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Carbon and economic performance of coffee agroforestry systems in Costa Rica and Nicaragua

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Award date:
2012

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Carbon and economic performance of coffee agroforestry systems in Costa Rica and Nicaragua

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A dissertation submitted in fulfillment of the degree of Doctor of Philosophy
Bangor University & CATIE Graduate School

August 2012

Abstract

Coffee agroforestry systems (CAFS) sustain the livelihoods of many people globally at the same time as providing important ecosystem services such as carbon sequestration that help mitigate climate change. These systems vary in their composition (especially density and species of shade tree) and management. Changes made to enhance their productivity will affect their climate change mitigation potential. With growing food demand and diminishing availability of agricultural land due to global population growth, as well as an increasing threat from global climate change the trade-offs between the socio-economic and net carbon sequestration performance in CAFS are important.

The carbon sequestration and socio-economic performance of a range of CAFS varying in composition and management were assessed in Costa Rica and Nicaragua. Measurements and modelled estimates were made of (i) greenhouse gas emissions (GHGs) from coffee cultivation (the carbon footprint (CF)), (ii) carbon sequestration potential into above-ground biomass and soil organic stocks and (iii) socio-economic performance (productivity and profitability), and their trade-offs analysed.

The effects of agronomic management (conventional versus organic) and shade type (ranging from timber trees to full sun) on the CF of two long-standing CAFS experiments in Costa Rica Nicaragua demonstrated that management is the best predictor of the CF whereas shade type has a minor effect. The greatest contributor to the overall CF was N₂O emissions from the input of N in applied organic and inorganic fertilisers. Shade systems with high levels of N input from leguminous tree pruning had the highest CF. Total soil organic carbon (SOC) decreased over the first nine years of coffee bush and shade tree establishment in these experiments, although this differed amongst soil layers. Organically managed systems tended to have an increase in SOC in the top 10 cm of soil, though organic and conventional systems had similar (larger) decreases in SOC in deeper soil. Shade type and above-ground biomass had a smaller effect on SOC.

Comparison of the CF of these experimental CAFS treatments with their C sequestration potential showed that increases in GHG emissions from production intensification can be compensated for or even outweighed by the increase in C sequestration into above-ground biomass, especially for shaded systems. However, if less productive, lower intensity CAFS are extended onto an area of currently forested land in order to compensate for the shortfall in profitability (compared with higher-intensity, higher-yielding systems), this land-use change causes additional GHG emissions from deforestation. This results in net GHG emissions for the whole system for the majority of shade types tested.

Evaluation of the C and socio-economic performance of coffee farms in the regions around the two experimental sites showed that due to the huge variation amongst CAFS there is no single strategy for climate change mitigation that could successfully be applied across the range of farms. Instead it will be necessary to carry out accurate and site-specific farm assessments to inform advice and decisions on system improvement tailored to the needs of individual farms and environmental settings.

The findings of this research suggest that there is a place in the C market for CAFS, however their design and management will determine the overall net benefits that can be achieved.

Acknowledgements

It's been one heck of a journey to get to this point, one that I would never have dreamt of when I set out to take on this challenge. There are an enormous number of people without whom I would have struggled to make this a successful and (most of the time!) exciting experience.

I am most grateful to my supervisors, John Healey, Jeremy Haggar, Gabriela Soto and of course the late Gareth Edwards-Jones who each, in their individual ways, continually supported me with their knowledge, enthusiasm, encouragement and not least with their valuable time. I cannot thank you enough for that.

I'd also like to thank everyone else at Bangor University who helped me in one way or another throughout my Ph.D. Particular thanks go to Davey Jones who kindly let me use his soil labs and made sure that my sampling design and methodology were up to the job; Paul, Freya and Neil for inspiring discussions over many cups of tea; and my 'adopted family' of Ana and Maria who were fantastic officemates.

In Costa Rica and Nicaragua a huge thanks goes to all the people who helped me with field work – I know it was very tough at times but I couldn't have done it without you; Elvin and Ledis Navarette who made the Nicaraguan farm studies and experiment sampling absolute bliss and are a joy to work with; Romain, Esthefanie, Luis and all the others who leant me a helping hand during my months in Costa Rica; Carlos and Jimena for being true friends.

To all the other great and wonderful friends I made during my time in Wales, Costa Rica, Nicaragua and last in York – thank you for making sure that I did not forget there was life beyond my studies. It's been a privilege to have had you around and I am very grateful for that. In particular I would like to thank Dilwyn and Mari Evans who let me use their workshop where I was often able to hide away for a few hours and draw new inspiration through my love for furniture making.

I would like to thank my sponsors CAFNET, Coalbourn Trust, ESRC and NERC who made this study possible and provided me with the necessary financial support.

And last but not least I am most indebted to my parents and most of all my wonderful wife-to-be Nicola and our little son Sami, without whom this journey would never have been possible. Many, many thanks for all your patience, love and support – you have and always will be a true inspiration to me.

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Abbreviations and acronyms

A/R	Afforestation and reforestation
AFS	Agroforestry system
AGC	Above-ground carbon
AIC	Akaike Information Criterion
BA	Basal area
BGC	Below-ground carbon
BSI	British Standards Institute
C	Carbon
CAFCA	Coffee agroforestry carbon calculator / Carbon agroforestry calculator
CAFS	Coffee agroforestry systems
CATIE	Centro Agronómico Tropical de Investigación y Enseñanza
CBA	Cost Benefit Analysis
CCBS	Climate, Community and Biodiversity standard
CDM	Clean Development Mechanism
CER	Certified Emission Reduction
CF	Carbon footprint
CH ₄	Methane
CO ₂	Carbon dioxide
CO ₂ e	Carbon dioxide equivalents
DBH	Diameter at breast height
DEFRA	Department for Environment, Food and Rural Affairs
EF	Emission factor
EU ETS	European Union Emissions Trading Scheme
FAO	Food and Agriculture Organisation of the United Nations
GHG	Greenhouse gas
Gt	Gigatonnes
GWP	Global warming potential
Ha	Hectare
ICO	International Coffee Organisation
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
JI	Joint Implementation

LCA	Life cycle assessment
LUC	Land Use Change
LULUCF	Land Use, Land Use Change and Forestry
MARENA	Nicaraguan Ministry of Environment and Natural Resources
MDGs	Millennium Development Goals
Mg	Megagram
MINAET	Costa Rican Ministry of Environment, Energy and Telecommunications
Mt	Million tonnes
N	Nitrogen
N ₂ O	Nitrous oxide
NB	Net benefit
NO	Nitric oxides
NPV	Net present value
NTFP	Non-timber forest product
PAS 2050	Publically Available Specification 2050
PCF	Product carbon footprint
PES	Payments for Ecosystem Services
REAL	Reducing emissions through avoided land use change
REDD	Reduced emissions from deforestation and forest degradation
RFA	Renewable Fuels Agency
SOC	Soil organic carbon
SOM	Soil organic matter
TC	Total carbon stocks
TD	Tree density
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
USDA	U.S. Department of Agriculture
VCM	Voluntary carbon market
VCS	Verified Carbon Standard
VER	Voluntary Emission Reduction
WRI	World Resources Institute

Chapter 1

Introduction

1.1. Background

The last decade has seen a dramatic shift in the focus of national and international policy towards climate change and environmental protection. Nevertheless, other development concerns such as poverty alleviation and global food security continue to exist. The challenge therefore stands for the international community to make sure that efforts directed towards protection of the natural environment work in partnership with socio-economic commitments such as the Millennium Development Goals (MDGs).

It is now widely agreed that climate change will have a profound negative impact on the rural poor in developing countries (IPCC, 2007a). The increase in extreme weather events and in some places shorter growing seasons coupled with a rapidly growing population signal an urgent need for solutions to satisfy the resulting food demand. It is thus estimated that food production will have to double within the next 35 years to meet further needs, including those of around 800 million currently malnourished people (Watson, 2001). At the same time deforestation through the conversion of land to agriculture due to its lesser economical value (Murdiyarso et al., 2010) continues to be a main driver of global emissions from LUC. As such, this intricate link between deforestation and food production and by extension agricultural intensification has long been a hard fought battle between conservationists and agriculturalists. This calls for combined climate change mitigation and adaptation strategies, which will allow individuals to prepare on a personal level for circumstances that will undoubtedly be experienced (IPCC, 2001).

On top of this already stressed global system, negative effects of a changing climate and increasing natural disasters, agriculture is believed to be one of the most vulnerable of human enterprises (Verchot et al., 2007). More and more efforts are being made for international climate agreements to halt the increase of atmospheric greenhouse gas concentrations and with it its global warming effect. Current efforts to do so, however, are unlikely to fulfil even the most modest greenhouse gas (GHG) reduction plans (Romero, 2005).

This research aims to contribute to and further develop the knowledge base for agroforestry systems (AFS), in particular shaded coffee agro-ecosystems, as a tool to mitigate and adapt to climate change impacts, both in biophysical and financial terms. It analyses what the wider

implications would be on local farmer livelihoods if they participated in carbon sequestration projects. In analysing carbon (C) storage, an emphasis is given in particular to C stored in the soil (soil organic carbon, SOC); a review by Harmand et al. (2007) on 21 studies in Central America revealed that 80% of C stored in the investigated agroforestry systems was located below-ground. At least 50% of above-ground C (AGC) was found to originate from the shade trees incorporated in the systems (Harmand et al., 2007b). As yet, however, little attention has been given to this substantial C pool in offset projects, providing renewed justification for such projects and a potential new income stream for farmers.

Here I intend to identify the main variables that affect changes in the C pools through analysing the effects of differing types of shade and management inputs (e.g. fertiliser, tree & coffee crop residues and pruned material etc.) on the overall carbon storage (AGC, below-ground C (BGC) and SOC) within coffee agroforestry systems (CAFS). From this, I go on to assess the problems and shortcomings of current methodologies in accounting for the various C pools, in particular that of SOC. The need to simplify and unify methodologies on assessing net carbon values for entire systems is of high importance. However, scientific rigour in assessing C stocks within CAFS must not be compromised if genuine climate change mitigation claims are to be made and validated. At the same time, in order to make financing through carbon markets more accessible and appropriate to local farmers, a holistic understanding of their livelihoods has to be developed. An accurate picture of natural resource consumption based on products drawn from CAFS will allow the development of a more detailed approach for coupling climate change mitigation and adaptation with sustainable development efforts.

1.2. Aims and objectives

In this thesis I aim to increase knowledge of the climate change mitigation potential of coffee agroforestry systems with particular reference to farming systems in Costa Rica and Nicaragua by assessing the effects of shade type and management on their C and economic performance. For this, I use two long-standing experiments in Costa Rica and Nicaragua as well as 50 farms across both countries as case studies. Through the quantification of above-ground, below-ground and soil carbon stocks and their development over time I assess the potential of CAFS to actively sequester additional C from the atmosphere. By adding a cost-benefit analysis I am able to evaluate the suitability of various shade types and management types in fulfilling the double imperative of sustaining local livelihoods and at the same time reducing greenhouse gas emissions from agricultural production. As such, my specific objectives in this thesis are:

- i. To quantify net C storage in soil and above-ground in two CAFS experiments and in a stratified sample of farms in Costa Rica and Nicaragua
- ii. To quantify and qualify litter input to the system
- iii. To quantify GHG emissions associated with the cultivation of coffee and identify emission hotspots within the farming boundaries
- iv. To identify which agroforestry system variables have greatest impact on net C fluxes in both experimental and on-farm systems
- v. To evaluate economic trade-offs between coffee productivity and payments for stored C
- vi. From Objectives iii, iv and v, to find the best combinations of socioeconomic and environmental solutions for farm-level C storage, crop productivity and GHG emissions taking into account alternative land-use scenarios such as ‘intensification’¹ and ‘extensification’
- vii. To evaluate the feasibility of including soil C into C trading markets focusing on established schemes such as the Clean Development Mechanism (CDM) under the Kyoto Protocol and the voluntary carbon market (VCM).

1.3. Thesis structure

The thesis structure is as follows:

Chapter 2 uses literature review to ‘set the scene’ on the wide range of topics forming the core of this thesis. This will first give an overview of the international C market and its role in emission reductions. It will then review the role of agroforestry within climate change mitigation, with a special focus on adaptation strategies. Last it will review and highlight biophysical aspects of CAFS that are of relevance to this research.

Chapter 3 assesses the GHG emissions associated with the experimental CAFS by calculation of carbon footprints (CF), highlights the differences in emission hotspots between different forms of management and evaluates the difference between conventional and organic systems in terms of their trade-offs of GHG emissions with coffee yield.

Chapter 4 examines the effects of shade and management type on the development of SOC stocks in the experiments and asks whether changes in SOC stocks can be considered real units

¹ Throughout the text “intensification” refers to an increase in productivity per unit area and time.

of sequestered atmospheric C that do fully take into account emissions attributable to differences between managements.

Chapter 5 examines the trade-offs between intensifying an existing coffee system compared with ‘extensifying’ (maintaining a lower-input-lower-output production system but expanding it in order to meet growing coffee market demands and resulting financial incentives) by evaluating the GHG emissions attributable to increased fertiliser input and land-use change emissions. This analysis is carried out to inform the current debate around calls for agricultural intensification to fulfil increasing demand for food and other agricultural commodities at the same time as curbing GHG emissions from deforestation due to scarcity of agricultural land.

Chapter 6 assesses the C and socio-economic performance of coffee farms in Costa Rica and Nicaragua and tries to identify common trends amongst farms that affect their climate change mitigation and adaptation potential.

Chapter 7 finally synthesises the different components of the research, highlights the emergent key findings and makes recommendations on C accounting and management within CAFS. It further recommends areas for future research to continue improving our knowledge of C performance when designing CAFS that are effective for climate change mitigation.

The **appendix** includes a detailed description of the development of a carbon agroforestry calculator (CAFCA), which forms the basis of all the C accounting, CF and land-use change calculations presented in the chapters.

