maps of their landholdings.

[3] https://whoownsengland.org/

- **Crown Estate**: GIS data supplied following Freedom of Information request. If the Crown Estate contacts us asking for this layer to be taken down, we will do so. An indicative map of land and property owned by the Crown Estate is already public.
- **Forestry Commission**: Covers both freehold and leasehold land. Contains public sector information licensed under the Open Government Licence v3.0. See the data download and blog post.
- **Highways England**: Land that Highways England manages as highway. Data released under the UK Open Government Licence. Contains Highways England and OS data © Crown copyright 2016. See the data download.
- **Ministry of Defence**: GIS data extracted from a PDF map released by the Ministry of Defence following a Freedom of Information request. No licensing conditions were provided with the released document. See the blog post.
- **National Trust**: GIS data supplied by the National Trust, also published on the NT's own more detailed Land Map. If the National Trust contacts us asking for this layer to be taken down, we will do so.
- **Network Rail**: GIS data supplied following Freedom of Information request, June 2016. No licensing conditions were provided with the released document.
- **Other Government departments**: GIS data extracted from online map that until recently accompanied the Cabinet Office's ePIMS Government Property Finder. Non-GIS data on Government Property is published under the Open Government Licence. See also past blog posts.
- **Overseas companies**: Data released by the Land Registry following Freedom of Information requests by Private Eye. Shows freehold titles registered in name of an overseas company between 2005 and 2014. See the Eye's investigation and map. Reproduced with permission of the investigative journalist who obtained this information. © Crown copyright Ordnance Survey.
- **RSPB**: GIS data published by RSPB and see the blog post. Data reproduced with the permission of RSPB. © Crown Copyright. Ordnance Survey licence number 100021787 2017.
- **Section 31 declarations**: GIS data supplied following Freedom of Information requests 2017-2018; no licensing conditions were provided with the released documents. Some data also acquired by scraping; we will take down the data if councils request we do so.

Sawmill (including wood chipping site) locations were acquired through online searches and word of mouth. The type of wood processed was recorded where possible and coded with appropriate icons. Icons to represent sawmill/chipping types were acquired from https://www.freeiconspng.com/ , but we note that the licenses for icons used cover personal use. Should the app be developed, licenses/icons would need reconsideration.

Distances to sawmills from selected locations were calculated using Emma Wiik's application programming interface with Google maps products, applying the R interface with Google mapping products. A separate account would need to be created should the app be developed for wider use. (under usage so far, the free quota has not been exceeded). The closest mill to the selection is not based on distance, but on driving time.

Distance to tertiary or higher-order road from selected locations were calculated using the Open Street Maps wiki page, where tertiary roads are described as (on 31.03.2020):

"There is a corresponding official alphabetic classification matching OSM's "tertiary" tag fairly well: 'C' roads. Note that this official designation is rarely seen on signs [3]. For the purposes of mapping, it's normally best to tag distributor roads according to their relative importance in the road hierarchy, as described above. One rule of thumb for UK roads is that highway=tertiary works well for

roads wider than 4 metres (13') in width, and for faster or wider minor roads that aren't 'A' or 'B' roads. In the UK, they tend to have dashed lines down the middle, whereas unclassified roads don't."

The wider than 4 m qualifier was assumed to be representative of roads with capacity for articulated lorries.

3.0 Results

3.1 Species suitability mapping

Most ALC grade 3b land is suitable for timber production with softwood conifer species (Table 1). Suitable in this context means achieving > 50% of the potential yield class for a given species in British conditions (climate, soil). For Sitka spruce, for example, this meant achieving YC14 or better.

Table 1 Area of ALC grade 3b land in Wales suitable for given tree species.

Species	Minimum yield class	Area suitable[1] (ha)	% Area suitable[1]
Sitka spruce	14	531,975	96.5%
Douglas fir	13	263,092	47.7%
Scots pine	7	544,274	98.7%
Pedunculate oak	4	522,053	94.7%
Silver birch	5	524,851	95.2%
Beech	5	344,971	62.6%

[1] Suitability of a tree species is defined as achieving 50% of the maximum yield class observed for that species grown under British conditions, see Appendix 1.

Species tolerant of very moist soils have the largest suitable areas of ALC 3b land across Wales. In practice, and in order to ensure that predicted timber production and/or carbon sequestration outcomes are achieved, higher yield class thresholds might be applied to sensitive species given the risks associated with their establishment.

Yield class estimates from ESC are occasionally subject to bias, particularly close to species-specific tolerance thresholds, where there is a tendency to err on the side of caution. Yields for Sitka spruce are known to be underestimated on certain poorer soils and on restock sites, where yields from improved genotypes can exceed the present maximum yield class considered in ESC. In all cases a key assumption is that the seed origin is appropriate for the site, any site-specific nutrient deficiencies are ameliorated, and adequate management is implemented to protect against mammal damage.

Using ESC, Sitka spruce established on ALC grade 3b land is approximately 4 $m^3 ha^{-1} yr^{-1}$ higher in productivity than existing forests in Wales, and 2 $m^3 ha^{-1} yr^{-1}$ greater than would be anticipated on ALC grade 4 land (Table 2).

Table 2 ESC-derived yield class for two conifer species on land of two different ALC grades in comparison with existing forest in Wales.

Land Class	Sitka spruce yield class ($m^3 ha^{-1} y^{-1}$)		Douglas fir yield class ($m^3 ha^{-1} y^{-1}$)	
	Mean	SDSD	Mean	SDSD
ALC grade 3b	22.2	4.1	9.4	9.4
ALC grade 4	20.2	4.6	9.6	8.4
Existing forest	18.8	5.9	10.4	9.4

ALC maps typically also include other land categories than current agricultural land, and existing forest was based upon an ALC category which includes a mix of site types. This explains the higher

performance of Douglas fir as, within existing forests this species is planted on the best sites, while Sitka spruce is planted on poorer upland sites with shorter (temperature-limited) growing seasons and poorer soil conditions.

Spatially explicit yield class models were developed for fifteen timber species (see examples of typical output in figs 6-9). These indicate the huge range in yield class values over a range of scales from the Welsh national scale to adjacent land areas within each Area Statement region. This will have a huge impact on the precise locations most favoured for commercial investment in woodland establishment, and the consequent synergies and trade-offs with the delivery of other ecosystem services from this land. The degree of spatial variation in yield class varies amongst species and is greatest for the commercially favoured, but very moist soil intolerant, Douglas fir (fig 6, 7, 10).

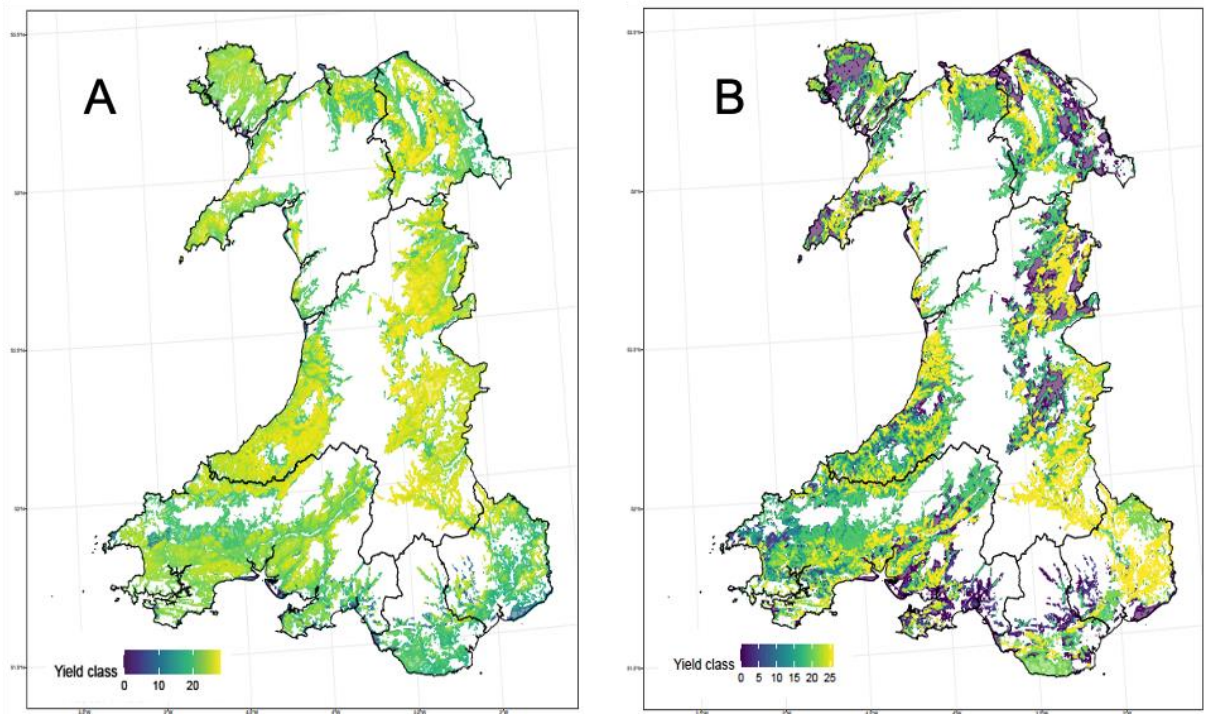

Figure 6: Tree species suitability maps for timber production on land classified as ALC 3b at an all-Wales scale: A Sitka spruce; B Douglas fir. The land area is sub-divided into the six area statement regions.

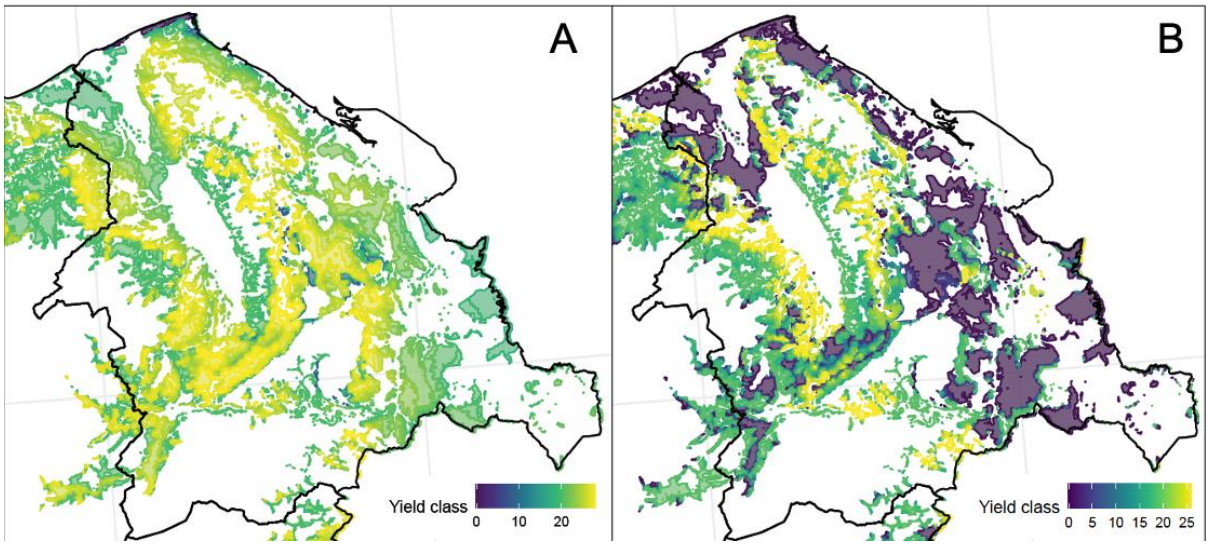

Figure 7: Tree species suitability maps for timber production on land classified as ALC 3b for the North-Eastern Area Statement Region: A Sitka spruce; B Douglas fir.

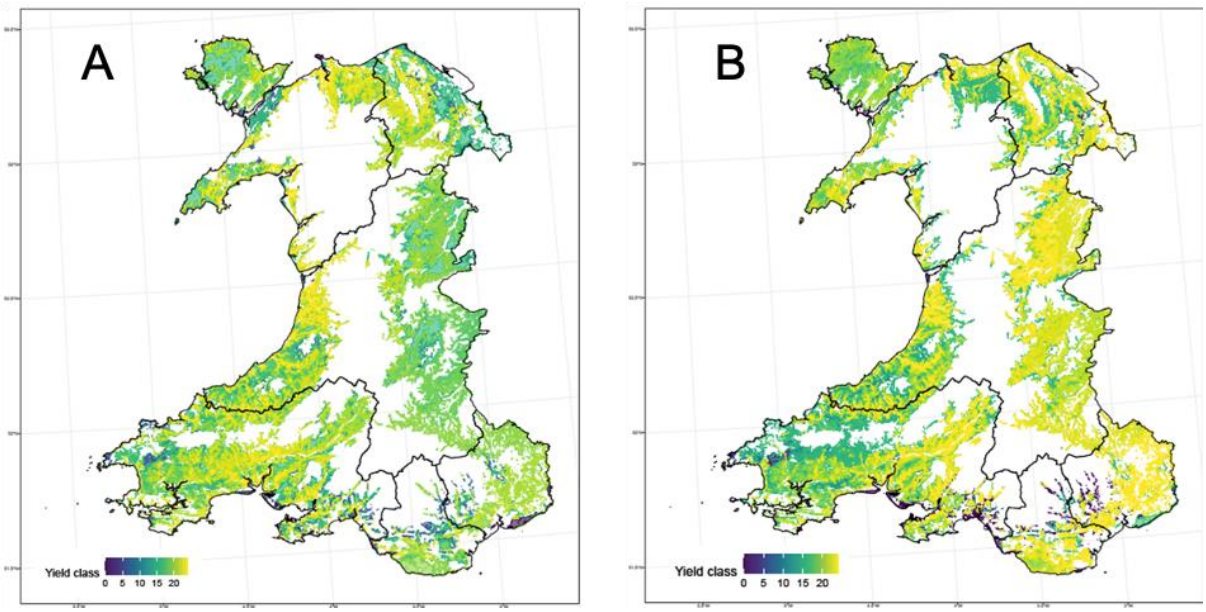

Figure 8: Tree species suitability maps for timber production on land classified as ALC 3b: A Scots pine; B western red cedar. The land area is sub-divided into the six area statement regions.

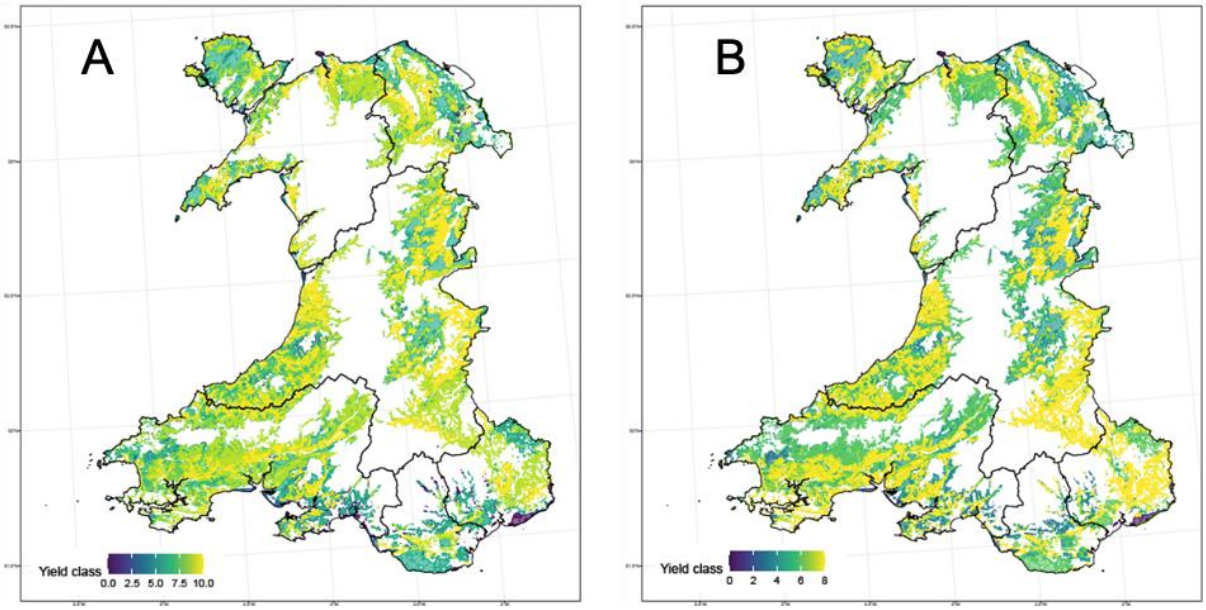

Figure 9: Tree species suitability maps for timber production on land classified as ALC 3b: A silver birch; B sessile oak. The land area is sub-divided into the six area statement regions.

There are regions in Wales where there is considerable complementarity amongst the species in terms of which areas of land (locations) are very suitable or suitable for their growth. Notably Sitka spruce and silver birch tend to be suitable in the same regions, and distinct from regions which are most suited to Douglas fir and sessile oak are (the latter two species tend to favour the same regions as each other, predominantly in the southern half of Wales) (fig. 10).

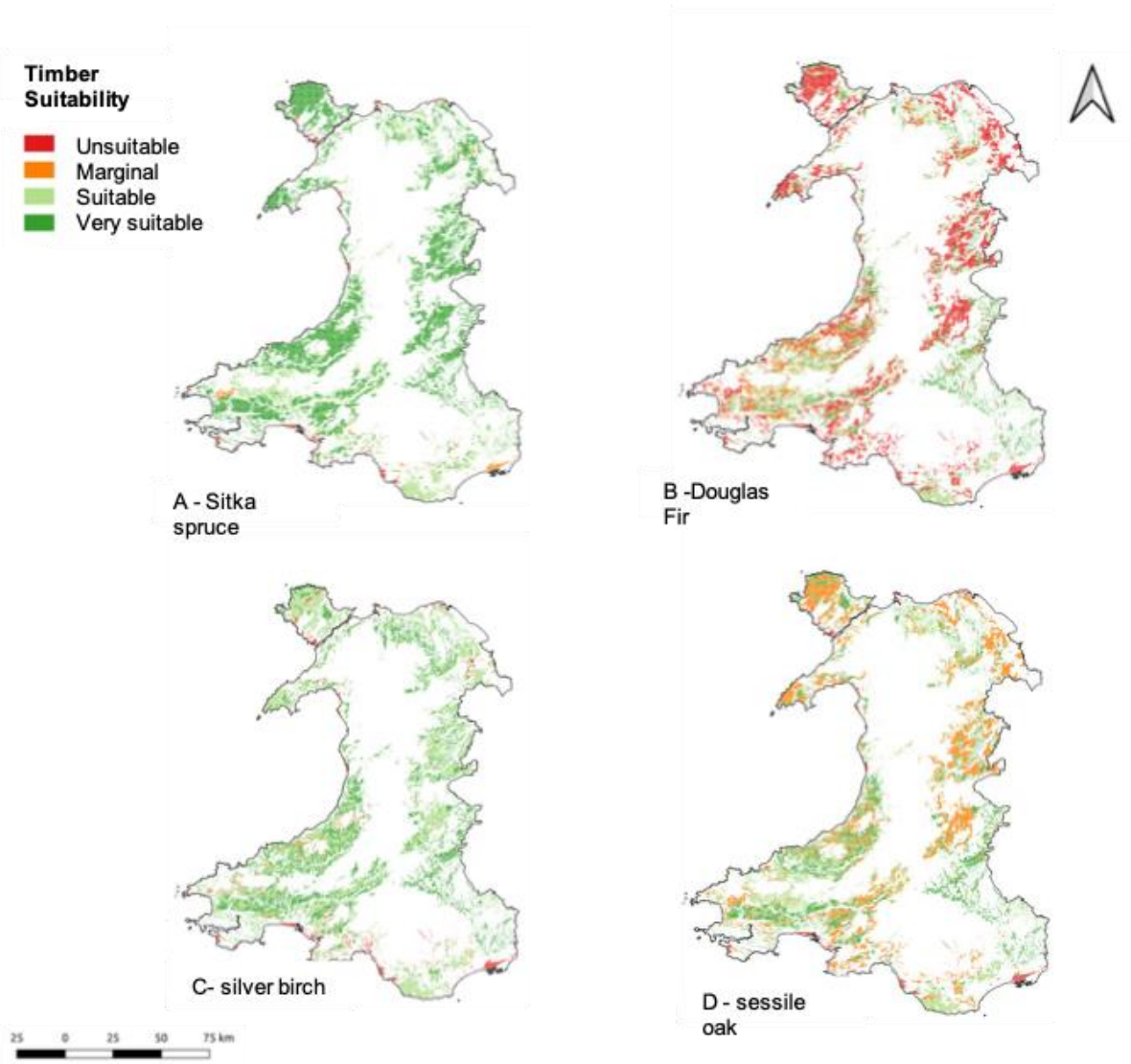

Figure 10: Tree species suitability for timber production. a) Sitka spruce b) Douglas for c) silver birch and d) sessile oak. Both Sitka spruce and silver birch are suitable across most sites on ALC 3b grade land, but there are substantial areas where Douglas fir and: sessile oak are unsuitable or marginal potential.

The high proportion of ALC grade 3b land that is suitable for high yield of western red cedar (RC) and Norway spruce (NS), and moderately high yield of western hemlock (WH) and grand fir (GF), as well as Sitka spruce (SS) (fig. 11), is also notable indicating the high potential of this grade of land to support commercial production forestry using a wide range of conifer species, achieving a mixed species national portfolio with higher economic and ecological resilience than the current heavy focus on Sitka spruce as the dominant commercial species. The main constraint on commercial forestry delivering this more resilient natural capital base is the challenge of marketing this range of timbers.

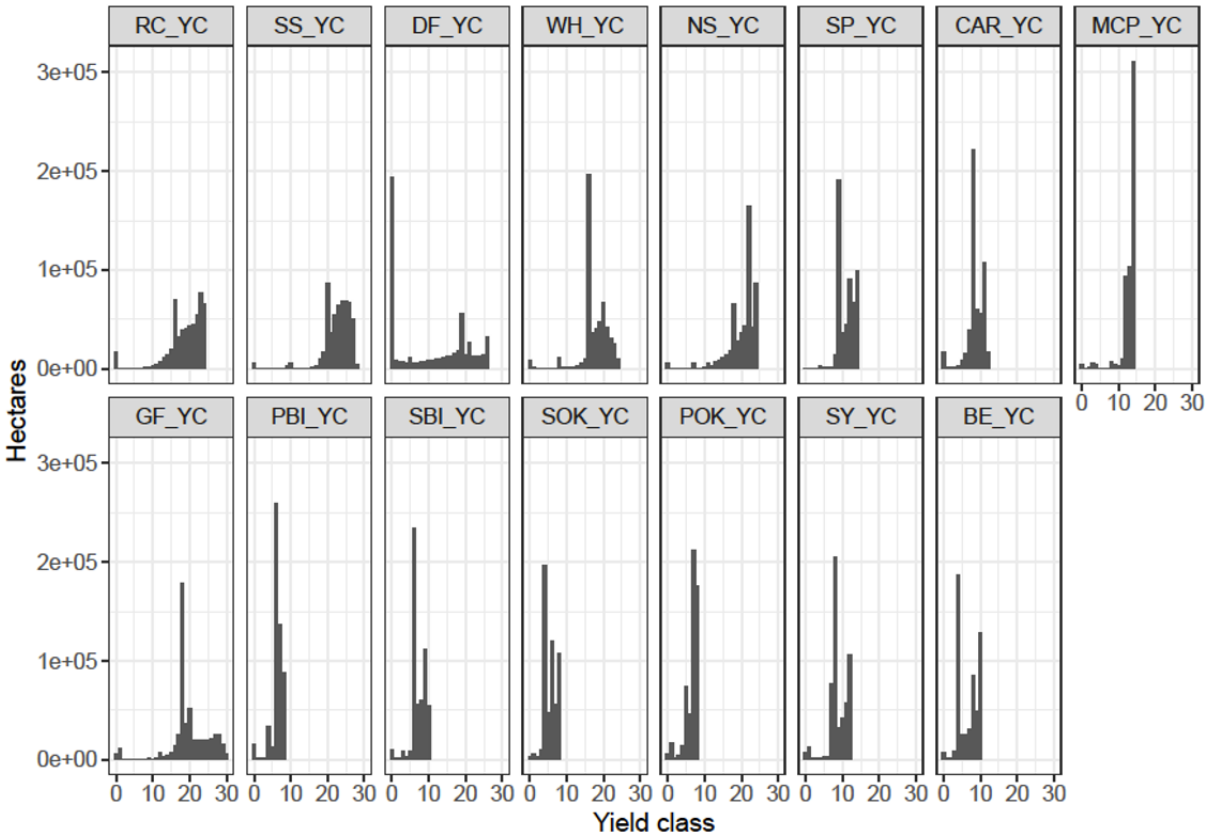

Figure 11: Variation in potential yield class of fifteen different tree species across land classified as ALC 3b (species abbreviations are defined in section 7.4.5).

3.1 Identifying a woodland creation space

3.1.1 Optimal Yield Class

Because of the geographical distribution of environmental variables across Wales (elevation, rainfall, soil type etc.) there will, however, be a distinct geographical pattern in the location of commercially optimal establishment of the most productive species (fig. 12, 13). This is predicted to show a marked spatial shift under future climate change scenarios, which will be an important factor in commercial decision-making to anticipate changes in climate over the next forest growth cycle. Subject to sufficient commercial optimism about future market development, the high potential of grand fir (GF) in South-east and South-central Wales is notable (fig. 13, 14). In addition, the potential of western hemlock (WH), in the west and north, and western red cedar (RC), in the east, to break up the spatial dominance of Sitka spruce (and grand fir) as the highest yielding species (fig. 13), offers the prospects of commercial forestry creating a much more mixed-conifer species landscape. This will be important as a functional replacement for the role of larch (at least until planting stock that is resistant to *Phytophthera ramorum* disease is available).

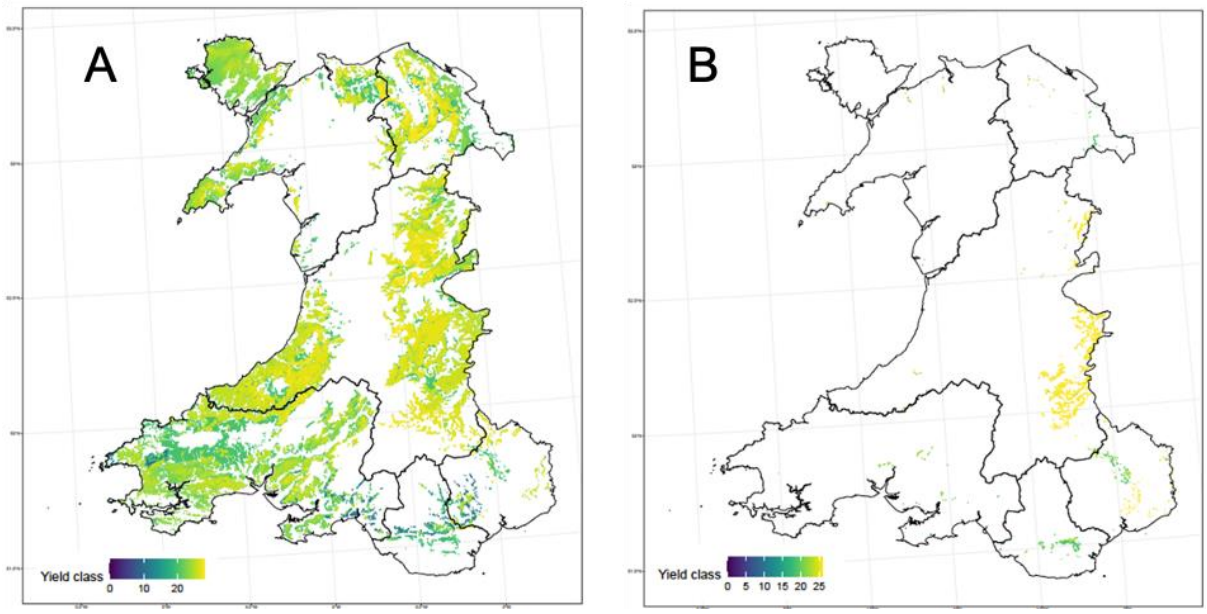

Figure 12: Areas of ALC3b land where A: Sitka spruce and B: Douglas fir are the highest yielding conifer species (from a potential pool of eight species). The land area is sub-divided into the six area statement regions.