Chapter 2

The operational framework for assessing the climate change mitigation potential of coffee agroforestry systems

2.1. The Carbon Market

2.1.1. Introduction

The carbon market has been growing rapidly since its inception in the 1990s, with an increase in value from US\$11 billion in 2005 to around US\$176 billion of the Compliance market in 2011 (Kossoy and Guigon, 2012). The Voluntary Carbon Market (VCM), in comparison, holds a much smaller market share (just over 0.3% in 2011) but nevertheless witnessed a significant rise from around US\$40 million in 2006 to almost US\$576 million in 2011 (Peters-Stanley and Hamilton, 2012). Here, in particular, the formal international recognition of reduced emissions from avoided deforestation and forest degradation (REDD) and conservation-based REDD+ project types can be attributed to the more recent success of the VCM. In the development of a holistic global strategy to fight climate change, the inclusion of developing countries in the control of greenhouse-gas (GHG) emissions has been a challenge. Deforestation of tropical is believed to contribute 17.4% of global GHG emissions in 2004, with agricultural sector emissions further accounting for 13.5% (IPCC, 2007b). Although industrialised countries produce much higher per capita emissions than developing countries (Wara, 2006), GHG emissions from developing countries as a whole are escalating and are predicted to overtake those of developed countries within the next decade (Environmental Protection Agency, 2009).

The Kyoto Protocol was formulated in 1997 by the United Nation Framework Convention on Climate Change (UNFCCC) and came into force in 2005 providing the basis for a global carbon market. Different from the Convention which brought together countries to discuss what could be done against global warming, the Kyoto Protocol laid out legally-binding GHG emission reduction for signatory countries (Annex 1 countries), upon which carbon markets were then built.

According to Kollmuss et al. (2008) carbon markets are generally believed to positively influence the following:

- contribute to climate protection through real and additional, permanent, and verifiable GHG reductions, while limiting unintended negative consequences
- reduce GHG emissions in an economically efficient way
- enhance social and environmental benefits to project hosts
- stimulate social and technological innovation and participation by new actors, sectors and groups
- create and build constituencies for more effective and comprehensive national and international solutions
- avoid perverse incentives that could stymie broader climate protection actions and policies
- synergistically work with other climate protection measures.

Nevertheless, behavioural changes within society to achieve the move to a low-carbon and more energy-efficient economy have also been highlighted as important (Ockwell et al., 2009). Therefore, carbon offsets are often seen as a last resort once individual measures to address an organisation's or individual's carbon footprint have been sought. As such, the Carbon Trust for example advises to focus first on reducing direct or in-house emissions by implementing cost-effective and energy efficiency measures (The Carbon Trust, 2006). Once these have been met satisfactorily the next recommended step is to encourage the reduction of indirect emissions, produced up- or down-stream of an organisation or individual's supply chain. Remaining emissions, which cannot be reduced through the previous steps, can then be offset through purchasing verified emission reduction units.

2.1.2. Structure

The international carbon market is made up of two separate entities: the regulated or compliance market and the voluntary market (Peskett et al., 2010). Both trade carbon commodities such as allowances and offsets but are fundamentally different in their approach; the former is compulsory with legally binding emission targets; the latter is voluntary, not governed by any globally agreed regulations. Emission reductions traded are mechanism-specific but all amount to one emission reduction unit equal to one tonne of carbon dioxide equivalent (Mg CO₂e).

2.2. Regulatory or compliance market

The compliance market is governed by international, national and regional mandatory emission reduction targets of (developed) countries listed in Annex 1 of the Kyoto protocol (Delbosch and de Perthuis, 2009). Countries which ratified the Kyoto Protocol in 1997 are obligated to reduce their emissions over the period 2008 – 2012 to 1990 levels, averaging around a 5% reduction for each country (UNFCCC, 2011a). Three mechanisms outlined in the treaty enable participating members to meet their emission targets, which are primarily met through national measures. The three mechanisms are:

- Emissions Trading
- Clean Development Mechanism (CDM)
- Joint Implementation (JI)

2.2.1. Emissions Trading (ET)

Emissions Trading is associated with an arrangement known as the cap-and-trade system in which each of the participating members is set a ‘cap’ or a finite number of allowances of emissions, called Assigned Amount Units (AAU) by the regulatory body. This cap is set according to agreed emission reduction targets. Allowances can then be traded amongst participating members. The market price is driven by the limitation of allowances, which can’t be created or removed. Caps are created to stimulate a cut of emissions while finding the most economically efficient way of doing so. Importantly, as this system requires no further reduction of emissions beyond the cap, the cap-and-trade system does not lead to additional emission reductions but only to a geographical shift where reduction occurs (Kollmuss et al., 2008). The baseline for emission reduction has been set to before 1990 and averages around 5.2% for the individual country. The first binding agreement has been set for renewal in 2012.

Other major cap-and-trade systems which are separate from the Kyoto Protocol are the European Union Emissions Trading Scheme (EU ETS), which is the biggest mandatory trading scheme (Capoor and Ambrosi, 2008), the New South Wales GHG Abatement Scheme (NSW GGAS), the Regional Greenhouse Gas Initiative (RGGI) and the Western Climate Initiative (WCI) (Kollmuss et al., 2008).

2.2.2. Clean Development Mechanism (CDM)

This mechanism was set up as part of the Kyoto Protocol to help Annex 1 countries meet their emission targets more cost effectively if allowances can't be met internally (UNFCCC, 2012a). The system works by allowing Annex 1 countries to invest in projects in non-Annex 1 (developing) countries that either (a) help to reduce emissions of the six GHGs listed in the Kyoto Protocol (clean technologies) or (b) absorb carbon through afforestation or reforestation activities (carbon sequestration). Projects based on the protection of existing forests under the subsequently developed Reduced Emissions from Degradation and Deforestation scheme (REDD), hydrofluorocarbon (HFC) destruction from new facilities and nuclear energy are not currently included within the CDM. Only a limited number of carbon credits, generated under the CDM, may qualify to account towards an individual country's emission reduction target as set by the Kyoto Protocol. The main difference from cap-and-trade systems is that no scarcity is created as every new project generates additional offsets and both buyers and sellers have an interest in maximising these. This has led to concerns about the net global impact of the CDM. A review of the CDM mechanism by Wara (2006) concluded that the main reason for the success of the CDM was due to it being "cheaper to construct low carbon energy infrastructures from scratch in developing nations than to modify or replace existing technology in industrialised nations". Such criticisms of these mechanisms are reviewed in more detail in section 2.5 below.

2.2.3. Joint Implementation (JI)

The Joint Implementation scheme is governed by the same principals as the CDM, with the exception that Annex 1 countries are instead allowed to invest into projects in other Annex 1 countries (UNFCCC, 2012b). Units generated under this mechanism are called Emission Reduction Units (ERUs) (UNFCCC, 2012c).

2.3. The Voluntary Carbon Market (VCM)

The voluntary carbon market (VCM) operates outside the compliance market and promotes the voluntary, corporate and individual efforts towards achieving a lower carbon economy by helping to reduce greenhouse gas emissions. Credits traded on the VCM can be generated either through the CDM or by projects verified under the VCM (House of Commons Environmental Audit Committee, 2007) and are generally known as Verified or Voluntary Emission Reductions (VERs). The main difference compared with the compliance market is that these offsets cannot

contribute to any legally-binding emission reduction commitment; they are voluntary and solely driven by the motivation of an offsetting party that wishes to go beyond the norm. However, government attitudes towards the VCM have shifted in recent years, from apprehension to active engagement, valuing its use in meeting domestic cap-and-trade regulations (Peters-Stanley and Hamilton, 2012). Indeed, the VCM has been promoted for its use by countries which have not ratified the Kyoto Protocol and would otherwise remain outside of carbon trading mechanisms through the CDM (Kollmuss et al., 2008). There are a number of standards, which offer offsets on the VCM, each operating under their own regulations and norms. Some, such as the Verified Carbon Standard (VCS), try to follow the procedures of the CDM as closely as possible to increase transparency and quality, whilst others, such as the Gold Standard (GS) and the Climate Community & Biodiversity Standard (CCBS) have even stricter accounting methods (Kollmuss et al., 2008).

Most commonly energy efficiency has been promoted as a first step to help businesses and individuals reduce their carbon footprint within their offices and homes (The Carbon Trust, 2010). The VCM offers those parties interested in going one step further the opportunity to offset their remaining carbon footprint and become 'carbon neutral', by purchasing carbon credits. This is achieved through investing in project-based activities that intend to either continue to act as a carbon pool (e.g. through the protection of standing forest), sequester carbon from the atmosphere (e.g. through forest-planting activities) or reduce emissions (e.g. through the replacement of fossil fuels with 'clean energy' such as hydropower) (Parliamentary Office of Science and Technology, 2007). Because the VCM has so far been operating on a much smaller scale than the compliance market (Figure 2.1) it is generally not considered to significantly contribute to global climate change mitigation. However, it has been suggested as an important tool in raising awareness amongst the general public towards changing consumption patterns such as more choice of a more efficient transport mode and preference for 'lower impact' products (House of Commons Environmental Audit Committee, 2007). Further, project-based activities funded through the VCM have been considered an important step in innovation and development of low carbon technology (Harris, 2007; Peskett et al., 2007), such as fuel-efficient stoves. Thus, the VCM, through its more flexible approach and diverse range of projects, supports regions which are currently under-represented in the compliance market, especially in Africa (Peskett et al., 2006).

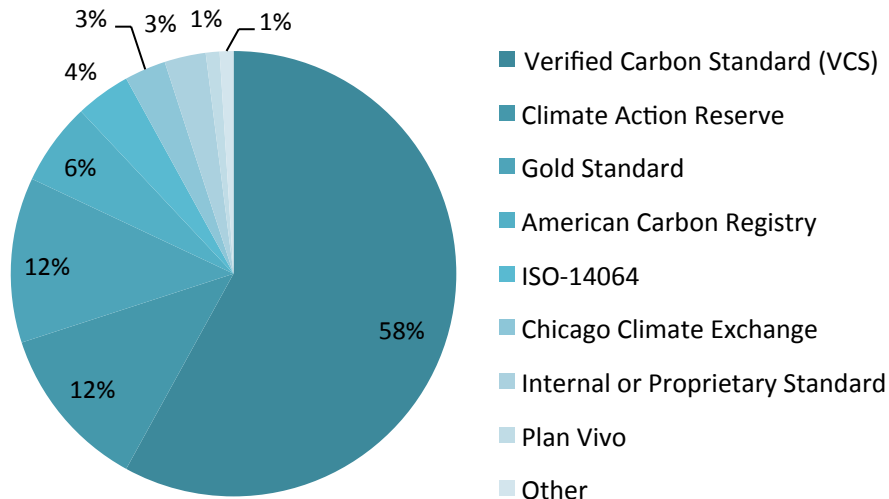


Figure 2.1 Market share of voluntary carbon credit transactions certified by different independent, 3rd party voluntary standards in 2011. Credits certified according to local or national government standards, which comprised 7% of the voluntary market in 2011, are not shown here (adapted from Peters-Stanley and Hamilton, 2012).

2.4. Key elements of offsets

There are a number of formal requirements inherent to all accepted carbon offset standards, which must be demonstrated to be met in order for project registration (VCS, 2008):

- **Additionality** - to qualify as an offset, greenhouse gas reductions achieved by a project need to be in addition to what would have happened if the project had not been implemented.
- **Verification** - monitoring and verification of emissions reductions guarantees that the reductions claimed by a project have actually been achieved
- **Permanence** – avoidance, as far as possible, of any potential reversibility of emission reductions or sequestrations
- **Leakage** – Any increase in emissions that take place beyond the project boundary as a result of implementation of the project. For example, a project that prevents deforestation in one area may cause this activity to increase in another area outside the project boundary
- **Double counting** and ownership – double counting may occur when ownership of the

carbon offset is contested. It can also happen at the national level, where voluntary reductions are counted towards national mandatory targets.

Whilst these criteria are formal requirements of all accepted standards, in reality they can be difficult to meet and indeed to prove prior to project implementation (Baker et al., 2010). The following section discusses these as a criticism of carbon projects and how their uncertainty can be addressed.

2.5. Criticism of carbon offsets

The move to a low carbon economy has often been stated as the most important step in reducing climate change (Stern, 2006). Carbon offset projects have sometimes been criticised as hindering this move because by purchasing carbon credits, continuation of a resource-intensive lifestyle may be justified (Parliamentary Office of Science and Technology, 2007). Further, the potential for carbon offsets to mitigate climate change has been questioned (Revkin, 2007; *The Economist*, 2006); offsetting all of the annual billion tonnes of global greenhouse gas emissions has been deemed physically impossible. For example, a study by Forest Research based on current CO₂ emissions for the UK calculated that in order for the UK to become carbon neutral by means of afforestation alone, 50 million hectares (about twice the land area of the UK) of forests with an average sequestration rate of 3 Mg C ha⁻¹ yr⁻¹ would have to be established (Broadmeadow and Matthews, 2003). This highlights the fact that offset projects can help to mitigate climate change effects but should not form the sole basis; alteration of the global culture of natural resource misuse will still be required.

Critics, in particular of the VCM, have commented on the inherent weakness of projects established under this umbrella as no mandatory rules or regulations have so far been established for standards offering offsets under such schemes (Gillenwater et al., 2007). Criticisms range from inaccuracy of individual carbon accounting methodologies (Schiermeier, 2006) to the quality of projects in which key elements such as additionality, permanence and leakage seem not to be addressed (Gillenwater et al., 2007). These concerns about the quality of carbon offsets and the wider impact this might have led the UK Government Department for Environment, Food and Rural Affairs (DEFRA) in 2007 to consult on producing a voluntary code of best practice for the VCM. At the same time the House of Commons independently consulted on the same topic and concluded that the VCM can play a vital role in helping fight climate change provided that it improved drastically on the clarity and transparency of its actions (House of Commons

Environmental Audit Committee, 2007). In particular a need for guidance for the consumer on the extent of effectiveness of carbon offsets in helping reduce carbon emissions was highlighted.