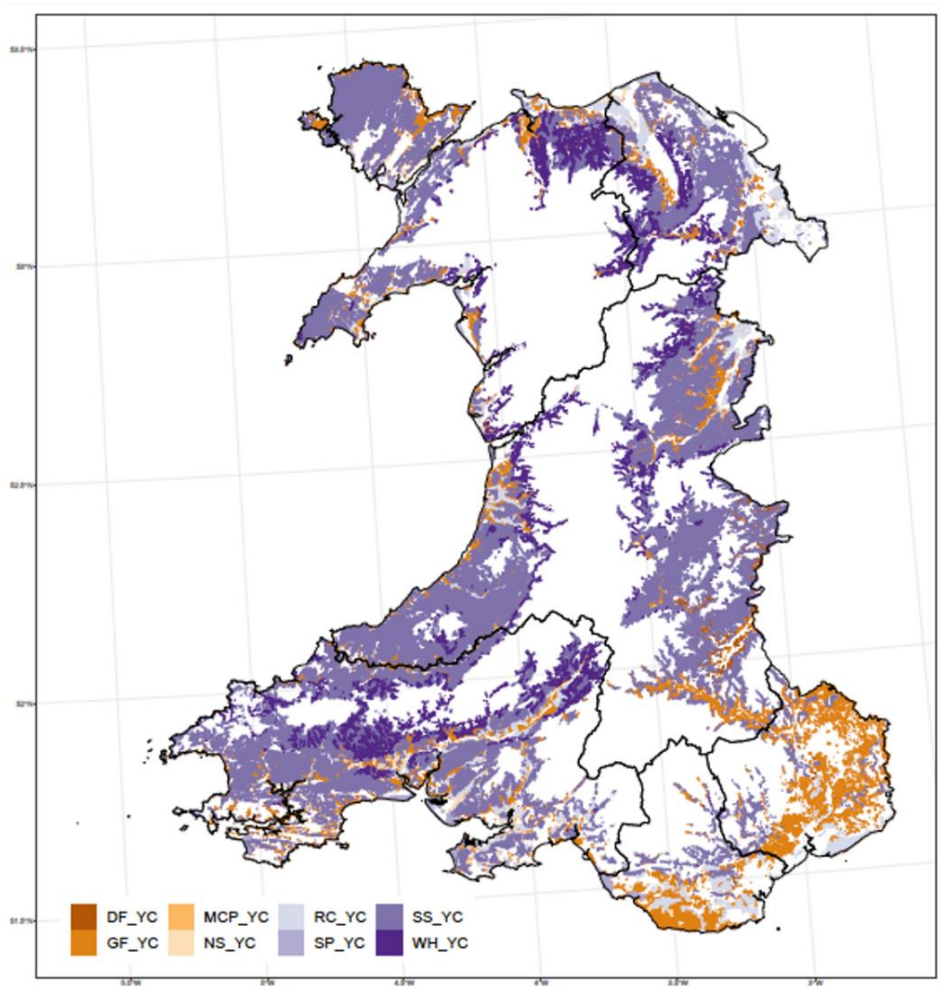

Figure 13: Map of tree species with the highest yield class from a model of site suitability for eight conifer species on ALC 3b grade land: DF= Douglas fir; GF= grand fir; MCP=Macedonian pine; NS= Norway spruce; RC= Western red cedar; SP= Scots pine; SS= Sitka spruce and WH= western hemlock. The land area is sub-divided into the six area statement regions.

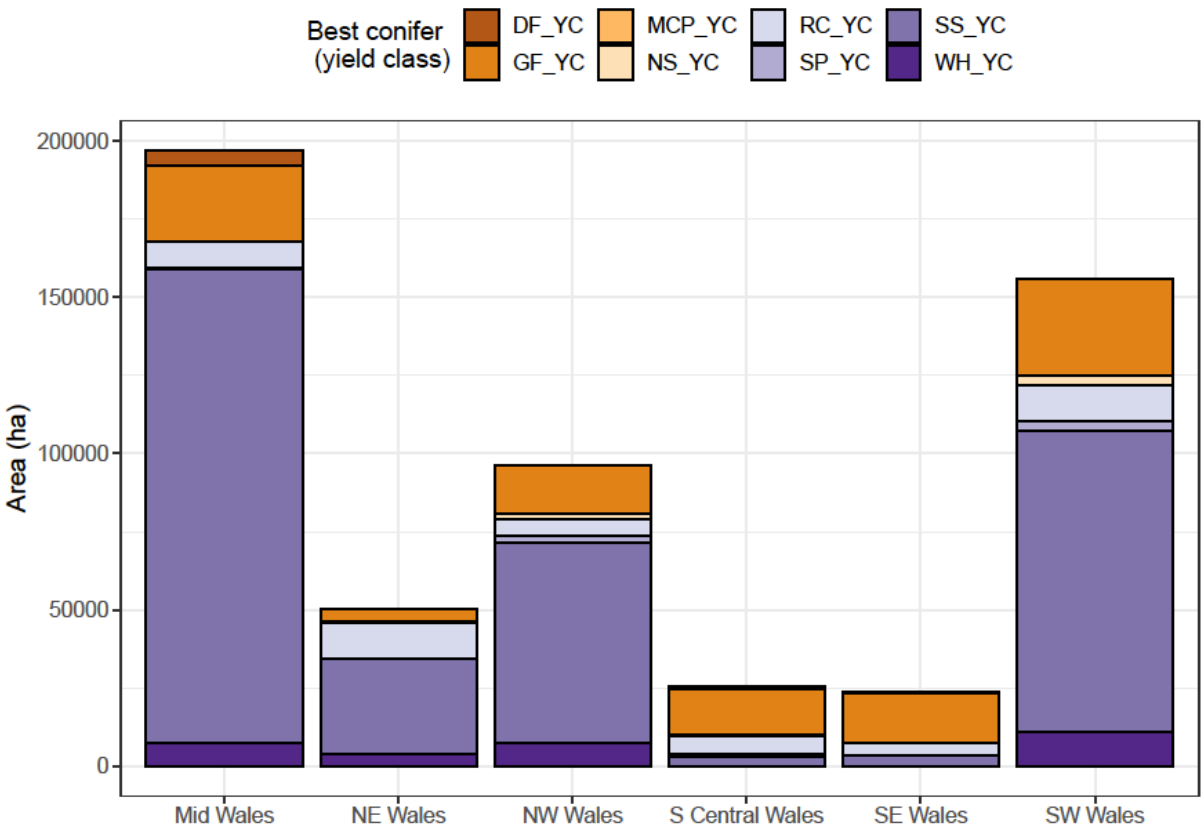

Figure 14: Area of ALC 3b grade land in each Area Statement region on which each of eight conifer species has the highest yield class from a model of site suitability.

3.1.2 Optimal carbon sequestration model

There is increasingly robust evidence (e.g. Forster et al. submitted) that conifer commercial production forestry achieves the greatest climate change mitigation benefit of any option for new woodlands in environments such as those in Wales. This is largely due to the net carbon sequestration benefits of wood use through the value chain. As a result, commercial forestry investment and achievement of Welsh Government carbon emissions reduction targets represents a "win-win" strategy. However, some carbon accounting methods applied to woodlands (such as the Woodland Carbon Code) are restricted to the carbon stocks within the trees of standing woodland. Tree growth rates (e.g. as captured in the "yield class" index) are traditionally measured in terms of wood volume. Because alternative commercial tree species different significantly in their wood density (and thus carbon density). Thus, for a given area of land there can be a different optimal tree species to select if the objective is maximum rate of carbon sequestration compared with maximum rate of timber volume production (yield class). As a result, for all ALC grade 3b land in Wales (ignoring constraints), for the eight conifer species tested in this study, following ranking[4] to resolve ties (comparing figures 14 and 16), Sitka spruce is the optimal species for 63% of the area by yield class, and for 60% by carbon sequestration (at 45 years); whereas the denser-wooded Douglas fir is the optimal species for 1% of the area by yield class and for 29% by carbon sequestration (at 45 years). There is also a spatial shift in which species have the highest performance across the ALC 3b grade land between the two criteria (compare figures 13 and 15), with carbon sequestration rate

[4] In order of preference: Douglas fir > Sitka spruce > Scots pine > western hemlock (then arbitrary for the lesser species)

notably promoting the establishment of denser-wooded Douglas fir over grand fir in much of eastern Wales and promoting Sitka spruce over western hemlock in the south-west.

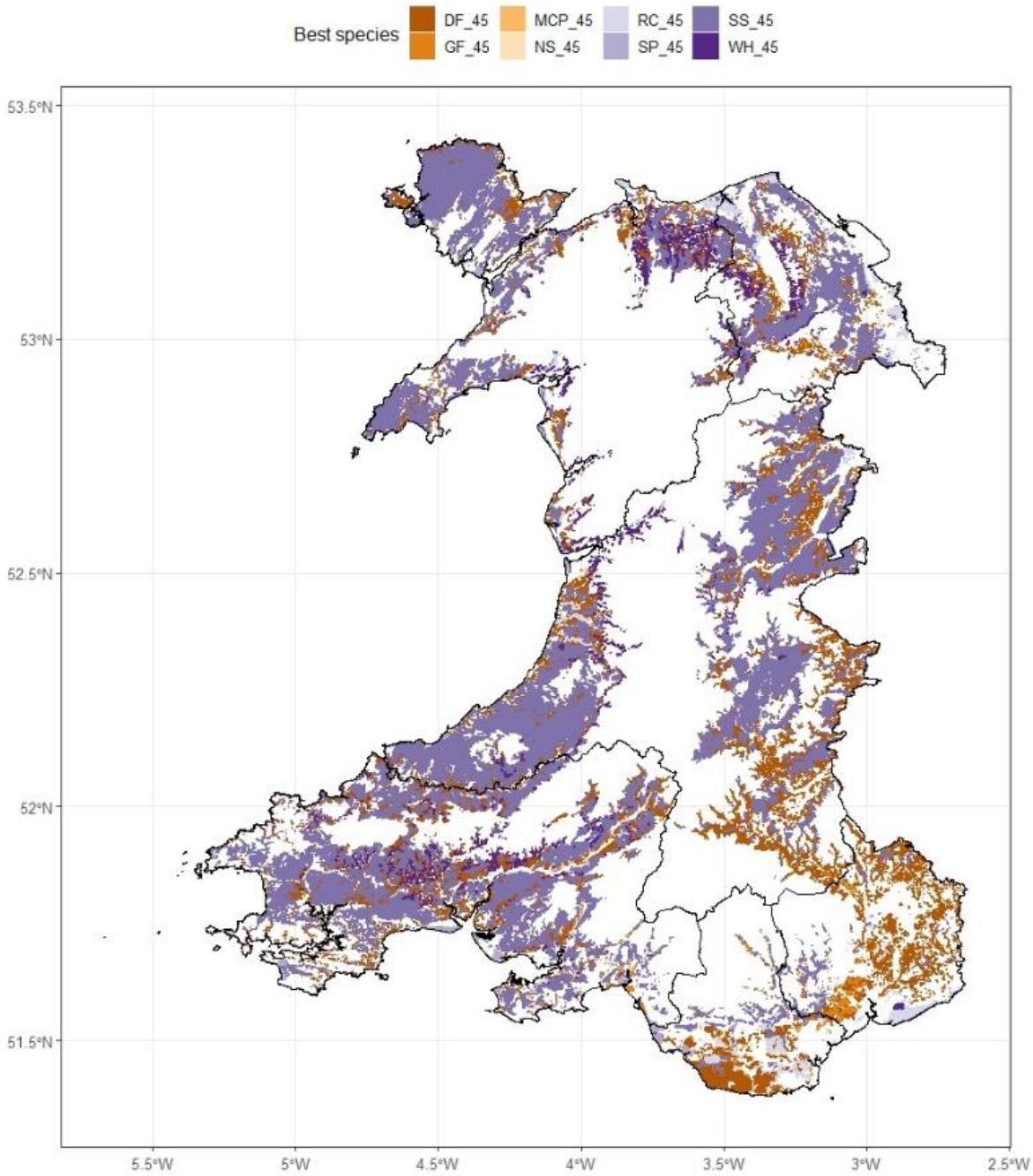

Figure 15: Map of tree species with the highest carbon sequestration at 45 years after establishment from a model of site suitability for eight conifer species on ALC 3b grade land: DF= Douglas fir; GF= grand fir; MCP=Macedonian pine; NS= Norway spruce; RC= Western red cedar; SP= Scots pine; SS= Sitka spruce and WH= western hemlock. The land area is sub-divided into the six Area Statement regions.

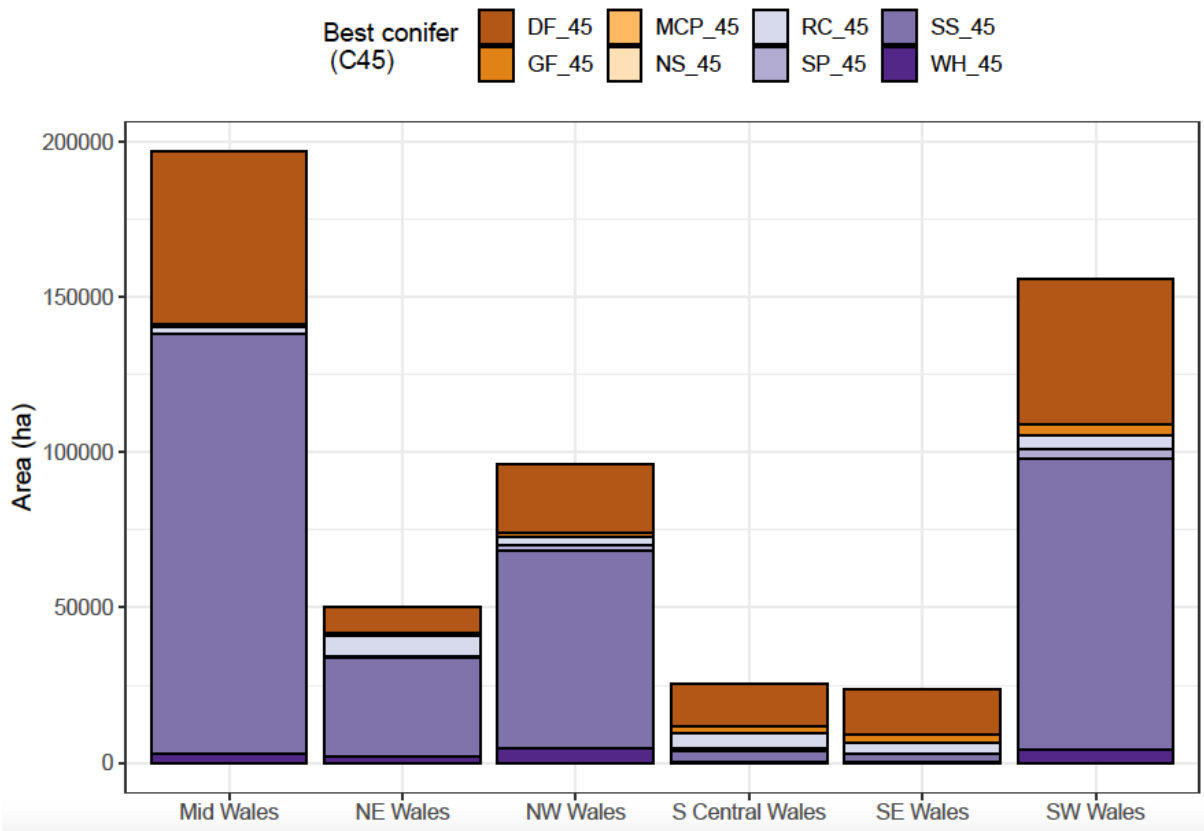

Figure 16: Area of ALC 3b grade land in each Area Statement region on which each of eight conifer species has the highest carbon sequestration at 45 years after establishment from a model of site suitability.

At a local scale, switching from tree volume growth (Yield Class) to carbon sequestration rate as the criterion for identifying the optimal species for each site causes a notable shift in the mapped boundaries of patches. In one illustrative example landscape, use of the carbon sequestration criterion notably favoured the denser-wooded Douglas fir over faster-growing western hemlock, but not over Sitka spruce (fig. 17), whereas in a second exemplar landscape, use of carbon sequestration favoured Douglas fir over both faster-growing western hemlock and Sitka spruce (fig. 18).

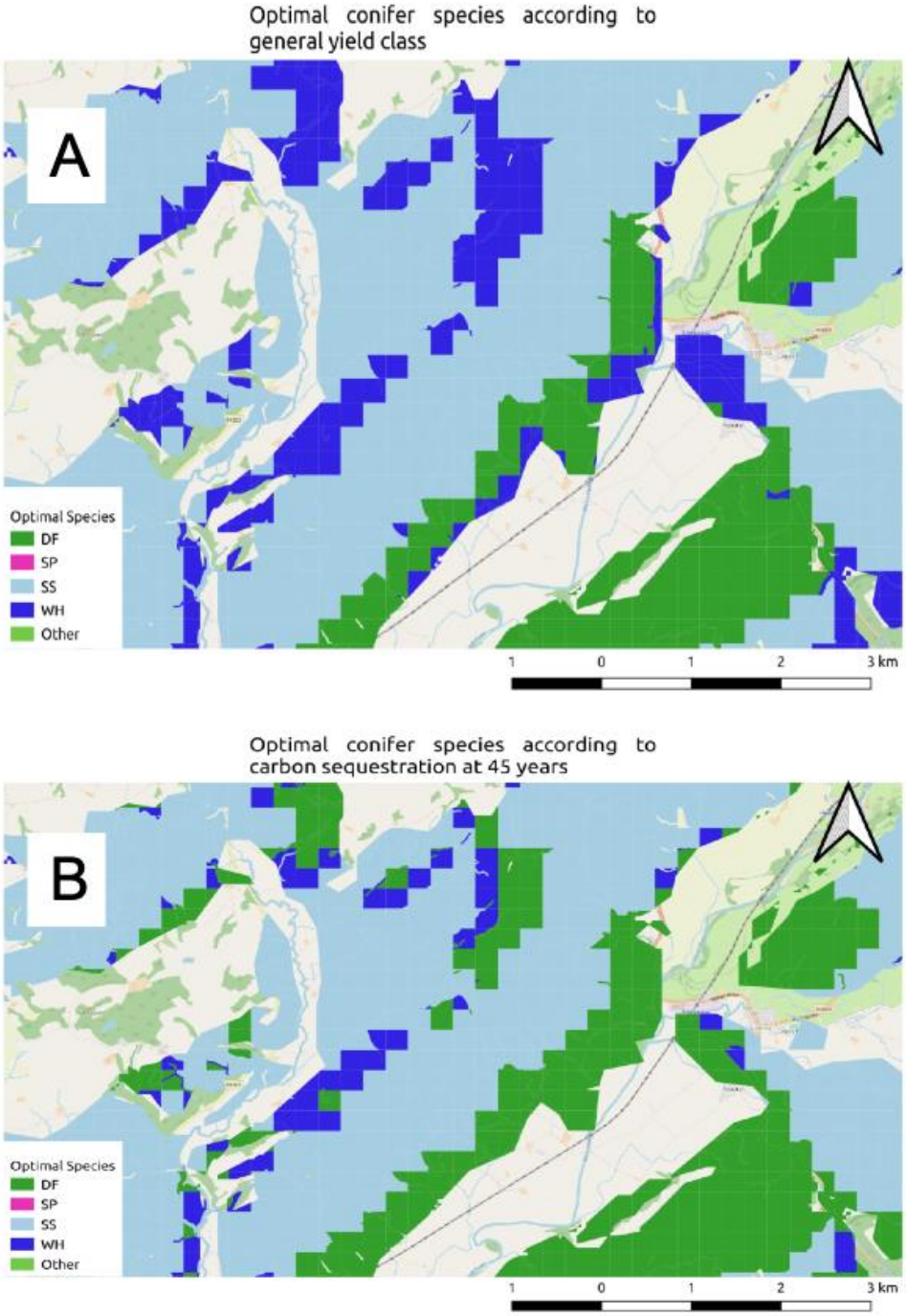

Figure 17: The optimal conifer species depends upon the selection criteria. For example landscape 1, in a) suitability is based upon yield class and in b) carbon sequestration.

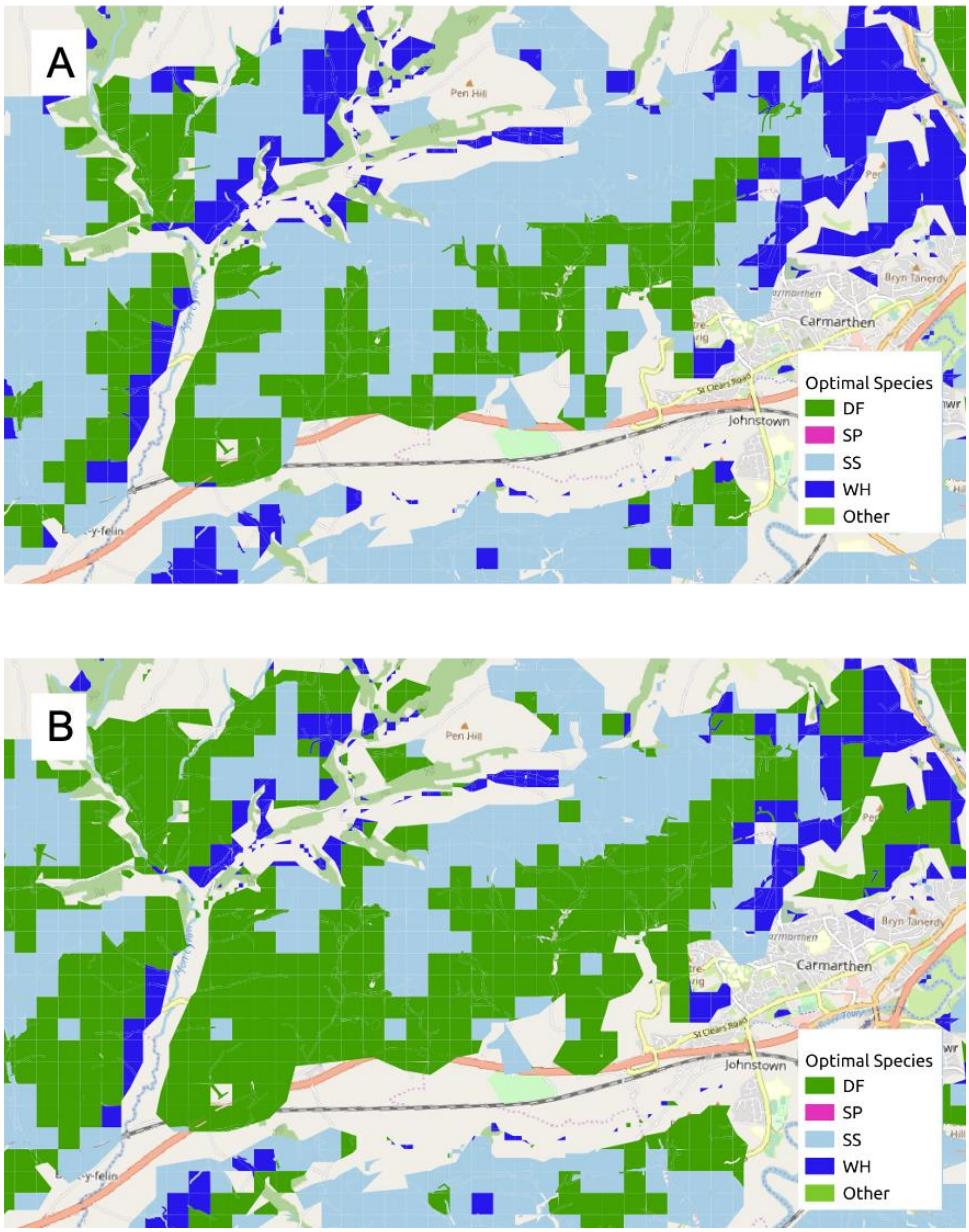

Figure 18: The optimal conifer species depends upon the selection criteria. For example landscape 2, in a) suitability is based upon yield class and in b) carbon sequestration.

3.1.3 Adding in constraints

Applying all of the constraints that correspond with those included in the Glastir Woodland Creation Opportunities Map shows the strong association with higher altitude land across Wales. Much of this land is ALC grade 4 and 5, which is of little value for agricultural production, though some also occupies ALC3b and better land (fig. 19). As a consequence, much of the unconstrained space that is available for woodland creation represents a potential conflict with productive agriculture, reinforcing the premise of this project that much of the land that represents a balanced economic choice for land use change to woodland is the ALC 3b land. The effect of applying the constraints on the available area of land on which each tree species is the optimal choice for wood productivity (yield class) is to reduce the area to the greatest extent for the species with the best relative performance in upland areas, e.g. Scots pine and Norway spruce (Table 3). The effect of applying the constraints does not alter the dominance of Sitka spruce as the species producing the highest yield of timber over a high proportion of available land for woodland expansion in Wales. After the constraints are applied it is notable that grand fir (and to a lesser extent western red cedar and western hemlock) continue to displace Douglas fir from almost all of the land area on better sites where the latter would be expected to be the preferred commercial species. This ties in with the growing commercial interest in these alternative conifer species, timber quality and market permitting. However, the better-established market for Douglas fir timber, combined with its high growth rate on favourable sites, would still make it the preferred species for many commercial foresters. Nonetheless, these results further demonstrate the potential to create a more species-diverse commercial conifer forest on more favourable sites.

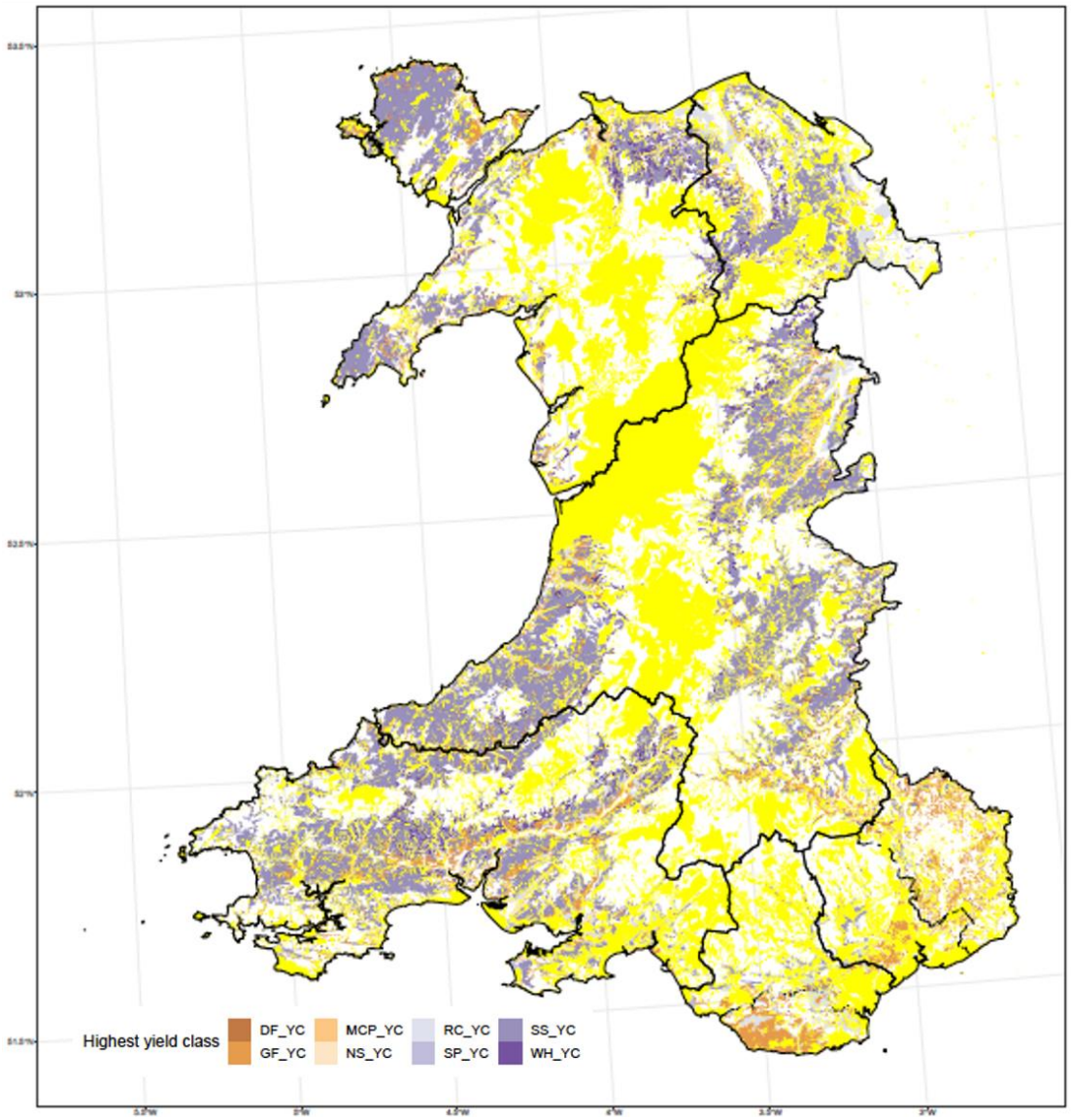

Figure 19: Yield class map with the Glastir Woodland Creation Opportunities Map constraints layer superimposed (yellow). Areas without constraints that are also not 3b land, are transparent (white).

Table 3. Effect of applying the Glastir Woodland Creation Opportunities map constraints on the area of ALC 3b land on which each of eight tree species is the fastest-growing (Yield Class).