Further, it has been suggested that the stringent requirements of proving permanence, leakage and additionality of a project may act as a barrier to the ability of developing nations to participate in carbon markets (ODI, 2010a), not only because of the difficulty of proving their achievability when compiling the project design document², but because of the perceived risk to financial investors of failing to meet them and therefore the difficulty of obtaining funding for project implementation (Sutter, 2001). Yet the CDM was created with the purpose of stimulating sustainable development (UNFCCC, 2012a) by establishing a mechanism for developing countries to benefit from the finances and technology transfer generated through carbon markets. In addition, the geographical distribution of projects developed under the CDM has been criticised, with 73 % of all projects being based in China compared with just 1.4 % in sub-Saharan Africa, due to the comparatively low cost of project activities in China (Boyd et al., 2009). Nevertheless, the voluntary carbon market is seen as providing greater scope for the development of projects with local community benefits in poorer nations due to the less-onerous requirements of voluntary standards compared with the CDM (Taiyab, 2006b).

2.6. Carbon markets and co-benefits

Although emphasis must be placed on developing clean technologies and reducing emissions through energy efficiency, activities financed by the VCM can have an additional benefit for combating the impacts of climate change; they can help local communities, depending directly on ecosystem services for their livelihoods, to adapt to the range of negative impacts of climate change (Tubiello and van der Velde, 2010). Carbon offset schemes can thus go beyond solely removing atmospheric greenhouse gases and produce a wider range of benefits for the people involved, including working towards sustainable development goals (Ebeling and Yasué, 2008).

That the CDM should set out to deliver not only carbon offsets but also development benefits for the host country of the project is specified in article 12 of the Kyoto protocol. It has been suggested, however, that the CDM has failed to deliver such co-benefits (Olsen, 2007) due in part to the fact that responsibility for ensuring sustainable development has been allocated to project host governments, who may in fact overlook this criteria owing to the considerable

²The Project Development Document (PDD) is the key document which describes in detail a carbon project in order for its validation, verification and registration (Baker & McKenzie, 2012).

economic benefit of the mechanism (Cole, 2007). Indeed, Sutter and Parreno (2007) concluded that 95% of GHG reductions come from projects that score low when analysed for co-benefits. Some argue this to be an inherent negative trade-off in the mechanism: cheap carbon credits can only be achieved if co-benefits are not taken into consideration, therefore preference will be given to cheaper projects than more expensive ones which contribute more to sustainable development (Olsen, 2007). The exclusion of co-benefits from carbon offset projects has led to business opportunities for richer countries, as low-cost offsets are cheaper than the alteration of a resource-intensive lifestyle. Kollmuss et al. (2008) argue that focusing solely on carbon offsets without including co-benefits is undermining the original goal of carbon offsetting set out by the Kyoto Protocol. Some critics have gone further, arguing that this has given rise to a new form of neo-colonialism in which developed countries dictate the circumstances in which such trade is handled (Bachram, 2004).

Finding ways to include the aims set out in the Millennium Development Goals (UN, 2012) are still considered to be a crucial part of any effort to create a sustainable future (Garrity, 2004). This analysis places human life as the most important purpose of sustainable development. Undoubtedly there will be trade-offs between the mitigation and adaptation potential of different types of offset projects but projects that include the delivery of co-benefits are more likely to yield high sustainability through their contribution to development via capacity building, participation and ownership of projects (Reynolds, 2012). In this light, although the VCM only holds a minor share of the global carbon market, because its projects have a higher rate of achievement of co-benefits than those of the CDM (Taiyab, 2006b) it is still considered to play an essential role in effectively mitigating and adapting to climate change.

2.7. Forestry and its role in carbon offsetting

Offset projects can be classified into two types: land-use-based projects including forestry, and technology-based projects which focus on energy efficiency and renewable energy production (ODI, 2010b). The former, which are also known as Land Use, Land Use Change and Forestry (LULUCF), have been criticised by many for their inherent uncertainties (Chomitz, 2002). These include methodological aspects of accounting for the amounts of carbon sequestered, additionality, leakage and permanence as set out in the stringent rules and regulations of the CDM (Maréchal and Hecq, 2006). One of the major drawbacks associated with developing afforestation and reforestation (A/R) projects under CDM methods is its handling of the risk of non-permanence of carbon sequestration benefits, and the high transaction costs resulting from

highly complex rules for these types of projects. Under the CDM, carbon credits generated through forest-based projects are by default temporary, meaning that they have a set validity period, after which they must be retired and replaced (Baker & McKenzie, 2012). The purpose of this rule is to tackle the issue of non-permanence, as forest-based credits are assumed to be at risk of reversal over the long-term. The combination of these uncertainties coupled with high transaction costs associated with A/R forestry projects, has resulted in them comprising only 39 out of 4441 registered CDM projects established up to July 2012 (UNFCCC, 2012a).

Within the VCM, however, forestry projects have been favoured and have benefitted from recent developments such as the formal acceptance of REDD project types as offset possibilities (Peters-Stanley and Hamilton, 2012). Trees are seen to be more ‘tangible’ and more ‘accessible’ for the consumer, and investing in them is often seen as an act of high social responsibility (Peskett et al., 2007). An association with the people and livelihoods directly dependent on this natural resource further increases the social acceptability of this type of project (Taiyab, 2006a). Different from forestry projects within the CDM, forestry projects under the VCM are considered a comparatively cheap offsetting option (Sedjo, 2006). For example, although many of their requirements are effectively the same, the interpretation of the complex accounting methodologies, as well as level of rigidity that auditors may assume during validation and verification, are considered to be handled more swiftly and easily under the VCM. As such, the VCS has become the most important standard in the voluntary C market (Figure 2.1) and is broadly respected and supported by project developers, verifiers and buyers alike as it has benefited from the development and associated problems of the CDM (Peters-Stanley and Hamilton, 2012).

A major criticism of the carbon market in general has been its lack of accessibility to small-scale producers (Skutsch, 2004). Although viewed as a tool to diversify and strengthen their livelihoods, barriers put up by stringent and costly regulations are difficult to overcome. Agroforestry projects, however, provide an opportunity for small producers to gain access to this growing market due to fewer input requirements such as physical infrastructure, specialised skills and silvicultural inputs (Peskett et al., 2006). Further, Verchot et al. (2007) concluded that the financial cost of carbon sequestration appears to be much lower in agroforestry than in other types of offset projects. The positive impacts of both forestry and agroforestry projects with respect to co-benefits and other contributions to development have been demonstrated (Boyd et al., 2005; Grieg-Gran et al., 2005).

There are a number of issues that still need to be addressed in order to strengthen the credibility and integrity of forestry and agroforestry as a holistic offset option. The inherently long-term nature of forestry projects means that a lasting commitment by project partners or host communities must be guaranteed in order to ensure permanence. This can only be achieved, however, while the project remains relevant and of net benefit to their needs. Too often, market-orientated interests drive project implementers. One such example is the establishment of carbon-rich strict protection conservation areas, in which local people are denied their rights to collect forest products to support their livelihoods. According to Boyd et al. (2007), access to surrounding natural capital for the rural poor is the closest thing to a safety net, which might compensate for other losses in their. If this access is compromised, not only can problems with permanence and leakage potentially nullify the carbon sequestration but also human lives can be jeopardised. As such, projects based on reducing emissions from deforestation and forest degradation, commonly known as REDD, that are aimed at conserving and protecting existing forests, face multiple challenges of delivering not only carbon sequestration, but also wider environmental benefits (e.g. biodiversity protection) and co-benefits contributing to sustainable livelihoods through provision of ecosystem goods (e.g. timber, non-timber forest products (NTFPs)) relied on by local communities (Peskest et al., 2008). Such projects have faced recent criticisms of not only displacing deforestation and degradation to other surrounding forest areas (leakage) but also being unable to compete with alternative land-use options as a livelihood opportunity (Butler et al. 2009). Impacts on food security, land tenure and territorial rights, and the livelihoods of local communities (including indigenous peoples) are of great importance and need to be taken into account. Stakeholder consultation in the early stages of project planning to identify the basis of local livelihoods and, based on that, common project objectives is therefore fundamental. Examples of voluntary standards that have adopted such an approach are the CCBS and Plan Vivo (CCBA, 2012; Plan Vivo, 2012)

Offsetting activities can be used as an interim way of helping to meet emission targets in the near future for sectors of the global economy that need to develop cleaner technologies. Although, to date, only a small number of offset actors in the VCM have integrated agroforestry into their standards, its practical potential in climate change adaptation and mitigation has become clear (Verchot et al., 2007). However, because agroforestry projects involve the complexity of both agricultural and forestry components, major challenges remain to find appropriate means of incorporating them into the VCM.

2.8. Mitigation and adaptation by means of agroforestry

2.8.1. Climate change impacts on the agricultural sector

Impacts from climate change will be felt hardest by subsistence farmers in the tropics as they have little access to resources to buffer and adapt to the changing climate (IPCC, 2007a). Lack of institutional support and reliance on the natural environment for their livelihoods place the rural poor in the most vulnerable position (Verchot et al., 2007). A small minority of areas which currently display a mesic subtropical cold-winter environment are nevertheless expected to witness increased productivity of food crops resulting from beneficial climate conditions such as an increase in temperature (Jones and Thornton, 2003) and increases in rainfall are predicted to occur in some seasonally dry tropical environments.

Although increased CO₂ concentrations are understood to increase agricultural productivity through increased plant photosynthesis (termed CO₂ fertilisation) (Robledo and Forner, 2005) its effect will heavily depend on nitrogen and nutrient availability in the soil (Bardgett, 2005) and geographical location. Temperature increase and change in level or frequency of rainfall will often have a greater effect. Climate change scenarios predict longer and warmer growing seasons in temperate regions but shorter and drier growing seasons in tropical regions (Hitz and Smith, 2004) (Figure 2.2). Jones and Thornton (2003) simulated climate change effects on maize production until 2055 by using a process-based model, and predicted that in many regions of Africa and Latin America, including Nicaragua and Costa Rica, crop yields for small-farmer rain-fed maize will fall due to less favourable growing conditions including temperature increases and less favourable rainfall patterns.

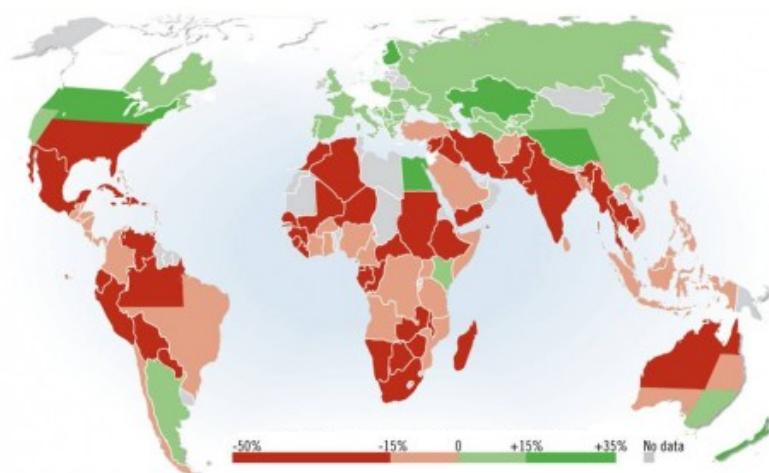


Figure 2.2 Projected changes in agricultural productivity by 2080 due to climate change, incorporating the effects of CO₂ fertilisation (Cline, 2007).

Stressed agricultural systems are more likely to suffer from pest and disease losses. An increase in pest numbers due to the warming of the climate is expected (Fuhrer, 2003; Harvell et al., 2002), though this is predominantly in temperate environments, such as Scandinavia, where warmer winters with shorter frost periods will enable greater pest populations to survive. Prolonged periods of drought, which are predicted to become more frequent (IPCC, 2007b), will further strain these systems and increase their vulnerability; for the agricultural sector in North America Rosenzweig et al. (2000) concluded that pest and disease occurrences coincided with more frequent and extreme weather events. They further reported that an increase in night-time and winter temperatures may alter pest survival rates and increase pest reproduction, as overall higher temperatures are said to enhance the development rate of pests, thereby shortening the time between generations (Rosenzweig et al., 2000). A major problem predicted to be caused by increased temperatures is that insect pests will extend their geographic ranges, leaving more areas vulnerable to attack (Bale et al., 2002).

2.8.2. Mitigation and adaptation - a role for agroforestry?

Negative climate change impacts present a major challenge in meeting the UN Millennium Development Goals (Robledo and Forner, 2005). Although the Kyoto Protocol had been set up as a multilateral agreement between member-states to counteract and therefore mitigate the negative effects of climate change, adaptation to a changing climate will play a crucial role in the lives of people depending directly on natural resources for their livelihoods (Murdiyarso et al., 2005; Romero, 2005; Rahman et al., 2007). However, mitigation and adaptation strategies have only recently been combined to form a holistic approach to fight climate change in the Delhi Declaration on Climate Change and Sustainable Development (UNFCCC, 2003). Until then, discussions about adaptation and mitigation focused on financial implications, failing to highlight wider impacts (Verchot et al., 2007). Although adaptation will certainly have limits too, approaches that promote adaptation as part of a wider climate change strategy will cushion the negative impacts to a greater extent.