Species	**Area of ALC 3b land in which it is the highest-yielding species (ha)**	
	Before adding constraints	After adding constraints
Sitka spruce	349,621	318,902
Grand fir	106,599	94,171
Red cedar	46,259	39,033
Western hemlock	30,060	24,837
Norway spruce	6,396	5,595
Douglas fir	6,336	4,899
Scots pine	7,337	2,387
Macedonian pine	0	0

3.1.4 Mapping access

Approximately 32.5% of ALC grade 3b land within Wales lies within 1000 m of an A-road or motorway. This percentage rises to 62.2% when a threshold of 2000 m is applied (Table 4). This indicates that the opportunity space of ALC 3b land suitable for establishment of commercial production woodlands in Wales has better proximity to the necessary road infrastructure than is the case, for instance, in more extensive upland areas, such as the Scottish highlands.

Table 4: Area of ALC grade 3b land by road class.

Road type	**ALC grade 3b land area (hectares) by distance from public roads**			
	0-500 m	500-1000 m	1000-2000 m	> 2000 m
A roads and Motorways	87,966	91,398	163,731	208,181
B roads	81,983	93,328	179,859	196,107

It is notable for the landscape area used for illustration (fig. 20) that there is no notable spatial correlation between the suitability of land for growth of Sitka spruce (as indicated by Yield Class) and its proximity to the nearest road.

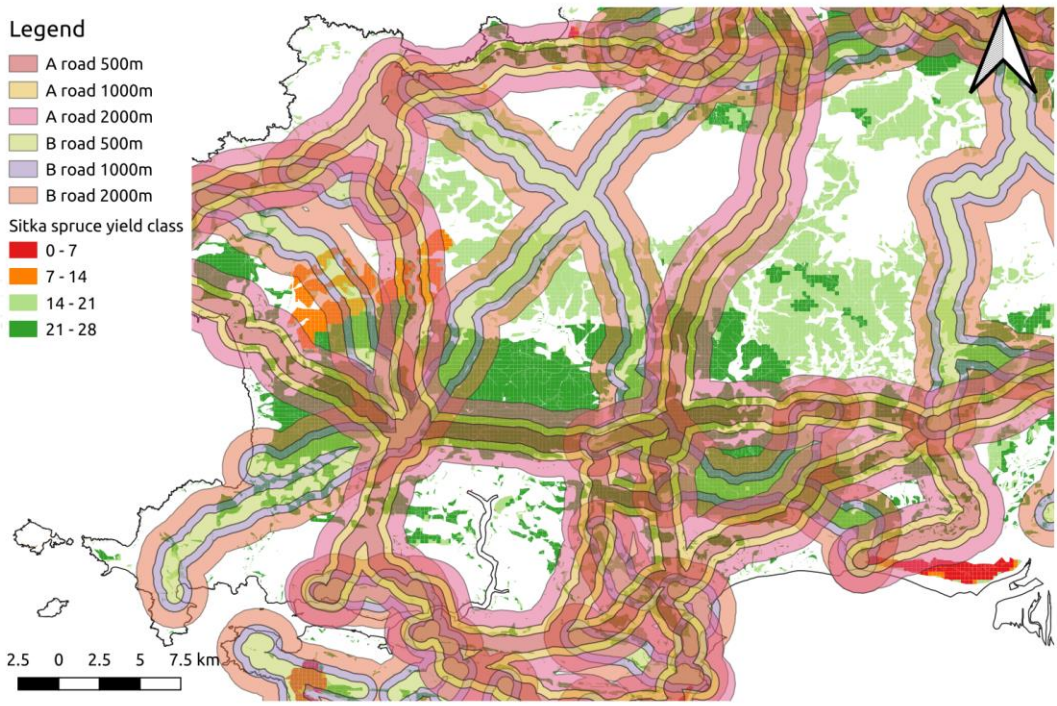

Figure 20: Proximity to road infrastructure for ALC3b grade land with Sitka spruce suitability as reference.

When comparing amongst the Area Statement regions it is clear that distance from the nearest road is the greatest constraint in Mid Wales followed by north-west Wales (fig. 21). However, a high proportion of the land more than 2 km from the nearest road is in areas considered unsuitable for woodland creation due to the constraints in the Glastir Woodland Creation Opportunities Map

(compare fig. 21 and 22). Thus, the effect of adding long distance to road as a factor limiting creation of commercial woodland only has a marginal effect of adding to the area that is unavailable beyond the existing environmental constraints, as illustrated for a 5 km-distance threshold in fig. 22.

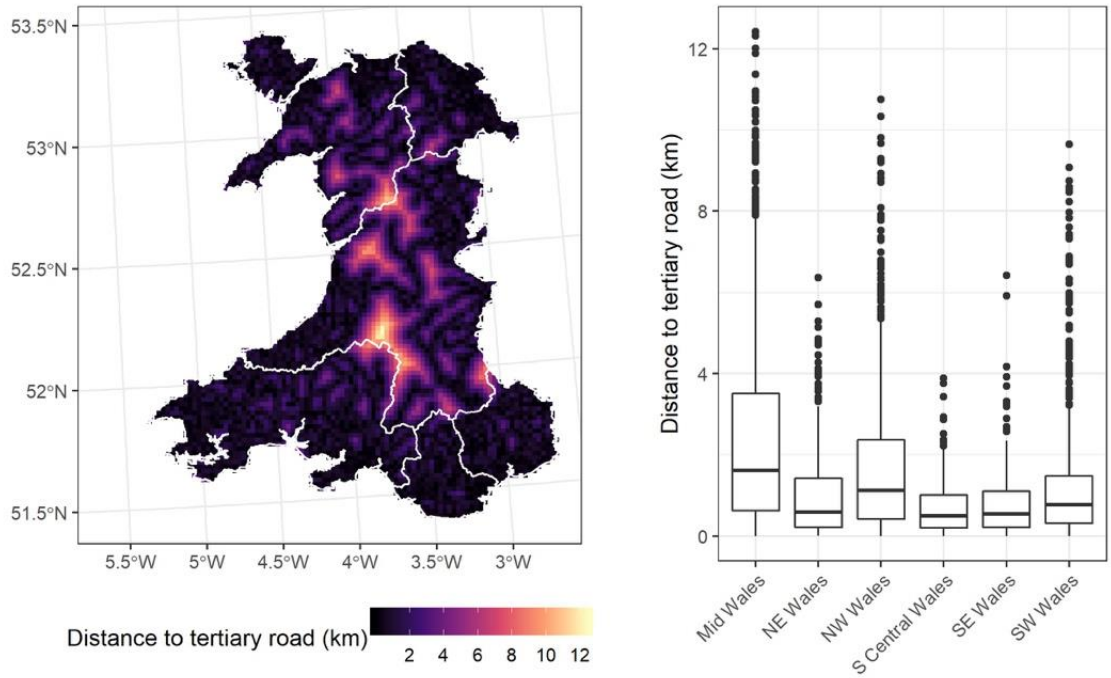

Figure 21: Distance to nearest tertiary or higher-order road from 5000 regularly-spaced points across Wales as a map (left panel) and showing the distribution of distances for each Area Statement region (right panel).

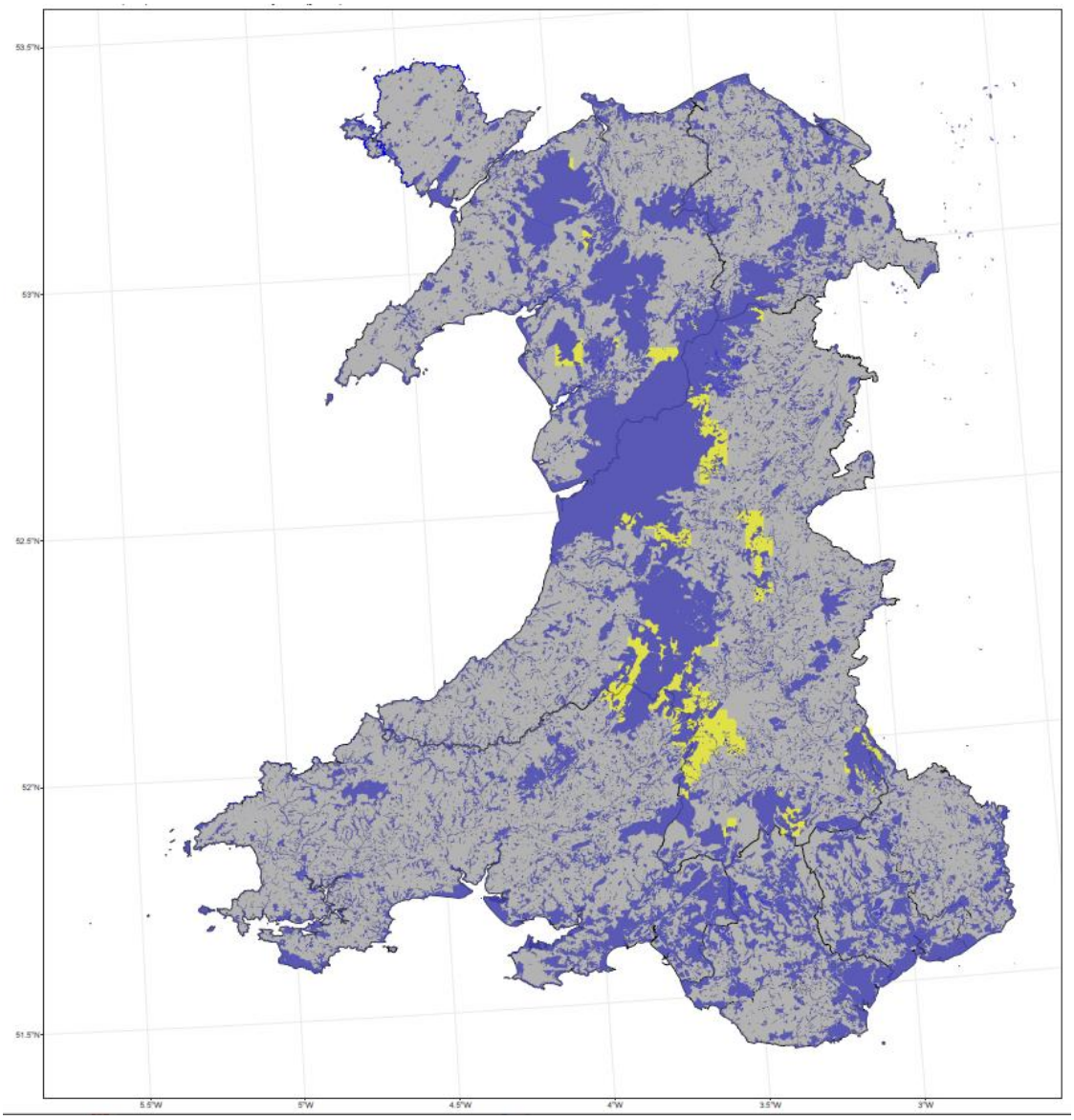

Fig. 22: Constraints layer (blue); placing a requirement of being within 5 km of a tertiary or higher-order road increases the constraints layer in remote areas (yellow).

A further factor having an incremental impact on the suitability of land for creation of commercial woodland is the access to market for harvested wood. Of course, there is considerable uncertainty about the spatial location of processing capacity at the end of a full timber rotation, several decades after woodland creation, due to the opening or closure or individual processing facilities, such as sawmills. Nonetheless, many in the commercial forestry sector consider that the long-distances to existing appropriate facilities from many area of land in Wales is a material factor disincentivizing investment in new woodland. This is illustrated in fig. 23, which highlights the low density of softwood mills and wood chipping sites in much of western central Wales, which accounts for a large proportion of the ALC 3b land suitable for softwood commercial woodland creation (compare fig. 6). It should also be noted that there are very few large-capacity softwood processing facilities in or near Wales, with those at Chirk (north-east Wales) and Newbridge-on-Wye (eastern mid-Wales) being the notable examples.

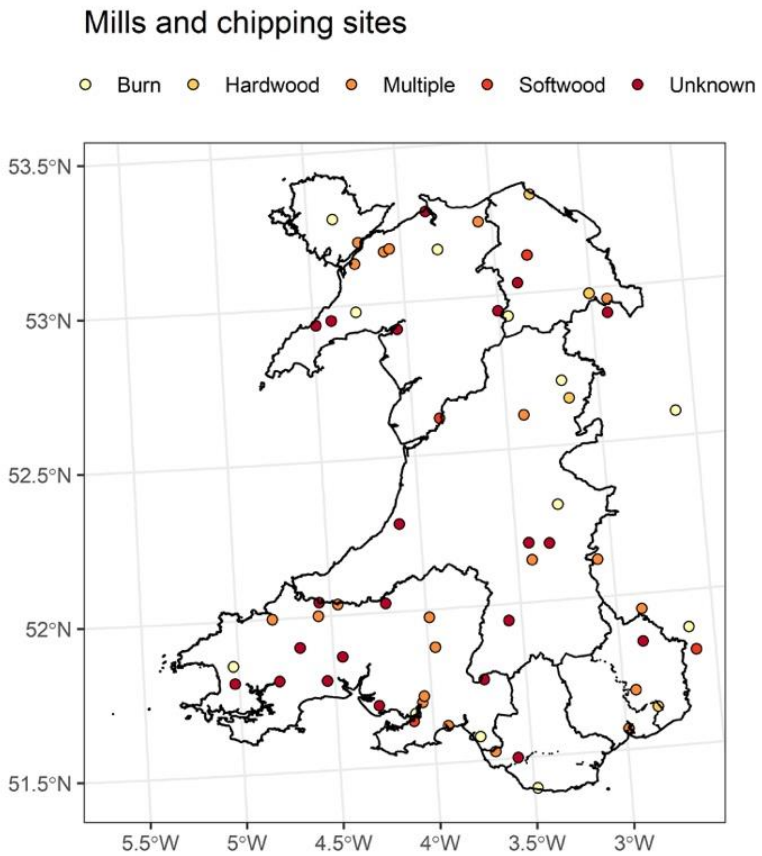

Figure 23: Locations of sawmills (with timber type indicated where known, otherwise labelled "unknown") and wood-chipping sites (labelled "burn"). The set of facilities shown is unlikely to be complete, but includes all the major facilities (as well as many small ones).

3.2 Additional considerations

3.2.1 Topography

In Wales topographic constraints of slope angles greater than the maximum threshold for safe harvesting operations do not exclude a significant area of ALC 3b land from production forestry (Table 5). This grade of land is less constrained by topography than is the case for ALC 4 grade land (Table 6) or for ALC 4 and 5 grade land (fig. 24).

Table 5: Total area of ALC grade 3b land notionally workable by typical harvester-forwarder machinery.

	Constraints mainly related to site conditions (hectares)	**Slope requires one-way working (hectares)**	**Slope too steep (hectares)**
Forwarder	533,380	17,897	0

Table 6:Topographic variables within the ALC grade 3b class in Wales.

Variable	**ALC grade 3b**		**ALC grade 4**	
	Mean	SD	Mean	SD
Elevation (m)	137	85	250	114
Slope (degrees)	5.1	3.9	8.6	5.6
Terrain roughness	-0.01	1.84	0.05	2.55

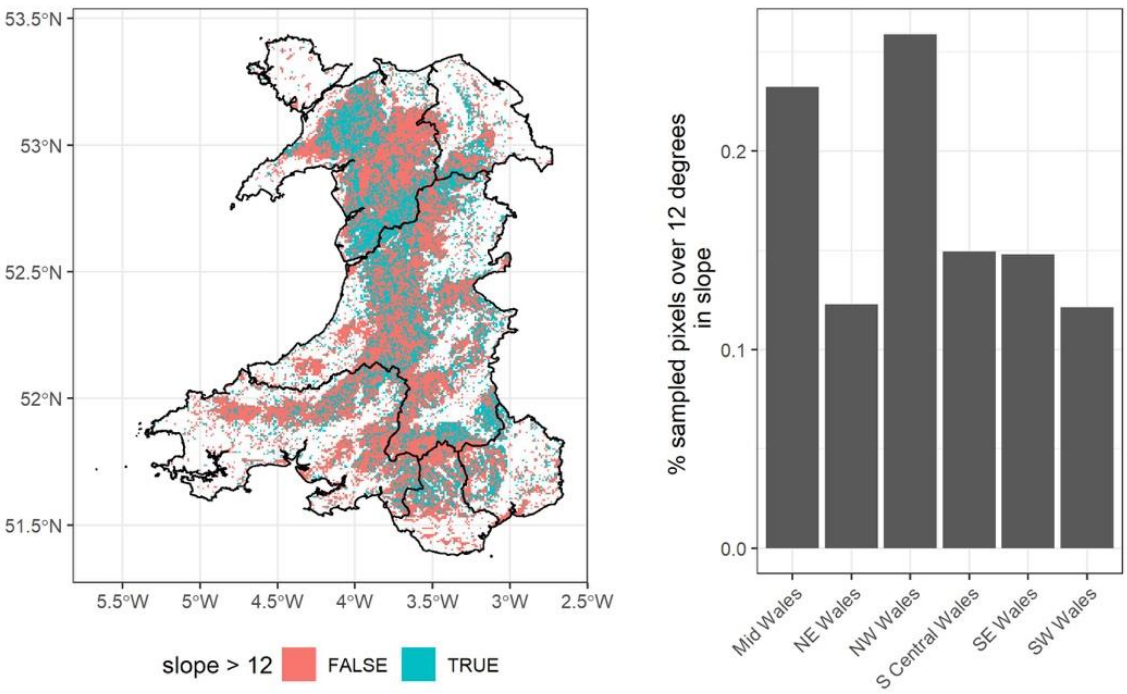

Figure 24: Topographic constraint indicated by slope angles ≥ 12° of land in ALC grades 4 and 5 for 5000 regularly-spaced points across Wales: map (left panel) and percentage of land in each Area Statement region (right panel).

3.2.2 Riparian areas

Approximately 40,139 ha (7.3%) of all ALC grade 3b land in Wales is classified as riparian under UK Forest Standard guidelines (Table 7), making this land unlikely to be suitable for the establishment of coniferous woodland.

For the landscape area used for illustration (fig. 25) the suitability of land for growth of Sitka spruce (as indicated by Yield Class) is linked to topography, being greater in lower slope locations. Thus, restrictions on tree establishment in riparian zones represents a notable trade-off between timber production/carbon sequestration and delivery of ecosystem services linked to water quality.

Table 7: Riparian and non-riparian area within ALC grade 3b land.

Land Class	Total Area (ha)	Area (ha)	
	All ALC grade 3b	Non-riparian	Riparian
ALC grade 3b	551,277	511,138	40,139

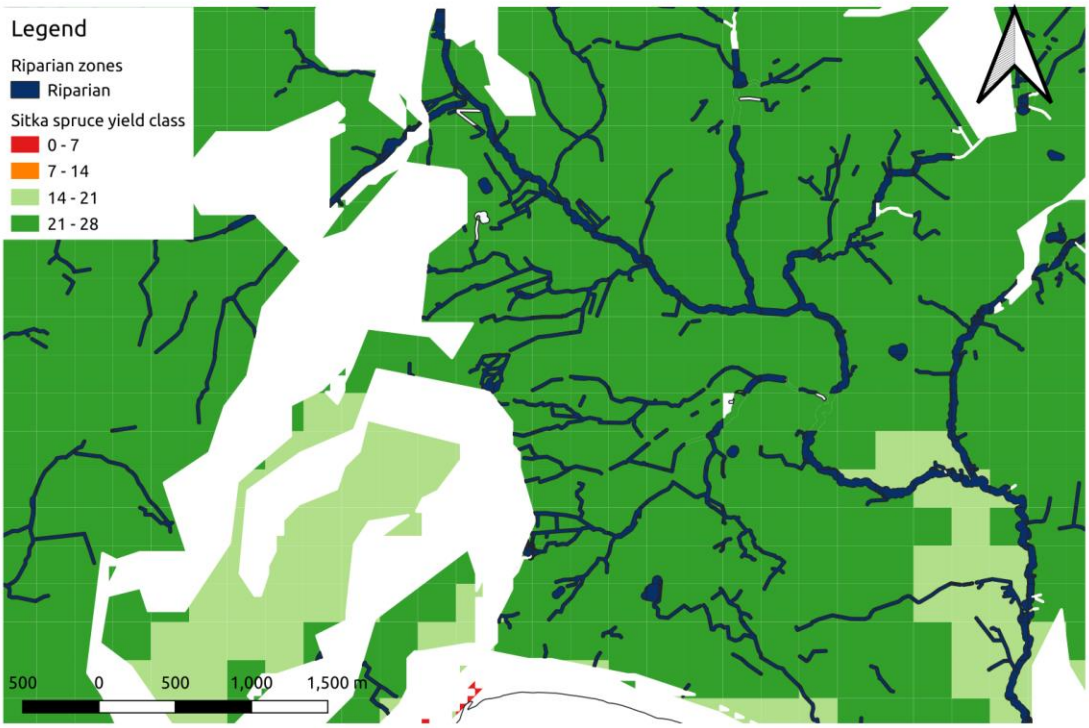

Figure 25: Riparian zones within ALC3b grade land for an exemplar landscape.

3.2.3 Proximity to existing woodland

Approximately 278,562 ha (50.5%) of ALC grade 3b land in Wales lies within 500 m of existing established woodland and more than 90% of ALC 3b grade land is within 2000 m of an existing woodland (Table 8), affording significant opportunities both for increasing woodland connectivity across Wales and for sharing infrastructure such as forest roads. Mixed and broadleaved woodlands form the majority of woodland cover within close proximity to ALC grade 3b land.

Table 8: Area of ALC grade 3b land by proximity to existing mature woodland types.

	ALC grade 3b land area (hectares) by distance to forest type			
Woodland type	0-500 m	500-1000 m	1000-2000 m	> 2000 m
Mixed and broadleaved	219,533	157,259	128,025	46,459
Coniferous	59,029	86,810	195,222	210,215

As an example, the Isle of Anglesey has few areas of existing conifer woodland, which are concentrated in its eastern half, whereas the majority of land most suited for establishment of high yielding Sitka spruce is in the north and west (fig. 26). As a consequence, there is little spatial synergy between the opportunity space for new conifer woodlands and the existing conifer woodland infrastructure. Nonetheless, the distribution of the opportunity space for new conifer woodlands is still sufficient to greatly increase the connectivity of this habitat type for the potential benefit of conservation priority species such as red squirrel.

While also concentrated in the east of the island the distribution of existing mixed/broadleaved woodlands is more widespread (fig. 27). While the opportunity space for high yielding sessile oak on Anglesey is small compared with Sitka spruce, should woodlands dominated by this species be established for conservation and amenity purposes (rather than timber production or carbon sequestration), in which case yield class is much less of a consideration, there is considerable potential to establish a highly connected broadleaved habitat network. Oak may have a considerable role to play here as native broadleaved woodland on much of Anglesey is dominated by common ash, which is rapidly succumbing to chalara ash dieback disease.

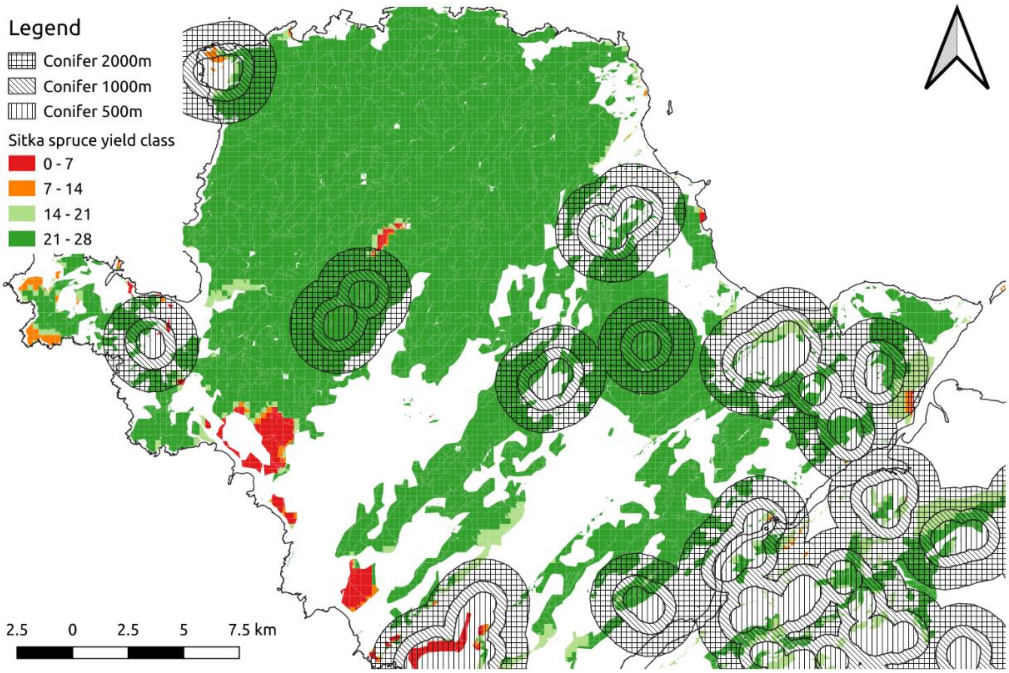

Figure 26: The proximity of existing conifer woodlands to areas of different suitability for establishment of Sitka spruce based on predicted yield class.

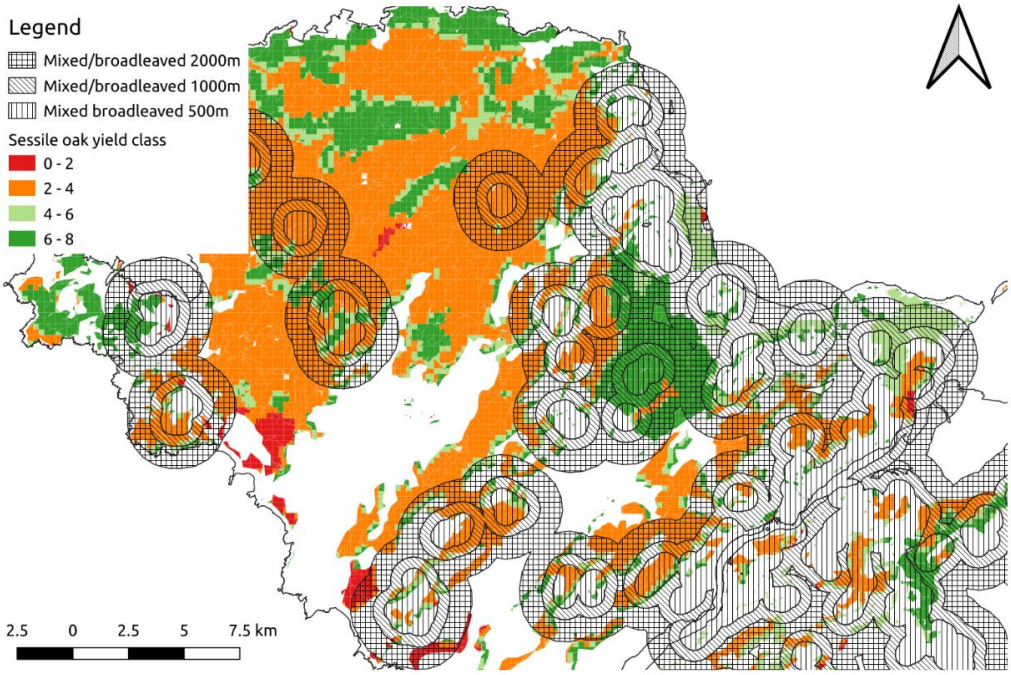

Figure 27: The proximity of existing mixed/broadleaved woodlands to areas of different suitability for establishment of sessile oak based on predicted yield class.

3.3 Opportunity for creation of large woodlands

In general, the area of land available for woodland establishment in land categorised as ALC 3b is characterised by a large number of relatively small-sized patches (< 1 ha) (fig. 28). Nonetheless, some patches > 1000 ha exist in all six Area Statement regions, with the largest patches being located in Mid Wales (both in Powys and Ceredigion), Northwest Wales (in Anglesey) and Southwest Wales (in both Pembrokeshire and Carmarthenshire).