Agroforestry is increasingly being advocated as an agricultural land-use system which could play an important role not only in mitigating but also in adapting to climate change (Nair et al., 2009a; Soto-Pinto et al., 2010; Verchot et al., 2007). In this thesis, agroforestry is defined as “any land-use system that involves the deliberate retention, introduction or mixture of trees or other woody perennials with agricultural crops, pastures and/or livestock to exploit the ecological and economic interactions of the different components” (Nair, 1993). The inclusion of trees in

farming systems will generally increase carbon sequestration above ground and may increase it below ground making it a potentially powerful contributor to climate change mitigation (Kandji et al., 2006) (Figure 2.3). Albrecht and Kandji (2003) found that in South America a total of 39 – 102 Mg C ha⁻¹ in above-ground biomass could be stored in agroforestry systems (AFS). Harmand et al. (2007) combined results from 21 studies on coffee farming systems in Central America and found an average of 26.5 Mg C ha⁻¹ in above-ground biomass in shaded AFS compared with 10.5 Mg C ha⁻¹ in unshaded, full sun coffee systems. This result lies within the range of values reported in a comparative study of coffee AFS across southern Costa Rica, which found a range of average stocks of 11 – 31.6 Mg C ha⁻¹ in above-ground biomass (Polzot, 2004). The variation of C stored within the systems in this study was heavily dependent on the variety of shade trees and the structural diversity of the systems in question. Primary forests and managed forests generally store a greater stock of carbon above-ground than AFS (Figure 2.3), but an important feature of the latter lies with the potential to convert parts of the global landscape that are under agricultural crop production into higher C stock agroforestry lands (Albrecht and Kandji, 2003). IPCC (2000) predicted carbon stocks to have the potential to grow by 390 Mt C yr⁻¹ by 2010 through land-use change to agroforestry.

Global demand for food is increasing but its supply is increasingly threatened by climate change (Foresight, 2011). Agroforestry systems can aid adaptation of agricultural commodities production to climate change by decreasing the vulnerability of agricultural crop productivity through buffering of extreme abiotic conditions, whilst also providing a safeguard against potential income loss due to crop failure, through the harvest of valuable tree products (Verchot et al., 2007). A more stable environment generally makes agricultural productivity more predictable, thereby leading to more secure market conditions.

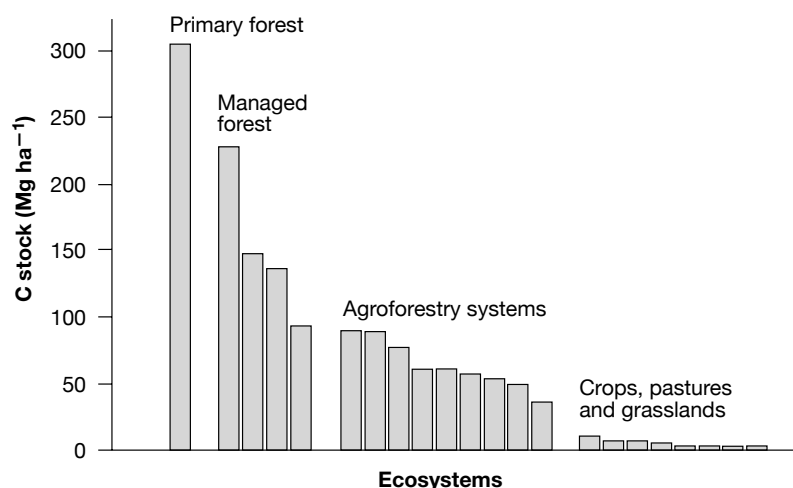


Figure 2.3 Above-ground C stocks in different mature ecosystems in the humid tropics (Kandji et al., 2006).

2.8.3. Effects of agroforestry on farming system vulnerability to climate change

With an evident and unequivocal warming of the atmosphere through continued emissions of GHGs (IPCC, 2007b) scientists have long attempted to predict the spatial variability in climate change impacts in order to assess the vulnerability of individual agricultural regions. This has led to a wide range of predictions, however there is some consensus about gross changes in temperature and precipitation patterns. More extreme weather conditions such as shorter but heavier rainfall and increased temperature will affect land biophysical properties such as soil water content, runoff and erosion, nutrient cycling, salinisation, biodiversity, soil organic matter and not least workability (Verchot et al., 2007). Thus, the impact on poor rural farmers who rely on rain fed crops for their food security and livelihoods could potentially be substantial. Further, degenerating processes, such as deforestation, continuous cropping and overgrazing, increase the vulnerability of already fragile systems in the tropics, especially in semi arid regions. Thus, the main goal of adaptation is to limit land degradation as this has a major effect on agriculture and economic development.

To reduce the vulnerability of small-scale subsistence farmers to inter-annual variability in precipitation and temperature, tree-based systems are often favoured as a primary adaptation strategy promoted by institutions such as the World Agroforestry Centre. The benefits of tree-based systems such as agroforestry are multi-fold. Through diversification and tree inclusion, positive effects on the environment as a whole can be identified (Boye and Albrecht, 2006). For example, beneficial soil properties such as porosity are increased which lead to higher water infiltration and water retention (Noordwijk et al., 2006) and therefore reduce run-off. Water deficiencies are a major problem for crop production in semi arid regions where drought can wipe out an entire harvest. It has been suggested that improved fallows can help to make water usage more effective and thereby produce a sufficient amount of crops from agriculture (Albrecht and Kandji, 2003). Shaded systems create more favourable microclimates, reducing heat stress on crop plants and, over the long-term, compensating for reduced yields compared with un-shaded crops (Jonsson et al., 1999). According to Verchot et al. (2007), evapotranspiration is increased in comparison to unshaded tree systems, which helps to aerate the soil quicker and reduce water logging but also shows the potential for shade trees to compete with crops for water. Agroforestry includes rotational systems with tree fallows, which have been demonstrated to significantly improve soil fertility before the next cycle of cropping, especially when they include N-fixing tree species (Sanchez, 1999). In addition, Gallagher et al. (1999) found that short-term improved fallows can significantly improve weed management in tropical environments. Nevertheless, conclusive scientific evidence is still lacking that the incorporation

of trees in agricultural systems can reduce their susceptibility to pest and disease attack (Kandji et al., 2006).

2.9. Other greenhouse gas emissions - CH₄ and N₂O

It has recently become apparent that through nitrogen fertilisation in agricultural systems, nitrous oxide (N₂O) emissions from the soil can be enhanced (Stehfest and Bouwman, 2006) and atmospheric methane (CH₄) uptake reduced (Chu et al., 2007). Both are powerful greenhouse gases with, respectively 25 and 298 times the global warming potential (over 100 years) of CO₂ (IPCC, 2006). In agroforestry systems, it has been reported that leguminous trees, which are often used for their shade or nitrogen-fixing properties, can also potentially increase soil emissions of N₂O (Chikowo et al., 2004; Verchot et al., 2007; Verchot et al., 2008) and reduce CH₄ uptake (Palm et al., 2002; Rochette and Janzen, 2005). However, these results vary and depend on the individual circumstances of study sites. For example, a study of improved fallow systems containing leguminous trees in eastern Amazonia detected no significant differences, compared with unimproved fallows, in N₂O emissions or CH₄ uptake (Verchot et al., 2008). Conversely, a study of a CAFS in Costa Rica, which compared a high input coffee unshaded monoculture with a high input, legume-tree-shaded coffee system found that a short-term increase in N₂O emissions by 84%, decreases in CH₄ uptake, as well as increases in soil respiration (CO₂ emissions), were mostly explained by inorganic N fertilisation (Hergoualc'h et al., 2008). Nevertheless, higher annual N₂O emissions by the shaded system from N input through litter fall also resulted in a higher potential soil N mineralization rate.

Greenhouse gases (GHGs) other than CO₂ (notably N₂O and CH₄) are often translated into CO₂ equivalents to allow for easier addition and comparison between their emissions. It is crucial that these other GHGs are not omitted from assessments of the impact of different land use systems on climate change. However, this presents complications when combined with the concept of calculating the “net carbon sequestration potential” of CAFS. Literature reporting on the relative levels of CO₂ sequestration in CAFS and emissions of GHGs (including N₂O and CH₄ as well as CO₂) is reported in Chapter 4.

2.10. Economic and environmental roles of coffee cultivation

Global trade in coffee has the highest volume of any tropical agricultural commodity (ICO, 2011). In Nicaragua, an average of US\$140 million or 23% of total export earnings between 2001

and 2006 were derived from coffee alone (FAO, 2011). Similarly, in Costa Rica coffee has been one of the most economically important commodities, accounting for almost 100% of the country's foreign exchange until the 1900s (Agne, 2000). This percentage has greatly reduced with the diversification of the Costa Rican economy, however in 2009, coffee still accounted for about 8% of the value of Costa Rica's exports (FAO, 2011). Traditionally, coffee in both Costa Rica and Nicaragua has been grown under a canopy of shade trees. Whilst the 1990s saw considerable expansion of intensive coffee production into new areas in countries such as Vietnam and India, Costa Rica and Nicaragua have so far maintained their market status by increasing yields and differentiating their produce as high quality, speciality, certified, shade-grown coffee (Clay, 2004). Nevertheless, maintaining coffee farms as diverse agroforestry systems can be costly, and with an average of only 30% of a farmers' certified coffee sold at the higher, certified price globally (Clay, 2004), extra incentives need to be developed if farmers are to maintain these high standards of environmental stewardship. This is especially so in the face of current rising production costs and unstable coffee commodity prices (Clay, 2004). The potential exists for farmers to earn additional income for on-farm environmental services such as C-sequestration. While the current international market for land-use based C offsets is still largely based on projects accounting for only above-ground C stocks, there is increasing pressure for the accounting to be expanded to all ecosystem C stocks (Lawlor et al., 2010). Carbon stored in the soil is estimated to comprise up to 80% of terrestrial carbon stocks (Harmand et al., 2007c), therefore data on the size of the soil C pool will need to be obtained in future C offset projects and incorporated into a respected model for C-accounting. However, there is a significant lack of data to quantify the mechanisms and processes that affect soil carbon sequestration on coffee farms especially for the regions of interest for this study.

2.11. National strategies of climate change adaptation and mitigation

2.11.1. Costa Rica

To-date, Costa Rica has been at the international forefront of climate change mitigation and adaptation activity. Land use change accounts for the majority of Costa Rica's GHG emissions due to deforestation (Figure 2.4) (World Resource Institute, 2009). This has therefore been the focus of the Costa Rican government's national action plan against climate change, which is based on activities focussed on both mitigation and adaptation. Through mitigation, the country strives to become a "climate neutral" economy by the year 2021 (Dobles, 2008). It is also anticipated that this move towards a "climate neutral" economy will enhance its competitiveness

and sustainability over the long term. In contrast, adaptation strategies are designed to reduce sectoral and geographic vulnerability, calculated by subtracting the adaptation capacity from estimated potential climate change impacts. Climate change predictions calculated by the Costa Rican Ministry of Environment, Energy and Telecommunications (MINAET) using three different scenarios suggest that future climate conditions for Costa Rica could be favourable for agriculture (Robledo and Forner, 2005). This would maintain economic pressure for land-use change further emphasising the emphasis on its reduction in the national action plan.

Costa Rica's mitigation strategy is based on the following three key elements:

- **A reduction of GHG emissions** by sources including energy, transportation, agriculture, land use (including land use change and the reduction of deforestation), industry, solid waste management and tourism (and its associated international air travel).
- **Carbon sink enhancement** through avoided deforestation, reforestation, natural forest regeneration and agroforestry.
- **Carbon markets** (national and international) including payments for environmental services (PES), voluntary markets (Verified Emissions Reductions (VERs)), official markets (Certified Emissions Reductions (CERs)) and “climate neutral” brands.

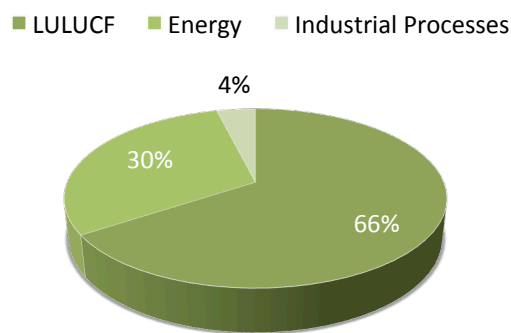


Figure 2.4 Breakdown of Costa Rica's greenhouse gas emissions by sector (land use, land-use change and forestry (LULUCF), energy and industrial processes) in 2009 (adapted from WRI, 2009).

Through its forward-thinking and pragmatic approach, Costa Rica anticipates achieving a goal that will put it as a nation at the forefront of international climate change efforts. It commits itself to “develop necessary capabilities to turn the challenging mitigation goals into opportunities of change to increase our human sustainable development potential” (Dobles,

2008). Although the road map to a “climate neutral” economy seems somewhat ambitious, progress has already been visible at some levels, for example Costa Rica’s forest cover increased from a total of 21% in 1986 to 51% in 2008 (Dobles, 2008). This was mainly due to the implementation of a payment scheme for environmental services from the protection and enhancement of forests. Further, participation in programmes such as the Coalition for Rainforest Nations, which is aimed at avoiding deforestation and the late Wangari Maathai’s UNEP tree planting campaign, have positively contributed to the progress in Costa Rica’s challenging quest to become a “climate neutral” economy. In 2011, the first coffee farm in Costa Rica claimed carbon neutral status, offsetting emissions from the cultivation and processing of their coffee, and thereby trying to set new standards for ‘climate-friendly’ coffee by adhering to PAS 2060 carbon neutral specifications (Martinez, 2011).

2.11.2. Nicaragua

Although Nicaragua makes only a small per capita contribution to global GHG emissions (0.7 Mg CO₂ in Nicaragua vs. 4.5 Mg CO₂ global average in 2004) (UNDP, 2008), it is considered one of the countries most at risk from negative climate change effects. The Global Climate Risk Index 2009 ranks Nicaragua at number three in order of countries most at risk (Harmeling, 2008). The score is calculated from specific indicators such as death toll, absolute losses, and losses per unit GDP caused by extreme weather events.

Land use, land-use change and forestry activities contribute the highest percentage of GHG emissions within the national economy. According to the World Resource Institute (WRI), around 93% of Nicaragua’s GHG emissions are accounted for by the LULUCF sector (Figure 2.5) (WRI, 2009). Other sectors such as energy and industrial processes only account for 6% and 1% respectively (WRI, 2009).