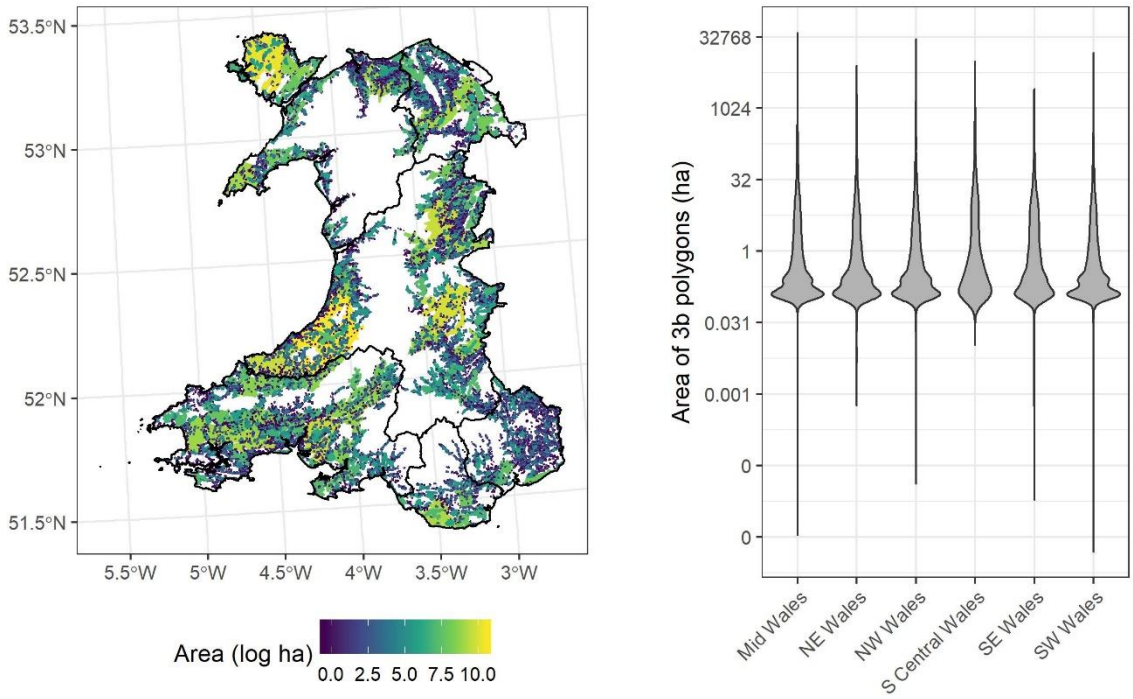

Figure 28. Distribution of sizes of patches (polygons) of ALC 3bn grade land in Wales shown as (a) a map, with Area Statement regions marked and (b) as frequency distributions of patch size for each region.

Where small ALC 3b patches (termed polygons in GIS) are isolated in a matrix of agricultural land of ALC 3a or better, the likelihood of them being converted into purely commercial woodland is comparatively small. However, they may offer good opportunity for establishment of farm woodlands as part of a strategy to diversify the incomes of continuing farm enterprises. In reality, small patches of ALC 3b land (< 1 ha) more often neighbour ALC4 land than ALC3a land (fig. 29). It is likely that these pathces adjacent to AC 4 land are less likely to remain economically viable for agricutlural production. Instead, subject to environmental constraints, they are more likely to be favoured for conversion to commercial forestry in larger patches spanning ALC 3b and 4 land. It is notable that several river valleys contain ALC 3b land on mid-slopes adjacent to upslope ALC 4 land (fig. 28, Table 6), and together these represent an opportunity for establishment of linear woodland habitat networks with potential for a additional benefits for hydrological ecosystem services as well as woodland habitat connectivity (as addressed in section 3.2.3).

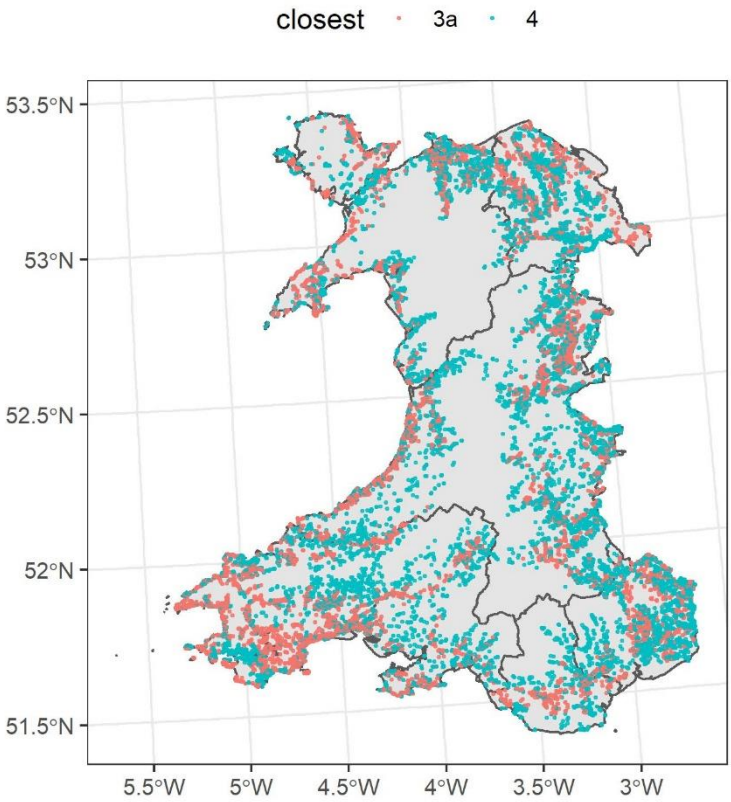

Figure 29. ALC class (3a or 4) of closest land to the centroid of each small patch of ALC 3b land in Wales.

4.0 Discussion

4.1 The suitability of ALC 3b land for creation of commercial production woodland in Wales

- There is an estimated 551,277 ha of agricultural land classified, on the basis of its productive potential, as ALC grade 3b in Wales.
- It is estimated that the productivity of Sitka spruce established on ALC grade 3b land would be approximately 4 $m^3 ha^{-1} yr^{-1}$ higher on average than in existing forests in Wales, and 2 $m^3 ha^{-1} yr^{-1}$ greater than would be anticipated on ALC grade 4 land.
- The area of ALC 3b grade land suitable for the commercial growing of Sitka spruce in Wales is estimated as 531,975 ha, which is 96.5% of the total land area in this ALC category.
- Comparable figures for other tree species included in this study were:
    - Douglas fir 263,092 ha (47.7%);
    - Scots pine 544,274 ha (98.7%);
    - pedunculate oak 522,053 ha (94.7%);
    - silver birch 524,851 ha (95.2%); and
    - beech 344,971 ha (62.6%).
- ALC 3b is, therefore, a good proxy of suitability for some tree species (e.g. Sitka spruce, Scots pine and silver birch) but less so for species susceptible to very moist soils (e.g. Douglas fir).

4.2 Opportunity to realise diversified woodland (and why that's important)

There is growing evidence of the benefits of establishing a woodland resource comprising a mixture of tree species rather than a single-species monoculture. However, most commercial foresters consider that intimate species mixtures impose significantly greater management costs than monocultures. There is a major unanswered question about what spatial scale of tree mixture (from individual trees up to a patchwork of large monoculture blocks of individual species of several square kilometres each represents the optimal compromise between low-cost efficiency of commercial operations and species mixture benefits, e.g. to increase resilience against tree diseases (Roberts et al. 2020). A priority for future research will be to calculate the distribution of sizes of the patches of ALC 3b land that are optimal (by timber volume growth or carbon sequestration) for the establishment of each individual tree species, and their spatial configuration, to assess this mosaic as a model for a commercially viable mixed tree species landscape of resilient new woodland in Wales.

4.3 Spatial options for establishment of new woodland on ALC 3b grade land in Wales

Most ALC 3b grade land is in patches of <1 ha, which is much smaller than the majority of existing commercial woodlands in Wales, thus restricting new commercial woodlands to land of this grade would significantly constrain the potential for conventional commercial investment. The fragmentation of these patches will also constrain the potential to establish de novo a woodland habitat network of high biodiversity value. Three potential scenarios can be envisaged of how this constraint will be overcome:

a) transfer of larger land units (encompassing a wider range of ALC grades (e.g. grade 3a land of higher food production value or grade 4 land, which may have higher biodiversity or amenity value, from agriculture to forestry, e.g. through the sale of whole agricultural land holdings (farms) to forestry investors. This may cause concerns of loss agricultural cultural values and

sub-optimal use of land resources amongst the objectives of food production, wood production (and carbon sequestration) and biodiversity conservation.

b) a switch of focus for timber producing forestry towards smaller forest blocks within continuing agricultural land holdings as part of a strategy towards diversification of income streams for farm holdings. Such smaller and more isolated woodland patches may also have advantages for reducing risk of tree pathogen infection (Roberts et al. 2020). They also have good potential to capitalise on and enhance existing social capital in the farming sector, through co-operative management, e.g. as promoted by Coed Cymru.

c) a greater focus of new woodland establishment on land that is adjacent/near to existing woodlands. The high potential for this is evidenced by the finding that approximately 278,562 ha (50.5%) of ALC grade 3b land in Wales lies within 500 m of existing established woodland. Use of this land has potential economic benefits because of the potential to share infrastructure, such as forest roads, and to increase connectivity of woodland habitats (of benefit to biodiversity but potential cost for biosecurity).

The evidence of the high proportion of ALC3b land that is suitable and unconstrained for commercial conifer production forestry provides the opportunity to spare large areas of existing woodland and newly established woodland to be managed primarily for biodiversity, public amenity and other benefits, e.g. through establishment and management of native broadleaved species. There is growing international evidence that this is a more efficient method of combining production and conservation objectives at a landscape scale (e.g. Phalan et al. 2011; Edwards et al. 2014), than the recently conventional land sharing approach in the UK (in which a compromise is sought trading-off these two objectives in every woodland).

5.0 Conclusions and recommendations

The viability of land for commercial investment in establishing woodlands for timber production is limited by a number of key constraints. The most important is distance to the nearest accessible road along which harvested timber can be transported by lorry. Others include slope angles greater than the maximum threshold for safe harvesting operations, however in Wales such topographic constraints do not exclude a significant area of ALC 3b land from production forestry. Road distance to the nearest sawmill with the capacity to process the harvested timber adds an incremental cost (both financial and in terms of transport carbon emissions). Other constraints are applied for reasons of environmental protection, many of which are already incorporated in the existing Glastir Woodland Creation Opportunities Map, e.g. no woodland establishment on deep peat or designated conservation sites, and others which are not, e.g. restrictions on woodland establishment in the UK Forest Standard-designated riparian zone adjacent to water courses. No land on deep peat is included in ALC grade 3b.

5.1. Recommendations for future work

5.1.1 Proximity of roads and existing forests

Distance-based metrics could be estimated using nearest neighbour approaches which would calculate precise distances between spatial objects such as a cell within the ALC grade 3b dataset and an A-class road. The reason this was not undertaken in the current study is that existing road geometries are of variable size so centroid-based values could be unreliable and the size of the dataset would require long processing times. However, the advantage of this approach is that distances would be available for every ALC grade 3b land unit, the current dataset groups land data into four categories with no differentiation within those.

The present study made the simple assumption that linear distance to a public road provides a reasonable estimate of the cost of installing infrastructure for timber extraction. In addition, it was assumed that A roads as a category are more suited for timber transport than B roads. However, the precise routing of timber extraction and transport requires further examination, for instance the impact of steep or wet ground, water-courses, weak bridges, tight corners and community approval.

5.1.2 Woodland connectivity

Future considerations, particularly in relation to the recently announced National Forest Programme for Wales, will require a more in-depth analysis of the potential for enhanced functional connectivity of woodlands, in particular the trade-offs between the benefit of habitat networks for woodland biodiversity and the costs of reduced biosecurity.

5.1.3 Optimal rotation lengths and forest management

Carbon sequestration values for no thin management are reported at 45 years and 90 years for each species to aid like- for-like comparisons between species and woodland types. The age of maximum mean annual volume increment, which can be considered the optimum felling age for maximising tree stem biomass over a series of rotations, was not reported, but could be included in a future

study to aid planning decisions. In addition, there is scope to include a variety of thinning management types.

5.1.4 Yield Class estimations

Growth rate data were reported from Ecological Site Classification based on general yield class estimates which are in turn derived from curves of total tree height growth against age. These yield class estimates are known to be subject to bias in certain situations. For example, yields are often underestimated for conifers on poorer sites, while broadleaved species might only attain the highest predicted yields when optimally managed. Yield estimates could therefore be tested against known data and models, and recalibrated where necessary. This would increase both the accuracy and precision of the analysis and improve the fit of the models within Wales.

5.1.5 Wind risk estimations

To further refine rotation length considerations, particularly for unthinned stands, ForestGALES could be used to determine the length of rotation to reduce the risk of catastrophic wind damage.

5.1.6 Future climate-adjusted growth

The growth projections could be adjusted for future climate conditions. UKCP18 data will be integrated within ESC within 12 months, and UKCP09 data is presently available for the A1b scenario.

5.1.7 Impact of prioritising timber growth versus carbon sequestration

The analyses carried out have shown intriguing complexity in the modelled results of the impact of optimising on the basis of timber growth versus carbon sequestration on the spatial distribution of ALC3b land on which each species is the best suited. The variation in these patterns between different landscapes demonstrates a complex interaction between site-specific variation in the relative growth rate of each species and their wood densities. The importance of timber production for carbon storage through the value chain provides a further vital component. Generating robust evidence to inform this crucial area of woodland policy in Wales will require further research combining tree-growth modelling and life cycle assessment.

6.0 References

Conrad, V. (1946) Usual formulas of continentality and their limits of validity. Transactions of the American Geophysical Union 27, 663-664.

Cosby, B.J., Thomas, A., Emmett, B.A., et al. (2019) ERAMMP Report 12: QuickStart-1. Report to Welsh Government (Contract C210/2016/2017)(CEH NEC06297)

Edwards, D.P., Gilroy, J.J., Woodcock, P., Edwards, F.A., Larsen, T.H., Andrews, D.J.R., Derhé, M.A., Docherty, T.D.S., Hsu, W.W., Mitchell, S.L., Ota, T., Williams, L.J., Laurance, W.F., Hamer, K.C. and Wilcove, D.S. (2014), Land-sharing versus land-sparing logging: reconciling timber extraction with biodiversity conservation. Glob Change Biology 20, 183-191. doi:10.1111/gcb.12353

Forestry Commission (2014). Managing forests in acid sensitive water catchments. Forestry Commission Practice Guide.

Forster, E.J., Healey, J.R., Dymond, C. & Styles, D. (2020). Commercial forestry delivers effective mitigation under multiple decarbonisation pathways (submitted)

Hallett, S.H., Sakrabani, R., Keay, C.A. and Hannam, J.A. (2017), Developments in land information systems: examples demonstrating land resource management capabilities and options. Soil Use Manage, 33: 514-529. doi:10.1111/sum.12380

Jenkins, T.A.R., Mackie, E.D., Matthews, R.W., Miller, G., Randle, T.J. and White, M.J. (2018) FC Woodland Carbon Code: Carbon Assessment Protocol (v2.0) [Online] available at https://www.woodlandcarboncode.org.uk/images/PDFs/WCC_CarbonAssessmentProtocol_V2.0_March2018.pdf accessed 17 February 2020.

Kennedy, F. (2002). The identification of soils for forest management. Forestry Commission Field Guide, 56pp.

LLE (2020) ALC for Wales.

Matthews, R.W., Jenkins, T.A.R., Mackie, E.D. & Dick, E.C. (2016). Forest Yield: A handbook on forest growth and yield tables for British forestry. Forestry Commission.

MAFF (1988) Agricultural Land Classification of England and Wales. Revised guidelines and criteria for grading the quality of agricultural land. Ministry of Agriculture, Fisheries and Food, October 1988. 60pp.

Murgatroyd, I. (2006) Forestry Commission Internal Report.

Nisbet, T.R. & Evans, C.D. (2014). Forestry and surface water acidification. Research Note. Forestry Commission.

Ordnance Survey (2020) Open Rivers.

Ordnance Survey (2020) Zoomstack.

Phalan, B., Onial, M., Balmford, A., Green, R.E. (2011) Reconciling food production and biodiversity conservation: Land sharing and land sparing compared. Science 333, 1289-1291.

Pyatt, D. G. (1982). Soil classification. Forestry Commission Research Information Note 68/82/SSN. Forestry Commission, Edinburgh.

Pyatt, G., Fletcher, J. and Ray, D. (2001) An ecological site classification for forestry in Great Britain, Bulletin 124, Forestry Commission, Edinburgh. https://www.forestresearch.gov.uk/documents/6593/FCBU124.pdf

Quine, C.P. and White, IMS (1993) Revised windiness scores for the Windthrow Hazard Classification: the revised scoring method. Forestry Commission Research Information Note 230. Forest Research, Alice Holt. 6pp.

Ray, D., Bathgate, S., Moseley, D., Taylor, P., Nicoll, B., Pizzirani, S. and Gardiner, B.(2014). Comparing the provision of ecosystem services in plantation forests under alternative climate change adaptation management options in Wales. Regional Environmental Change. 15.

Roberts, M., Gilligan, C.A., Kleczkowski, A., Hanley N., Whalley, A.E. & Healey, J.R. (2020). The effect of forest management options on forest resilience to pathogens. Frontiers in Forests and Global Change 3:7. doi: 10.3389/ffgc.2020.00007.

Stonevicius, E., Stankunavicius, G. and Rimkus, E. (2018) Continentality and Oceanity in the Mid and High Latitudes of the Northern Hemisphere and Their Links to Atmospheric Circulation. Advances in Meteorology, Volume 2018, Article ID 5746191, 12 pages https://doi.org/10.1155/2018/5746191

7.0 Appendices

7.1 Area of ALC 3b land in Wales by soil moisture and soil nutrient regimes.

Table 3: Area of ALC 3b land in Wales by soil moisture and soil nutrient regimes.

Soil variable	ESC class	Area of ALC 3b grade land (hectares)	Comments
Soil moisture regime	Very moist - wet	237,662	Drainage recommended, rooting limited by water table – *e.g.* clays, peaty gleys
	Fresh - moist	290,074	Optimal for most species
	Slightly dry and drier	23,541	Drier soils with sandy texture and/or shallow rooting
Soil nutrient regime	Very poor	22,129	N required at establishment except for pine/birch* P likely K on peaty soils
	Poor	83,660	N possibly required except or pine/ birch* P possibly required
	Medium or richer	445,487	Fertiliser inputs only likely on N deficient geologies

* Note that N requirements can be met by intimate mixture of 50% target species and 50% pine/birch/alder.

7.2 Tree species used in study

Table 10: Tree species analysed in this study including their abbreviation, maximum Yield Class achieved and minimum Yield Class considered suitable for commercial production.

Common name	Scientific name	Abbreviation	Maximum Yield Class $m^3ha^{-1}y^{-1}$	Minimum YC for timber production $m^3ha^{-1}y^{-1}$
Sitka spruce	*Picea sitchensis*	SS	28	14
Norway spruce	*Picea abies*	NS	24	12
Douglas fir	*Pseudotsuga menziesii*	DF	26	13
Western hemlock	*Tsuga heterophylla*	WH	24	12
Western red cedar	*Thuja plicata*	RC	24	12
Scots pine	*Pinus sylvestris*	SP	14	7
Macedonian pine	*Pinus peuce*	MCP	14	7
Grand fir	*Abies grandis*	GF	30	15
Beech	*Fagus sylvatica*	BE	10	5
Silver birch	*Betula pendula*	SBI	10	5
Downy birch	*Betula pubscenens*	PBI	8	4
Sycamore	*Acer pseudoplatanus*	SY	12	6
Sessile oak	*Quercus petraea*	SOK	8	4
Pedunculate oak	*Quercus robur*	POK	8	4
Common alder	*Alnus glutinosa*	CAR	12	6

The definition of suitability for timber production in the Ecological Site Classification software is that a species can achieve a minimum of 50% its predicted maximum yield class under British growing conditions. Below this threshold outcomes can become unsatisfactory, for example though slower growth and higher mortality, particularly for sensitive species with, for example, limited tolerance of waterlogged soils. For those reasons it is common practice to set the threshold yield class higher for sensitive species such as Douglas fir (where the suitability threshold would be raised from YC13 to, e.g., YC18) and lower for more accommodating species such as Sitka spruce (where the suitability threshold would be reduced from YC14 to, e.g., YC12). When considering the use of improved planting stock, the higher costs associated with this material would usually dictate tree establishment on a more productive site (i.e. at the upper end of suitability for that tree species), where significant gains in stem volume growth can be realised.

7.3 Carbon sequestration values

Carbon sequestration values were calculated for stands at ages 45 and 90. Those ages reflect typical rotation lengths of fast-growing coniferous species and broadleaved species respectively. However, values were calculated for both to provide an ability to compare options between species and management regimes (for example long term retention of conifer stands). For the purposes of this study management was assumed to be no thinning in all cases. A limitation of the models for alder and birch is that competition-related mortality is accounted for but senescence, which is a factor with those relatively short-lived species, is not. ESC generates outputs yield class estimates as a continuous variable so show changes more smoothly across a landscape. Carbon sequestration estimates for woodland established on ALC 3b land were obtained, for trees at ages 45 and 90, using the linear models for CO_2 sequestration and yield class contained in the Forestry Commission's woodland carbon code (Jenkins et al., 2018).

$$CO_2 \text{ sequestration} = a \times YC + b$$

Where species-specific data were unavailable, e.g. for Macedonian pine, species were mapped according to WCC rules. Minimum YC thresholds were set to represent the cut-off points where there was a high probability of establishment failure alongside slow growth. In most forestry situations where timber production is an objective, ESC is set to categorise species achieving less than 30% of their theoretical maximum YC as unsuitable, and between 30 and 50% as marginal.

Table 11: Parameters for the linear models for CO_2 sequestration taken from the Forestry Commission's Woodland Carbon Code (Jenkins et al., 2018) for trees at ages 45 and 90 years.

				Age 45			Age 90		
Species	**WCC Table**	**WCC Spacing (m)**	**Minimum YC**	**a**	**b**	**R^2 RMSE**	**a**	**b**	**R^2 RMSE**
Sitka spruce	SS	2.0	6	20.4697	-49.3455	0.99 2.3	34.4303	74.9455	0.99 7.6
Norway spruce	NS	1.5	6	15.3208	-21.6583	0.99 1.8	30.0417	53.6389	0.99 2.1
Douglas fir	DF	1.7	6	20.6042	33.1111	0.99 7.6	34.2250	153.6222	0.99 6.8
Scots pine	SP	2.0	4	23.800	-71.700	0.99 2.5	42.1571	22.0857	0.99 7.5
Macedonian pine	CP	1.4	4	18.1875	8.3750	0.99 7.4	30.2738	100.9405	0.99 6.0
Grand fir	GF	1.8	6	14.5576	31.4909	0.99 3.6	26.4727	134.0727	0.99 2.1
Western hemlock	WH	1.5	6	21.7411	-69.0536	0.99 3.2	31.2143	131.5714	0.99 4.7
Western red cedar	RC	1.5	6	17.94643	-41.5357	0.99 0.7	30.946	82.679	0.99 2.3
Beech	BE	1.2	2	31.800	-12.350	0.99 11.2	54.300	122.400	0.99 54.3
Common alder	SAB	1.5	2	35.4500	47.0000	0.99 6.1	53.450	144.400	0.99 9.1
Sessile oak	OK	1.2	2	46.000	-43.833	0.98 17.6	57.500	134.667	0.99 4.1
Pedunculate oak	OK	1.2	2	46.000	43.833	0.98 17.6	57.500	134.667	0.99 4.1
Silver birch	SAB	1.5	2	35.4500	47.0000	0.99 6.1	53.450	144.400	0.99 9.1
Downy birch	SAB	1.5	2	35.4500	47.0000	0.99 6.1	53.450	144.400	0.99 9.1
Sycamore	SAB	1.5	2	35.4500	47.0000	0.99 6.1	53.450	144.400	0.99 9.1

7.4 Instruction sheet for Plant Trees App

7.4.1. Introduction

Information about the purpose, design and utilisation of the App is provided at https://rstudio.bangor.ac.uk/content/3

7.4.2 Map tab

The map tab initially displays an OpenStreetMap near Bangor. It can be navigated like a regular Google Maps interface to find areas of interest.

The map further shows, in grey, a layer of large estates. The owner appears when an estate polygon is hovered upon. This layer can be deselected in the tick box list to the right, where ALC classes 3b and 4 can be activated.

Symbols with trees represent known sawmills; they are divided by wood sawn into Unknown (?), Hardwood-only (broadleaf tree symbol), Softwood-only (conifer symbol) and Mixed (both). Upon clicking, the name of the mill is shown with a hyperlink to the website. A factory symbol is displayed for biomass processors (plants with chipping capacity/chipping sites).

To select an area to analyse, click the square button and draw a rectangle of your choice. **Currently, the edit button is not working (below the square button).** To draw a new rectangle, click the button again. You can delete rectangles using the bin button; however this will have no practical implication to the analysis.

When you are satisfied with your area, click the Crop button. This activates the Area explorer.

The Area explorer zooms into the area selected and shows additional information (large estates are no longer shown at this zoom level). These consist of

1. Conservation areas ("cons"): Many conservation areas are overlapping, and they are therefore displayed one at a time. When you activate the layer by ticking the 'cons' square, the drop-down menu defaults to showing the first designation in the alphabet. You can select others from the drop-down menu. The names of individual sites are displayed upon hovering on polygons.
    a. The following designations are presumed to prevent planting: Sites of Special Scientific Interest (SSSI), Biosphere reserves, Local Nature Reserves (LNR), National Nature Reserves (NNR), RAMSAR sites, Special Areas of Conservation (SAC), Special Protection Areas (SPA). Their combined area is used to calculate the total area assumed excluded from planting in the selected area.
    b. Acid-sensitive areas, nitrate-vulnerable zones, areas of outstanding natural beauty, national parks are presumed to perhaps pose restrictions (e.g. no conifers in acid-sensitive areas) but not to exclude planting. Decisions of proposing planting in such areas are left to the user.
2. Woodland classes: Existing woodland, including recently felled woodland, as per the Phase I Habitats survey, is displayed in the selection to indicate what type of land use exists in the area (for example, existing conifer plantations would indicate that the land is suitable for economic venture; areas of broadleaf could be linked with future broadleaf to create a

contiguous wildlife habitat for the allocated broadleaf quota in UKFS). All existing woodland, excluding recently felled, is combined to calculate the total area excluded from planting in the selected area.

3. Slope ("slope"): Slope is based on the DEM 5m data set from Ordnance Survey. It has been cropped to ALC classes 4, 5, and non-agricultural. This is because all classes of equal or higher quality than 3b are by default less than 11 degrees in slope. Slope varies widely within the classes retained, and so the user is allowed to explore the effect of slope exclusions on the total plantable area. The default value is 90, which therefore shows all areas as plantable. Once the user changes this value (and confirms by clicking 'Calculate'), the map creates a slope layer, which shows polygons encompassing the slopes above the threshold – the layer is not automatically selected so make sure to tick the box to see the calculated area. The total area excluded from planting updates to the selected slope.
4. Tree species information: Forest Research have produced an ALC 3b layer which gives information on yield class and carbon capture for specific tree species (see Methods section). Upon hovering on a polygon showing best trees, a label pops up which shows the coded list of tree species that were best. The table linking codes to a species is at the bottom of this user guide.
    a. Best-yielding tree species ("trees"): The app selects the species with the highest yield class scores in the selected area. The yield classes are sometimes tied for some tiles. The app creates a polygon layer of the best-scoring species tiles where each polygon is the merger of all identically ID'd tiles (e.g. for single-species polygons it's all tiles of that one species, for combined-species polygons it's all tiles with that specific combination of species). The ties are why the user can select which species to display on the map. Text in the left panel describes the distribution of yield class for the selected species.
    b. Best tree species for carbon capture ("treesC45"): The app selects the species with the highest cumulative carbon capture score at 45 years after establishment. Same principles as above, but no text summary of carbon capture values given.
    c. Yield classes of tree species, user's choice ("treesmine"): All species in a dropdown menu. Upon selection, the distribution of yield class values across the area selected is shown. This allows exploration of broadleaf species that do not generally get selected into the 'best' list.

The total area excluded from planting, in addition to existing woodland, restrictive conservation areas, and user-defined slope, also includes urban areas (using the ALC urban layer) and lakes. It does not include individual houses, roads, or rivers and the effect of these on the total area left over for planting is left for the user to eyeball.

The nearest sawmill is identified based on the driving time. The starting point for the calculation is the nearest point on a tertiary or above to the centre of the selected area. **It would be good to allow the user to select what type of sawmill they are after before calculating this, however, due to this data set being incomplete anyway (for example we do not know their capacity, or what type of logs, they take), we are currently restricting this function to a simple prototype.**

7.4.3 Data summaries tab

The total area available for planting applies to all ALC classes.

The first plot summarises existing woodland cover across the ALC classes, with the size of each panel representing the proportion of the total area occupied. If there is no woodland, nothing is shown.

The second plot summarises wooded and unwooded areas across ALC classes, thereby also identifying which ALC classes are, in theory, available for planting. **Further developments of the app could be set to summarise this information for the areas identified as available for planting in the Map tab. i.e., the non-wooded panels will exclude conservation areas and slopes too high as per user selections.**

The table at the bottom shows the exact area of the panels of the second plot so that users know exactly how many hectares are concerned. **Areas are currently calculated assuming flat surface.**

7.4.4 Data attributions tab

Data attributions are currently incomplete, and we therefore stress that the app is currently **strictly confidential.**

7.4.5 Abbreviations

Tree code list: (In the app, 'yc' denotes yield class)

DF = Douglas fir

MCP = Macedonian pine (to provide option on poor wet sites)

NS = Norway spruce

RC = Western red cedar

SBI = Silver birch

SOK = Sessile oak

SP = Scots pine

SS = Sitka spruce

SY = Sycamore

WH = Western hemlock

CAR = Common alder

GF = Grand fir

PBI = Downy birch

POK = Pedunculate oak

BE = Beech