In 2007, Nicaragua adopted a National Climate Change Strategy which laid out guidelines to combat predicted climate change impacts as described in the National Climate Change Action Plan (MARENA, 2009). Emphasis was put on adaptation strategies as a large proportion of the rural population depend directly on agriculture and forestry for their livelihoods. It is acknowledged in the national strategy that both the agricultural and forestry sectors are highly vulnerable to climate variability especially in terms of flooding and storms (World Bank, 2008).

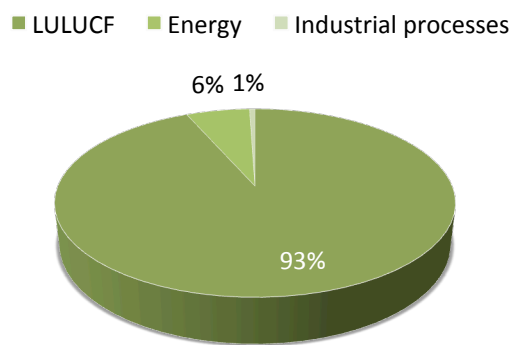


Figure 2.5 Breakdown of Nicaragua's greenhouse gas emissions by sector (land use, land-use change and forestry (LULUCF), energy and industrial processes) in 2009 (adapted from WRI, 2009).

Land-use change from forest to pasture land or agricultural cropland has been identified as the main activity contributing to Nicaragua's GHG emissions, with annual emissions of 53.7 Mt CO₂ (World Resource Institute, 2009).

The strategy based its objectives on climate change scenarios which predict a temperature increase of 2.5 to 2.8 C° between 2010 and 2100 for the Caribbean and Pacific side respectively. Similarly, an average decrease in precipitation and cloud cover of 27.9% and 12.6% respectively for the same regions between 2010 and 2100 is predicted according to the most pessimistic scenario (World Bank, 2008).

2.12. Key land issues in climate change policy

The national climate change programmes of Costa Rica and Nicaragua form a platform for much-needed research into areas which have so far been neglected in discussions about carbon sequestration mechanisms. Soil carbon, the biggest terrestrial carbon pool with around 2000 Gt C (compared with around 500 Gt C in vegetation) (IPCC, 2001) presents not only a great opportunity as a carbon sink through further carbon sequestration and storage by applying appropriate management, but at the same time presents a potential risk of becoming a major source of GHG emissions through mismanagement. In both countries, LULUCF activities already form the majority of GHG emissions. Methodologies that can help to avoid furthering this trend and help adapt to a changing climate are urgently required.

2.13. Coffee farming in the Central American study areas

2.13.1. Coffee farming systems

Traditionally, coffee in Central and South America has been grown under a dense layer of shade with large species diversity (Rice, 1990). These agroforestry systems historically would use few material inputs from outside their system boundaries. With technification of coffee farming in the 1970s much of the original shade structure and management has changed and most farms are managed with varying levels of fertiliser and pesticide inputs (Rice, 1990). As such, a number of different farming types and classification exist in the wider landscape of coffee farming. Most commonly coffee production systems have been categorised according to their structural diversity and complexity: rustic (unaltered natural forest canopies), traditional poly-culture (altered natural forest canopies that include tree species with economic importance), commercial poly-culture (planted trees of species with economic importance), shaded monoculture (planted trees of a single species with economic value), and un-shaded monoculture (full sun) (Moguel and Toledo, 1999).

2.13.2. Historical background of coffee farming in the study areas

In Nicaragua the present study is located in the Masaya department in the Masatepe municipality (11°53'54"N, 86°08'56"W) at low altitude (455 m above sea level), where the climate is semi-dry tropical with a distinct rainy season between May and November (mean annual rainfall is 1386 mm and mean annual temperature is 24°C (Hagggar et al., 2011). The area has traditionally been one of the major coffee producing regions in Nicaragua with over 120 km² under production. However with the Sandinista revolution which took place in the early 1980s, an agrarian reform was introduced which saw the majority of coffee farming systems in the Carazo and Masaya region being “modernised” and transformed (Hagggar pers. comm.). This ‘technification’ of coffee farming was introduced for a number of reasons. First, during the intense fighting of the Sandinista revolution, much of the agricultural sector suffered from neglect, with the exception of coffee which more or less stayed intact. To sustain an economy that was heavily dependent on its agricultural exports, coffee quickly became the number one crop earning more than a third of national export earnings in 1980 (Westphal, 2002). Second, since the mid 1970s, the infamous coffee pest, coffee leaf rust (*Hemileia vastatrix*, a fungal disease), started spreading on Nicaraguan coffee farms. New, higher yielding and leaf rust-resistant coffee varieties were recommended to replace the existing plants. However, in order to fulfil the expectations of national export earnings through coffee, these new varieties needed higher inputs and a greater level of

technology. The region of Carazo was chosen as a starting point for the modernisation process where over 8000 ha were to be replanted (Westphal, 2002). As a result of the ‘technification’ of these farms, most of the shade trees within the coffee plantations had to be removed to allow for an easier use of farming equipment and the use of agrochemicals. This had a huge impact, not only on the production of coffee but also on ecosystem functioning. Climatic conditions and the high speed and acidic winds in this volcanic region, as well as the high costs associated with high input farming systems, made the anticipated mechanisation and upscaling of production of much of the region unsuccessful. As a result, much of the clear felled area was subsequently replanted with more traditional coffee systems including shade trees as farmers, who had originally warned about the negative consequences of the removal of shade cover, having no choice but to convert back to more traditional farming systems although with new improved plant varieties (Navarette pers. comm.).

In Costa Rica the study site is located in Turrialba ($9^{\circ}53'44''\text{N}$, $83^{\circ}40'7''\text{W}$) at 685 m above sea level located in the Central Valley of the Cartago province. The climate is humid tropical with no marked dry season: annual precipitation is 2600 mm yr⁻¹ and annual mean temperature is 22°C (Haggard et al., 2011). Due to the favourable environmental conditions regions such as Tilarán, Puriscal, Acosta, Tarrazú and Turrialba in and around the Central Valley have been the major commercial coffee production in Costa Rica which began in 1832 (Hall, 1976). To date, the Central Valley has remained the main focus of Costa Rica's coffee production (Agne, 2000).

2.14. Soil carbon

Soil carbon is the biggest terrestrial carbon pool, holding an estimated 2500 Gt (Lal, 2004). It is made up of soil organic carbon (SOC), which accounts for around 1550 Gt and soil inorganic carbon (SIC) accounting for around 950 Gt (Lal, 2004). Globally, soil holds almost twice as much C as vegetation and the atmosphere put together (Earth Observatory, 2009). Changes in soil carbon content can therefore be very significant for the global carbon budget (Bellamy et al., 2005).

Discussions on soil carbon sequestration potential focus on two main themes: sequestration by means of (a) elevated atmospheric CO₂ levels or (b) management. There are major concerns about the possibility for increased CO₂ emissions from soil to amplify climate change due to rising atmospheric temperatures increasing the rate of soil organic matter (SOM) decomposition (Bardgett, 2005). However, this outcome is uncertain because it is highly location specific and will also depend on the trade-offs between the increase in soil organic matter decomposition and

increased organic matter inputs due to increased plant production with higher temperatures (Knorr et al., 2005; Powlson, 2005). With elevated levels of atmospheric CO₂, some believe that the resultant increased primary productivity of ecosystems will increase rates of carbon sequestration in the soil (Canadell et al., 1995; Post et al., 1992). More recently however, others have argued that a limitation in availability of nutrients is likely to constrain the increase in primary productivity with elevated atmospheric CO₂ levels (Bardgett, 2005; Oren et al., 2001). In addition, other variables such as soil moisture could be more important than elevated atmospheric CO₂ in controlling soil carbon dynamics.

Changes in SOC stocks depend on the balance between organic C inputs and outputs (Johnston et al., 2009; Lützow et al., 2006). These inputs can come in the form of plant litter residues and root turnover, from debris/mulch resulting from harvesting and pruning, and from applied organic fertilizers such as chicken or cow manures and coffee pulp. SOC stocks are governed by the interaction of the quality and quantity of these inputs; outputs are determined by factors regulating the rate of decomposition of organic matter. For subsistence farmers using little or no fertiliser, the maintenance of SOM is crucial for sustainable crop production (Zingore et al., 2005). Further, there is evidence that physical soil properties such as aggregation, which are important for crop production, depend on the presence of small fractions of SOM (Loveland and Webb, 2003).

A more certain way of ensuring that soil can mitigate climate change is therefore through the adoption of appropriate management practices. Tremendous amounts of the previous global soil C stock have been lost as CO₂ emissions to the atmosphere since the initial conversion of natural lands to agricultural cultivation and grazing; it is estimated that agricultural conversion has accounted for as much as 75% of C loss from cultivated tropical soils (Lal, 2004). Within LULUCF activities, an average of around 78±12 Gt C are estimated to have been released as CO₂ emissions from soils globally (Lal, 2008). This is attributed to deforestation, soil tillage and erosion, and other degradation processes.

As well as reducing emissions there is also the potential to (re-)sequester atmospheric CO₂ into soils through appropriate management and use of technology (Herzog, 2001). However, this also depends on biophysical attributes such as soil structure and texture, precipitation, temperature and farming system, which may subsequently reduce soil C stocks, allowing this sequestered CO₂ to be re-emitted. Practices to enhance SOC sequestration and thereby increase the SOC pool include forest regeneration through management, no-tillage or conservation farming and agroforestry systems that incorporate fallow practices or other diverse cropping

systems (Nair et al., 2009b; Powlson et al., 2011a). Nevertheless, Lal (2004) predicted that only 50-66% of historic loss of C from global soils, which is estimated at 58-78 Gt, can be reversed by new sequestration in soil through recommended management practices (RMPs). Nonetheless, a new soil carbon equilibrium can be reached with RMPs that help to increase the rate of SOC accumulation. Systems that favour such an increase share the following characteristics: high biomass addition to the soil, improvement of soil structure, water and soil conservation, enhancement of soil biological activity and minimal soil disturbance (Lal, 2004). Soil C sequestration could therefore play a major role in mitigating climate change though its potential is limited by time and its finite limits. As argued earlier, it is an important component of global and national climate change mitigation strategies and can help buy time until better and more enabling technologies are put in place and take effect (Herzog, 2001).

In the tropics soils are often highly depleted and degraded. Potentially this can mean a high C sequestration capacity (Robert, 2001). But due to high turnover rates C sequestration rates can be low. Applying the right RMP can be crucial in providing a two-fold benefit for tropical regions; food security and C sequestration can be achieved using the same strategy of increasing SOM and therefore enhancing soil carbon stocks. The effect of this on the production of different agricultural commodities will be very dependent on site environment (existing SOM stocks and the relative effects of different factors limiting productivity). Nonetheless, enhancing soil quality by increasing SOM by 1 tonne on degraded cropland soils may result in an increase of crop yield for wheat, maize and cowpeas by 20 to 40 kg ha⁻¹, 10 to 20 kg ha⁻¹, and 0.5 to 1 kg ha⁻¹ respectively (Lal, 2004).

With coffee traditionally being grown under shade in Costa Rica and Nicaragua, although much research has looked into above-ground C sequestration and the effects of shade on crop productivity and other ecosystem services (Haggar et al., 2011; Idol et al., 2011), to date relatively little is known about the impacts of farm management on SOC. It is therefore of great importance to develop a sound understanding of the processes and management activities that affect the potential of SOC to either act as a C sink or source. Methods need to be developed that help to estimate soil C storage for coffee agroforestry projects. These could then be applied to other coffee growing regions, which display similar climatic and soil conditions and help to build a case for including soil C sequestration projects into future carbon offset programmes. In order to identify farming systems that are beneficial for climate change mitigation this research aims to develop a holistic understanding and evaluate the trade-offs of the underlying processes and mechanisms that affect their GHG balance with a particular focus on above-ground and soil C pools and GHG emissions associated with the cultivation of coffee.

Chapter 3

Greenhouse gas emissions in coffee grown with differing input levels under conventional and organic management

Published as:

Noponen, M.R.A., Edwards-Jones, G., Haggard, J.P., Soto, G., Attarzadeh, N., Healey, J.R., 2012. Greenhouse gas emissions in coffee grown with differing input levels under conventional and organic management. *Agriculture, Ecosystems and Environment* 151:6-15.

3.1. Introduction

The need for sustainable intensification of food production has recently been emphasised in the development of global food policy (Foresight, 2011). Given the likely impacts of climate change and rising human populations (UN, 2009), a key challenge for achieving such sustainable intensification is to develop farming systems which produce increased yields without associated increases in greenhouse gas (GHG) emissions. In order to achieve this aim there is a need to fully understand the types and amounts of GHGs that are emitted by different food production systems.

Product carbon footprinting (often referred to as ‘carbon footprinting’) is commonly used to calculate the GHG emissions released from food supply chains. Developing a carbon footprint (CF) has some similarities to developing a life cycle assessment (LCA), and many of the CF methods currently in use are based upon the ISO method for Life Cycle Assessment, ISO 14040/44 (e.g., the GHG Protocol’s Product Life Cycle Accounting and Reporting Standard (Bahatía et al., 2011) and the British Standard Institute’s Publicly Available Specification 2050:2011 (hereafter referred to as PAS 2050) for assessment of the life-cycle greenhouse gas emissions of goods and services (BSI, 2011)). Both the draft GHG Protocol method and PAS 2050 have been developed in response to a call for standardised and transparent CF methods, as ISO 14040 and 14044 have been criticised for being flexible in their approach and therefore

open to some interpretation in application (Plassmann et al., 2010). By maintaining consistency in the calculation method it should be possible to compare the CFs of different supply chains, thus enabling identification of systems with lower GHG emissions per unit of production.

A number of problems, however, exist with the methods currently used for making CF calculations, most notably the fact that despite the calls for consistency, different CF schemes do adopt different analytical methods (Bolwig and Gibbon, 2009; Plassmann et al., 2010). For example, Plassmann et al. (2010) found that the CF of a kilogram of sugar can vary by up to 1900% when calculated by different CF methods. By far the greatest contributor to CF variation was the treatment of land use change emissions (emissions released during the conversion of non-agricultural land to agriculture). This is of concern for agricultural production in developing countries, where contemporary conversion of land use from non-agricultural tree-dominated to agriculture is more likely than in developed countries, and where few data currently exist to enable the accurate calculation of these emissions (Brenton et al., 2009; Plassmann et al., 2010).

A second problem associated with CFs relates to the availability of relevant emission factors (EFs). In essence, CFs are calculated by multiplying the quantities of all inputs which contribute to a product's life cycle (e.g. kg fertilisers, kWh electricity, litres diesel) by their relative EF, and summing these emissions together to form the total CF. Emission factors represent the contribution of a product or process to global warming, and are expressed in units of carbon dioxide equivalents (CO₂e). Emission factors are published in commercial databases and the scientific literature, but as the majority of CF research and method-development to-date has taken place within industrialised countries there is a lack of location-specific EFs for many production systems that occur in less industrialised countries, e.g. coffee. This is a major challenge for understanding the levels of emissions from these regions.

As one of the most traded commodities in the world and with over 10 million hectares of land devoted to its production (FAO, 2011), coffee continues to be one of the most widely grown cash crops, sustaining the livelihoods of up to 25 million people globally (FAO, 2004). As a result, the coffee supply chain is an important contributor to global GHG emissions. However, whilst a major emission hotspot within the coffee supply chain has been found to lie within the production of coffee at the farm level (PCF Pilotprojekt Deutschland, 2008), its GHG emissions remain relatively understudied (Hergoualc'h et al., 2008; Verchot et al., 2006). Against this background the present study uses PAS 2050:2011 and IPCC CF methods to (i) estimate the relative GHG emissions from different levels of management and material inputs (high versus moderate) and from different types of input (organic versus conventional production systems),

(ii) identify the greatest source of GHG emissions from each system (their “emission hotspots”) and (iii) determine the effects of uncertainty in EF on the overall CF. Results from studies such as this should make an important contribution to quantifying global GHG emissions from agricultural production and designing sustainable and efficient systems that can meet human needs with a reduced environmental impact.

3.2. Methods

3.2.1. Site description

The research was conducted at two 3-ha field sites, in Costa Rica and Nicaragua respectively, chosen to represent low altitude coffee growing regions, and both managed by the ‘Centro Agronómico Tropical de Investigación y Enseñanza’ (CATIE). Both sites were established at the end of 2000. The Costa Rica site is located in Turrialba (9°53’44”N, 83°40’7”W) at 685 m above sea level. The climate is humid tropical with no marked dry season: annual precipitation is 2600 mm yr⁻¹ and annual mean temperature is 22 °C (Hagggar et al., 2011). Two soil types have been identified at the site and classified as Typic Endoaquepts and Typic Endoaquults under the USDA Soil Taxonomy classification system (Soil Survey Staff, 1999); both are poorly drained. The previous land-use was sugar cane cultivation. For establishment of the current experiment, the site was prepared with extensive drainage channels of up to 1.5 m in depth. The coffee cultivar *Coffea arabica* L. ‘Caturra’ was planted. The Nicaragua site is located in Masatepe (11°53’54”N, 86°08’56”W) at 455 m above sea level. The climate is semi-dry tropical with a distinct rainy season between May and November: mean annual rainfall is 1386 mm and mean annual temperature is 24 °C (Hagggar et al., 2011). Two soil types have been identified at the site and classified as Andisols or Andosols (Humic Durustands and Humic Haplustands) under the USDA Soil Taxonomy classification system (Soil Survey Staff, 1999). The previous land-use was long-established shaded coffee. In the experiment, the coffee cultivar planted was *Coffea arabica* var. ‘Pacas’. A more detailed description of the experiments and their productivity is reported elsewhere (Hagggar et al., 2011).

3.2.2. Experimental design

The experiments were set up to study the ecological efficiencies of coffee production. A main aim is to compare organic and conventional coffee production systems under various types of shade. The five main-plot treatments at each site are full sun and four different individual species

or combinations of shade tree (Tables 3.1 and 3.2). The four sub-plot treatments are systems combining the two different types and levels of nutrient and pest management inputs (Table 3.3). The tree species used in the experiment (Table 3.2) are selected from those most commonly grown in association with coffee production in the two regions. The design is a randomized block with three blocks per site, each containing one replicate of each treatment combination. An incomplete factorial design comprising 14 of the potential 20 main-plot/sub-plot treatment combinations at each site was chosen as some combinations are not representative of real farming systems (e.g. full sun with organic management, Table 3.1). The sub-plots range in size between 500 and 800 m² including borders. Coffee bushes were planted at a density of 4000 and 5000 plants per ha in Nicaragua and Costa Rica respectively which did not differ amongst the main-plot or sub-plot treatments. Shade trees were planted in 2000 at a density of 416 and 667 trees per ha⁻¹ in Costa Rica and Nicaragua respectively but have since been progressively thinned and pruned to achieve a uniform shade level (Table 3.1).

The tree management regime varied according to species; *Erythrina poeppigiana* in Costa Rica and *Inga laurina* in Nicaragua (both Leguminosae) were pruned for the management of shade and to provide organic matter (including N) input to soil. All *E. poeppigiana* trees were heavily pruned twice per year and their prunings left on the ground. In the conventional intensive (CI) sub-plot treatments of *E. poeppigiana*, trees were pruned at a height of 1.8-2.0 m with the removal of all branches above this height (pollarding). This practice is frequently found in conventional high-intensity coffee agroforestry systems in Costa Rica. In the other three sub-plot treatments, however, *E. poeppigiana* trees were managed according to the recommendations of Muschler (2001) whereby trees were pruned at a height of around 4 m and a minimum of three branches were left for partial shade cover. In Nicaragua, *I. laurina* was managed to create a homogeneous canopy cover of approximately 40%, through annual pruning of branches at any height, accounting for overall smaller pruning residue inputs compared with *E. poeppigiana* in Costa Rica. In contrast, the timber tree species were managed to promote the development of a straight trunk and thus maximise timber value but were not subjected to a systematic pruning regime. Trunks and major branches of thinned and pruned timber trees were removed from the plots whereas leaf and small branch material was left as an organic amendment. All the material pruned from coffee bushes was also left in the plots (coffee bushes were pruned according to standard coffee agronomic practice, to the same level across all treatments).

3.2.3. Calculation of carbon footprints

PAS 2050 (BSI, 2011) is the only transparent and publically available product CF method published to-date and has therefore been chosen here for all CF calculations. Although other GHG accounting methodologies at the time of the study existed (e.g. IPCC guidelines on National Greenhouse Gas Inventories) these were not deemed appropriate to calculate the CF of this particular product. Within this method, all GHGs (including CO₂, N₂O and CH₄) are accounted for and converted into units of CO₂-equivalents (CO₂e) according to their global warming potential (GWP) over 100 years. All GHG emissions associated with the provision and use of raw materials and energy are included in the calculation. Capital goods, human energy inputs such as manual labour, transport of employees to and from the workplace and animals providing transport are excluded from PAS 2050. Of specific relevance to agricultural CFs are non-CO₂ emissions from livestock, their manure and soils, which must be included, calculated according to IPCC Guidelines for National GHG Inventories (De Klein et al., 2006). Nitrous oxide emissions from soils are accounted for by including direct and indirect emissions resulting from N additions, deposition and leaching. As all land under study here was in agricultural production prior to 1990, no direct emissions from land use change (LUC) have been included. Changes in soil carbon, either as emissions, sequestration or in eroded material, are excluded from PAS 2050 unless they are a direct result of LUC activities. Carbon stored in living organisms such as trees or perennial crops is excluded from the PAS 2050 method; therefore if LUC results in net carbon storage, no recognition is given by way of a reduced CF. Although this is of particular relevance to agroforestry systems with perennial crops such as coffee, which have been shown to provide long-term carbon stores in shade-tree and crop biomass (Segura et al., 2006; Dossa et al., 2008), currently these gain no recognition for their net carbon storage benefit when compared, for example, with coffee grown in full sun or with annual crops.

3.2.4. Data Collection

As the aim of this study is to compare emissions from different farming methods, the system boundaries were drawn at the farm gate, including only those emissions directly associated with the production and management of a particular system. Carbon footprint calculations for each system were based on annualised averages of all inputs and yields since the second year of coffee production, to best represent the different production systems. The functional unit (unit of production) was set at 1 kg of non-processed fresh coffee cherries.

Data on coffee yields, management and material inputs were recorded for all sub-plot treatments. For both conventional managements (Table 3.3), emissions from the production of inorganic fertilisers and pesticides were extracted from the Ecoinvent database (Nemecek et al., 2007). For all four sub-plot management treatments, only commercial fertiliser and pesticide products were assigned production emissions; PAS 2050 states that emissions should be assigned according to a product's economic value rather than its mass, thus the production emission from one industry (e.g. chicken farming) should be partitioned between its products (e.g. chicken meat and manure) according to their respective commercial values. In the case of these coffee production systems, however, organic fertilisers such as chicken manure and coffee pulp were assumed to be waste products of another industry with no economic value, and thus were assigned no production emissions. Furthermore, although data on GHG emissions from poultry manure can be found within the Ecoinvent database, we considered these values excessive for this study as the database values include processing emissions from drying, granulation and packaging (Nemecek et al., 2007) which are not part of the manure production process in Costa Rica or Nicaragua.

Emissions were calculated for the transportation of materials and fertilisers from their place of purchase to the on-farm experimental sites; to allow for comparability a default transport distance of 10 km was chosen for both sites. Emissions arising from the production and use of fuels such as gasoline and lubricants, used mostly for weed control, and materials and sundries used in the farm management of the experimental sites were also included in the calculations. Emission factors for the production and manufacturing processes of individual inputs were obtained from the publically available database of the Renewable Fuels Agency (RFA) and Ecoinvent (Althaus et al., 2007; Classen et al., 2009). Costa Rica-specific EFs for diesel and gasoline were sourced from a report used in the Costa Rican national GHG inventory (Ministerio de Ambiente y Energía de Costa Rica, 2007) and used for both countries' footprints. No electricity was consumed in the on-farm operations.

For calculating N₂O emissions from soil we followed IPCC Good Practice Guidelines for calculating GHG emissions (De Klein et al., 2006) and chose a regional-specific EF (Table 3.1) from Costa Rica for N fertiliser application of 1% for timber-tree and full-sun coffee production systems established by Hergoualc'h et al. (2008), 1.2% for leguminous-shade systems and a value from the same study of 0.3% for N applications from pruning inputs (Hergoualc'h pers. comm.). To assess the effects of using different EF's on the overall CF we compared the results of (i) using the IPCC tier 1 default value of 1% for all N inputs (scenario 1) (De Klein et al., 2006), (ii) using a region-specific EF (scenario 2) and (iii) excluding emissions from pruning inputs (scenario 3) (Hergoualc'h et al., 2008). N contents of pruning residues, needed to calculate soil

N₂O emissions, were obtained from analyses carried out at the Laboratorio de Análisis de Suelos, Tejido Vegetal y Aguas at CATIE, in Costa Rica.

3.2.5. Statistical analysis

To investigate the relationship between main-plot and sub-plot treatment effects on individual CFs in the experiment and to avoid problems commonly associated with e.g. stepwise multiple regression such as bias in parameter estimation, inconsistencies among model selection algorithms and an inappropriate focus on a single best model (Whittingham et al. 2006) we fitted linear mixed effects models in R (R Development Core Team, 2010) using the lme4 package (Bates et al., 2011). Main-plot/sub-plot treatment combinations were fitted as a factor with 15 levels for each country (model 1: fixed effects = main-plot + sub-subplot; model 2: fixed effect = main-plot; model 3: fixed effect = sub-plot). Results were assessed using the Akaike Information Criterion (AIC, Burnham and Anderson, 1998), and the model presenting the smallest AIC selected.

Table 3.2 Shade tree species used in the main-plot experimental treatments in the sites in Costa Rica and Nicaragua

	a) Costa Rica		b) Nicaragua			
Species	<i>Terminalia amazonia</i> (J.F. Gmel.) Exell	<i>Chloroleucon eurycyclum</i> Barneby & J.W. Grimes	<i>Erythrina poeppigiana</i> (Walp.) O.F. Cook	<i>Inga laurina</i> (Sw.) Willd.	<i>Samanea saman</i> (Jacq.) Merr. DC.	<i>Simarouba glauca</i> (Bertol.) DC.
Phenology	evergreen	evergreen	evergreen	evergreen	evergreen	deciduous
N-fixer	no	yes	yes	yes	yes	no
Dominant use	timber ¹	timber ¹	service ²	service ²	timber ¹	timber ¹

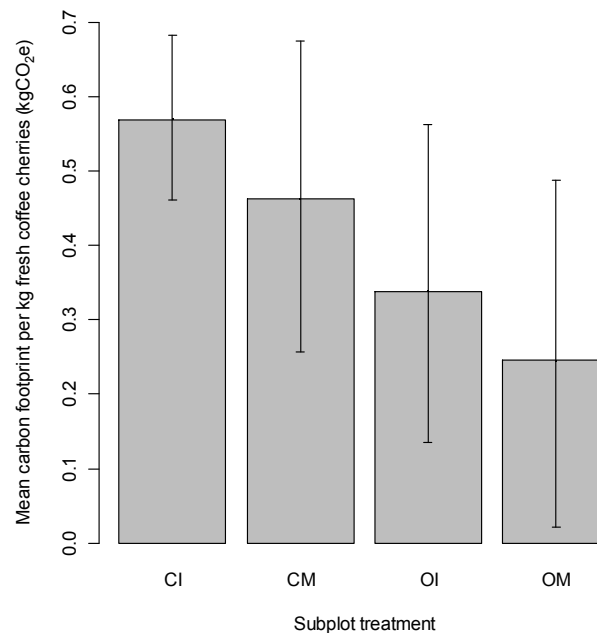
¹'timber' = 'shade trees that are managed for their timber; ²'service' = shade trees that are managed for their 'services' to coffee production, e.g. N-fixation, organic matter inputs.

3.3. Results

3.3.1. Carbon footprinting of different management systems

The best fitting model for predicting carbon footprints from the main-plot and sub-plot treatments of the experiments is model 3 based on only sub-plot treatments as a fixed effect with random slope effects of replicate blocks and main-plot treatments nested within replicate blocks (the AIC values for this model for Costa Rica and Nicaragua were respectively -32.4 and -66.0; in comparison those for model 1 were -13.6 and -49.5, and for model 2 were -4.0 and -35.6 respectively). This shows that management system and input level (the sub-plot treatment) accounts for most variation in CFs amongst the treatments in the experiment with little remaining variation explained by shade type (the main-plot treatment). This is reflected in their relative coefficients of variation between treatment mean values (CV is 0.17 and 0.18 amongst the sub-plot treatments and only 0.03 and 0.08 amongst the main-plot treatments for Costa Rica and Nicaragua respectively). Interactions between main-plot and sub-plot treatments cannot be tested separately for each of the experiments as a whole because of the incomplete factorial design. Therefore, results presented here are largely aggregated at the sub-plot level (Figure 3.1 and Table 3.4).

a) Costa Rica



b) Nicaragua

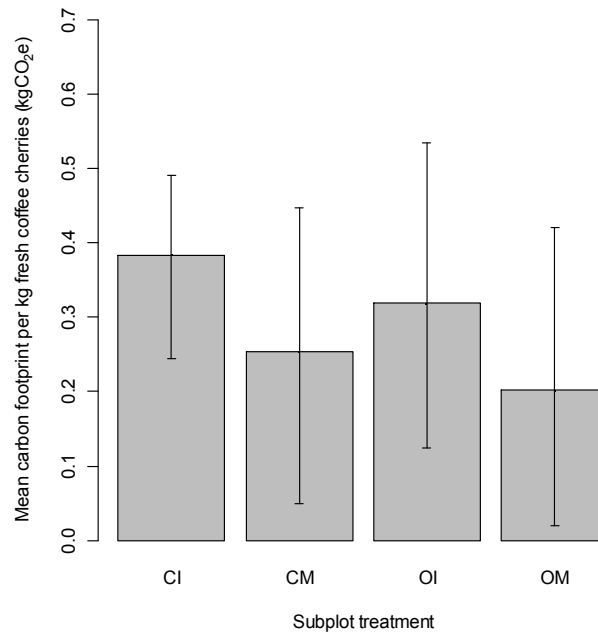


Figure 3.1 Mean coffee product carbon footprints based on model predictions for four sub-plot treatments across five main-plot shade treatments and three replicate blocks in a) Costa Rica and b) Nicaragua. Conventional intensive (CI); Conventional moderate (CM); Organic intensive (OI); Organic moderate (OM). The bars represent the mean CF per kg of fresh coffee cherries (kg CO₂e); whiskers indicate the upper and lower boundaries of the 84% confidence interval values (appropriate for judging significance of differences at $p < 0.05$).

Nonetheless, for both countries, based on non-overlap of 84% confidence intervals of sub-plot intercepts for the best-fit model (Payton et al., 2003), there were no significant differences at the $p < 0.05$ level amongst the sub-plot treatments (Figure 3.1). However, in Costa Rica there was a notable trend in the association of CF with management type (conventional versus organic) followed by input level, with the conventional intensive (CI) treatment showing the highest mean CF, followed by conventional moderate (CM), then organic intensive (OI) and finally organic moderate (OM). In Nicaragua, the positive association with level of inputs was dominant over management type: the highest mean CF was again shown by the CI sub-plot treatment, but it was followed by OI, and then CM and, again last, OM.

Direct and indirect soil N₂O emissions account for a high proportion of the total product CF (average of 67% across treatments) and are therefore highly correlated with total CF for both conventional and organic management systems (Figure 3.2). These emissions result from inorganic and organic fertilisers and from pruned material from coffee bushes and shade trees (Appendix 3, Tables A3.1 and A3.2). Nitrogen inputs vary considerably across the main-plot/sub-plot treatment combinations due to variation in pruning inputs from shade trees and in coffee bush management

(Tables 3.2 and 3.3). The significantly steeper (CF/soil N₂O emissions) slope of the conventional than organic treatments is due to the fact that soil N₂O emissions form a greater proportion of the CF for the organic treatments.

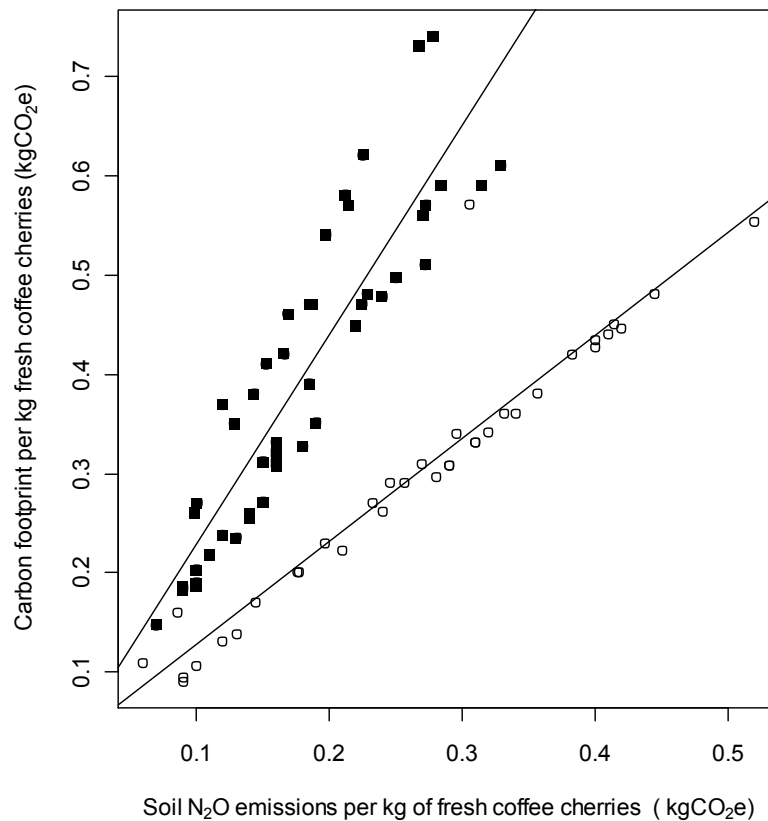


Figure 3.2 Relationship between soil N₂O emissions (direct and indirect) resulting from applications of organic and inorganic N in fertiliser and prunings and the overall carbon footprint of conventional (■) and organic (○) coffee management treatments in Costa Rica and Nicaragua. Fitted lines: $y_{conventional}(CF) = 0.031 + 2.03$ (kg CO₂e); $y_{organic}(CF) = 0.007 + 1.11$ (kg CO₂e). There was no significant difference between the intercepts but there were significant differences in the slopes between conventional and organic management systems (as judged by the non-overlap of 84% confidence intervals of sub-plot intercepts for best-fit model predictions), highlighting a significant difference between the two groups.

3.3.2. Carbon footprint emission ‘hotspots’

The main CF emission hotspots for the conventional management treatments in both countries were from fertiliser production and direct and indirect soil N₂O emissions from fertiliser N inputs (Table 3.4). Emissions from fertiliser production accounted for 50% and 45% of the CI and CM footprints respectively, averaged across both countries. The main CF emission hotspots for the organic management treatments were direct and indirect soil N₂O emissions, resulting from applications of organic fertiliser (such as chicken manure or coffee pulp) and prunings. Soil N₂O

emissions accounted for 92% and 82% of the CF for OI and OM treatments respectively, averaged across both countries, in contrast to only 45% and 47% for CI and CM treatments respectively. The contribution of N₂O emissions specifically from pruning inputs varied greatly amongst the four treatments ranging from 7% in CI to 42 % in OM. The lower yields of coffee cherries with moderate (OM) compared to high input (OI) organic management (Table 3) resulted in soil N₂O emissions from pruning residues accounting for 1.6 and 1.4 times higher CF per kg of coffee cherry yield in the OM than the OI treatments in Costa Rica and Nicaragua respectively. Similarly, between the different shade types, in Costa Rica emissions from pruning residues were highest with *E. poeppigiana* (Appendix 3, Table A3.1) at 0.14 kg CO₂e per kg of coffee cherries (averaged across all sub-plot treatments), followed by mixed legume and timber trees (ET) with 0.08 kg CO₂e, timber trees (C, T) with 0.01-0.02 kg CO₂e and lowest was full sun (FS) at 0.01 kg CO₂e (Appendix 3, Table A3.2).

In Nicaragua a similar trend was detected with the highest emissions from pruning residues arising in the mixed legume and timber tree types (ILSG, ILSS) with 0.04-0.05 kg CO₂e per kg of coffee cherries followed by timber trees (SGTR, SSTR) with 0.02-0.03 kg CO₂e and full sun was again the lowest with 0.02 kg CO₂e per functional unit (Appendix 3, Table A3.2). The main difference in emissions from pruning residues between the countries however is due to the fact that these are smaller in quantity in Nicaragua compared with Costa Rica. A more detailed description of pruning residue inputs within the experiments can be found in Hagggar et al. (2011).

3.3.3. Impact of different emission factors and the importance of pruning residues

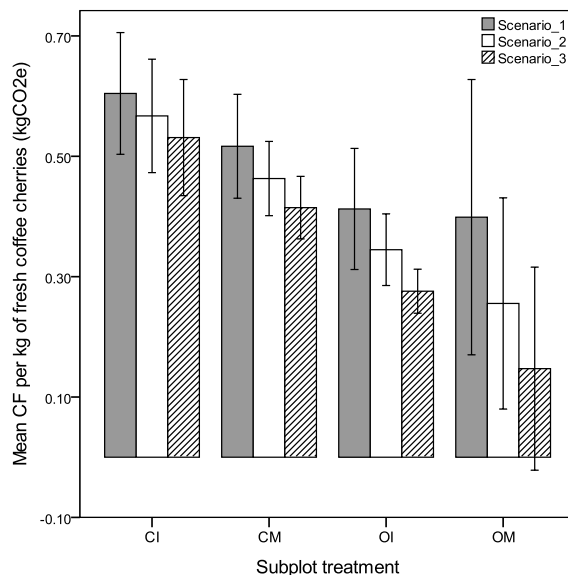
Nitrous oxide emissions released from soils following the addition of fertilisers are commonly estimated using global, rather than location-specific, EFs. However, soil N₂O emissions from pruning inputs are often overlooked completely in CF analyses. To explore their impact on system CFs we calculated the mean CF of the four sub-plot coffee management treatments in each country using three different EFs for the soil N₂O emissions resulting from fertiliser and pruning inputs. Using each of the three different EFs produced a similar trend in CF amongst all four sub-plot treatments in both countries. The greater variation between the EFs for organic (24-244%) than for conventional (14-40%) management (Figure 3.3) was mainly due to the effect of inputs of pruned material.

Table 3.4 Mean greenhouse gas emission contributions ($\text{kg CO}_2\text{e t}^{-1}$ fresh cherries, $\pm\text{SE}$) of each emission category to the total product carbon footprint, for the four sub-plot treatments (Conventional intensive (CI); Conventional moderate (CM); Organic intensive (OI); Organic moderate (OM)) for a) Costa Rica and b) Nicaragua. The emissions are shown on a per land area per time basis in Appendix 3, Table A3.1.

Country	Sub-plot management treatments	Fertiliser production	Pesticide production	Fuels (used for non-transport purposes)	Materials and sundries	Transport	Direct/indirect soil N ₂ O emissions from fertiliser application	Direct/indirect soil N ₂ O emissions from pruning inputs	Total
a) Costa Rica	CI	305 (± 25)	30 (± 3)	¹ - ²	- ²	- ²	196 (± 14)	35 (± 12)	567 (± 41)
	CM	227 (± 13)	13 (± 1)	19 (± 1)	- ²	- ²	152 (± 9)	50 (± 14)	463 (± 29)
	OI	7 (± 0)	- ²	20 (± 1)	- ²	- ²	244 (± 15)	69 (± 18)	345 (± 27)
	OM	10 (± 4)	15 (± 7)	51 (± 23)	4 (± 2)	3 (± 1)	65 (± 28)	108 (± 30)	256 (± 68)
b) Nicaragua	CI	162 (± 16)	12 (± 1)	- ²	- ²	- ²	147 (± 15)	25 (± 4)	347 (± 36)
	CM	103 (± 6)	13 (± 1)	- ²	- ²	8 (± 8)	93 (± 6)	36 (± 4)	255 (± 18)
	OI	18 (± 1)	- ²	- ²	- ²	5 (± 0)	303 (± 21)	32 (± 4)	359 (± 26)
	OM	- ²	- ²	- ²	3 (± 1)	4 (± 1)	94 (± 22)	45 (± 10)	145 (± 34)

¹In Costa Rica CI weed control was managed with chemical herbicides applied manually. ²Emissions are considered here to be negligible if $< 1\%$ of total CF. Sub-plot treatments in a) Costa Rica (CI, n = 9; CM, n = 15; OI, n = 12; OM, n = 6) and b) Nicaragua (CI, n = 9; CM, n = 15; OI, n = 12; OM, n = 6).

a) Costa Rica



b) Nicaragua

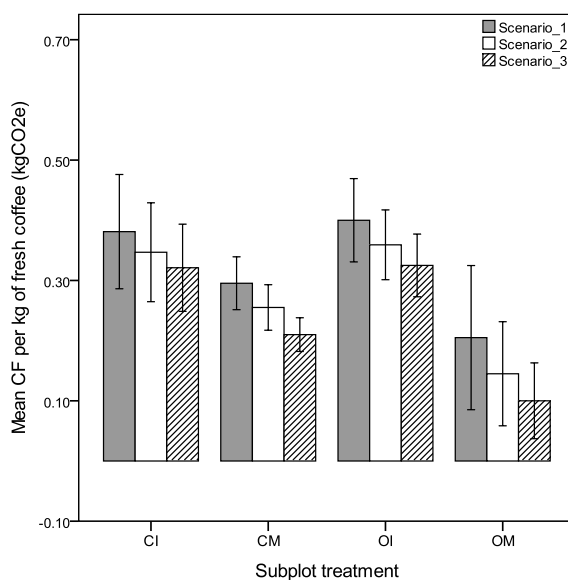


Figure 3.3 Mean carbon footprint (kg CO₂e) for all main-plot treatment x sub-plot treatment combinations over the three replicate blocks for a) Costa Rica and b) Nicaragua using three different emission factor scenarios (as described in the Methods section); scenario 1 (■), scenario 2 (□), scenario 3 (▨). Bars represent the mean CF per kg of fresh coffee cherries (kg CO₂e); whiskers indicate the upper and lower boundaries of the 84% confidence interval values.

Scenario 1, which is based on IPCC tier 1 global default values for calculating direct and indirect soil N₂O emissions, does not distinguish between organic, inorganic or pruning/crop residue inputs; it assumes that 1% of applied N in all the residues is lost as emissions. Scenario 1

produces a greater mean CF than that from scenario 2, which uses the region-specific lower value of 0.3% for the proportion of N applied to the soil in pruned material that is emitted as N₂O. Scenario 3, which uses the same N fertiliser EFs as scenario 2 but omits soil N₂O emissions from pruning inputs, produced the lowest CF across all treatments with the greatest reduction in OM sub-plots. Overall, the choice of EF did not change the rank order of CFs across the four management treatments in either country. However, the effects of EF choice are more marked in the organic management treatments because N₂O inputs from pruning inputs form a comparatively large proportion of their CF. Further, high variability in CF between main-plot shade treatments is observed for both of the organic sub-plot treatments in Costa Rica in the scenario 1 calculations due to the comparatively large contribution to the CF of pruning inputs from the fast-growing leguminous shade tree *E. poeppigiana* with a 1% EF.

3.4. Discussion

3.4.1. Effect of coffee system management on carbon footprint

In Costa Rica and Nicaragua together, coffee cultivation covered over 212,000 ha of land in 2010 (FAO, 2011), making it a significant contributor to both countries' agricultural GHG balance. Results from this study found that the carbon footprint per kg of coffee production increased with higher levels of management input in both conventional and organic systems in both the Costa Rican and Nicaraguan experiments. The type of farm management was found by the mixed effects models to account for most variation in CFs. By intensifying coffee farming systems within the experiments, GHG emissions per unit output are increased for conventional and organic treatments.

However, no general conclusion can be made about the comparative CF of organic and conventional systems because the results differed between the two countries. While the organic moderate intensity (OM) treatment had the lowest CF in both countries, the organic intensive (OI) treatment in Nicaragua had a slightly higher mean CF than the conventional moderate (CM) treatment, whereas in Costa Rica it was lower. This difference between the countries is associated with the variation in local implementation of 'conventional' and 'organic' systems. In Nicaragua, the OI management had higher N inputs than the three other management systems, whereas in Costa Rica, total inputs of organic and inorganic N reduced from the CI to CM to OI to OM management (Table 3.3). To determine the effects of organic compared to conventional systems on the carbon footprint it would be necessary to evaluate the N-use efficiency of the two management strategies at the same level of inputs.

Although the mixed effects model selection procedure showed that shade type had little overall influence on total CF, there were notable differences in the calculated N₂O emissions associated with their prunings, which were highest from the heavily pruned legume shade trees (Appendix 3, Table A3.2), even when accounting for the differences in EF used between leguminous and non-leguminous shade (the change in the overall CF for the highest pruning residue input system ECI due to a change in EF from 1.2% to 1% of N, is less than 5%). Hergoualc'h et al. (2008) concluded that annual N₂O emissions from a legume-shaded tree system of coffee were 1.3 times higher compared with an un-shaded coffee monoculture. With leguminous shade trees contributing 60-340 kg N ha⁻¹ yr⁻¹ through pruning residues in coffee agroforestry systems (Beer, 1988), the resulting soil N₂O emissions can account for a significant part of the CF. This is reflected in the present study; relative N₂O emissions per unit of coffee production from pruning residues were 84% and 33% lower for timber shade tree only treatments compared with those using the heavily pruned leguminous shade trees (E and IL) in Costa Rica and Nicaragua respectively (Appendix 3, Table A3.2). For FS treatments the emissions were 92% and 63% lower than those with the heavily pruned leguminous trees respectively (Appendix 3, Table A3.2). This underlines the importance of quantifying the different factors that contribute to overall coffee production system greenhouse gas emissions to provide a broader knowledge base to differentiate the emission factors associated with different N₂O sources.

3.4.2. Emission 'hotspots'

In the intensive and moderate input organic coffee management treatments in Costa Rica, and all four management treatments in Nicaragua, N₂O emissions from soil were the greatest emission hotspot. These emissions stem from the application of mineral and organic fertilisers to the soil, and from decomposition of pruning residues where applicable. This is in-line with findings from studies of other crops such as by Plassmann et al. (2010) and Röös et al. (2010) who found that N₂O emissions form the largest portion of the CF of a sugar cane farm in Mauritius and a potato farm in Sweden, respectively. Despite coffee's global significance economically and agro-ecologically, there appears to be only one study published to-date which has analysed the GHG emissions from its cultivation; this pilot study of two coffee estates in Tanzania found that the production and transport of agrochemicals formed over 79% of the CF of coffee production and primary processing (PCF Pilotprojekt Deutschland, 2008). This is comparable with findings from the intensive and moderate input conventional management systems in Costa Rica in the present study, where fertiliser and pesticide production combined accounted for ≥ 50% of the

CF (Table 3.4). However, the N₂O emissions resulting from N fertiliser application were calculated to be much higher in the present study than those in Tanzania. This may be because the present study includes direct and indirect N₂O emissions from soils, whereas the Tanzanian pilot study only included direct emissions (PCF Pilotprojekt Deutschland, 2008). Furthermore, for the two organic management systems of the present study, emission hotspots were dominated by release of N₂O from soils, with virtually no emissions included from fertiliser production because the fertilisers used are by-products or wastes of other industries. Although the organic fertilisers used in these experiments contained relatively small percentages of N, they were applied in large quantities – up to 10 tonnes of chicken manure and 7.5 tonnes of coffee pulp per ha per year in the intensive organic management. As a result, while in the intensive organic treatment soil N₂O emissions were largely caused by application of these organic fertilisers, in the moderate input organic management, over half the N₂O emissions resulted from pruning inputs from the shade trees and coffee bushes (Table 3.4).

There is significant scope for managing farm-level GHG emissions through improved planning of N application, and this should be seen as a priority by farm extension workers when making recommendations for climate-friendly farming systems. Examples of such GHG-mitigating actions include switching from urea to use of fertilisers with lower rates of nitrification such as ammonium nitrate; improved timing of N application, taking into account crop requirements, weather patterns and availability of mineral N in the rooting zone, so that N is applied at times of greatest demand by the plant; and subsurface application of fertilisers to reduce losses of NO (Matson et al., 1996; Skiba et al., 1997; Smith et al., 1997). However, currently the methods used to calculate the CF would not differentiate between these management practices, and research is needed to quantify their impacts on N₂O emissions and develop appropriate emission factors associated with these practices. Any recommendations requiring capital investment or a change in farming practice will need wider support in order to encourage farmer uptake, and indeed further research on improving the efficiency of both organic and mineral fertiliser use should be seen as a priority in order to determine optimal fertiliser management mechanisms (Tilman et al., 2002).

3.4.3. Choice of emission factors

It is clear from this study that, for coffee production CFs, the accuracy of EFs used to calculate direct and indirect N₂O emissions from soil is important; within the production systems analysed here, N₂O emissions formed between 45% and 92% of the total CF, making them the single

largest source of emissions in the organic management treatments and the second largest emissions source in the conventional treatments. As a result, using different EFs for calculating N₂O emissions had a large effect on CFs, with CF varying by between 14 - 244% depending on the EF used for individual coffee management treatments (Figure 3.3). Three categories of soil N₂O emissions are commonly accounted for: direct emissions from N-fertilisation of soils, ‘secondary’ emissions resulting from various transformations of N compounds, and indirect emissions resulting from leaching and volatilisation of deposited N (Smith et al., 2010). ‘Secondary’ emissions include those produced by application of crop residues or pruning material, dung and urine from livestock to the soil, and N mineralisation from soil organic matter and root residues (Smith et al., 2010). In the IPCC tier 1 methodology (scenario 1 in the present study), however, no differentiation is made between direct emissions from N-fertilised soils and secondary emissions from crop residues or pruned material, as both are given the same EF. Further, its value of 1% for direct N₂O emissions has a large uncertainty of 30-300% depending on localised variables such as climate, soil properties and the quality of the incorporated material (De Klein et al., 2006). Therefore, calculating a farm’s CF with this global IPCC tier 1 N₂O emissions factor can introduce significant error, and indeed its use will not enable the estimation of emission reductions resulting from actions such as improved N use efficiency, as outlined in section 3.4.2.

In tree-based agricultural systems, and in particular in coffee agroforestry systems in which shade-tree prunings contribute a significant proportion of “crop residues”, the choice of EF can have a large influence on the overall CF result as shown in Figure 3.3. Here, we found that the heavily pruned leguminous tree species (*E. poeppigiana* and *I. laurina*) had much higher relative emissions from pruning residues per kg of fresh coffee cherries than other shade types (Appendix 3, Table A3.2). However, the complexity and interaction of variables influencing soil N₂O emissions is vast and, because of their major importance for the specification of accurate EFs, they should be a priority for further research to underpin improved carbon footprinting. Factors found to affect N₂O release from pruning residues include: the presence of N-fixing tree species (Hergoualc'h et al., 2008; Verchot et al., 2008), the quality or chemical composition of plant residues (Seneviratne, 2000; Baggs et al., 2001; Millar and Baggs, 2005) including specifically its C:N ratio (Millar and Baggs, 2004), the interaction between residues and inorganic fertilisers (Frimpong and Baggs, 2010), and the timing of pruning relative to plant nutrient demand and supply (Mosier et al., 2004). However, there is a lack of published literature to enable the accurate calculation of N₂O emissions from tropical agricultural systems (Matson et al., 1996; Erickson et al., 2001; Mosier et al., 2004) and indeed the IPCC default EF is based

heavily on data from temperate and subtropical zones rather than from tropical regions (Stehfest and Bouwman, 2006).

3.4.4. Implications for carbon footprinting methodology

So far, carbon footprinting in agricultural systems has neglected the role of shade trees (often used in coffee cultivation) in sequestering significant amounts of C, even beyond the lifetime of the crop. Indeed, carbon storage in living biomass is omitted from the UK carbon footprinting specification, PAS 2050:2008 (BSI, 2008), and its recent revision (BSI, 2011) only gives credit for carbon stored in biomass when that carbon is sequestered as a direct result of land use change occurring in the past 20 years. Importantly, 'land use change' is defined here as a change from one land use type (e.g. forestry) to another (e.g. agriculture), therefore the addition (or removal) of trees within a coffee farm during its lifetime would not be recognised as a form of land use change, thus the resulting change to farm GHG balance would not be included in the carbon footprint. In the case of shade-grown coffee, however, trees tend to be planted as a result of coffee farming taking place, thus stored carbon in these systems arises as a direct result of the agricultural production system and should be recognised within the farm GHG balance calculation. To allow for more representative analyses of agricultural systems, a full balance based on emitted and sequestered carbon should be calculated, using the carbon footprinting method followed in this study but including C sequestration and emissions from biomass and soil. Sequestration of C in some shade systems could outweigh their emission costs resulting in a net C-balance benefit and potentially making the whole production system carbon neutral over its life span.

3.5. Conclusions

Carbon footprinting enables improved understanding of the most important GHG emission hotspots within a food supply chain. This will help in developing systems which achieve higher agricultural productivity without a proportionate increase in emissions (or lower emissions without a proportionate reduction in productivity). The results of this study highlight the importance of determining which impacts and variables are relevant in calculating the net environmental efficiency of agricultural production systems. While the moderate intensity organic coffee management system had the lowest CF per kilogramme of coffee produced it also had substantially the lowest yield of coffee per hectare. Maintenance of the overall level of production from such systems with low GHG emissions but also low yield per unit area would

require conversion of more land to coffee production, locally or elsewhere, but if this land was converted from forest or grassland this would result in additional emissions. This emphasises the potential conflict between increasing food production and creating incentives for climate change mitigation (Angelsen, 2010), which CF methodology needs to encompass.

Identifying emission hotspots through carbon footprinting enables the targeting of farm management recommendations to reduce the impact of agricultural production on GHG emissions. For six of the eight coffee management systems studied here, N₂O emissions from soil were the greatest contributor to coffee production CFs, for the other two systems fertiliser production made a larger contribution. This indicates the value of improvements in fertiliser use efficiency for mitigation of agricultural GHG emissions on coffee farms.

While methodologies such as those of the IPCC are important in standardising estimation of the contribution of overall N₂O emissions to the CF for gross system comparisons, in order to compare CFs of different supply chains, accurate emission factors have to be used for each, as demonstrated by the large variability in CF found when using different EFs for calculating N₂O emissions. However, for products such as coffee, originating in developing countries, despite their huge global impact, there is a shortage of evidence to enable calculation of EF for different sources and management of nitrogen inputs which are locally specific. Although much has been published on soil N₂O emissions from agricultural systems, a more detailed understanding of the underlying processes is needed, particularly in tropical regions. Our research supports the conclusions of Smith et al. (2010) that the link between input parameters and release processes is a research priority in order to recommend changes in agricultural management that will reduce emissions. In particular, we recommend new research into the effects of practices aimed to improve N use efficiency, not only on soil N₂O emissions, but also nitrogen use efficiency of coffee production.

Chapter 4

Intensification of coffee systems can increase the effectiveness of REDD mechanisms

Submitted as:

Noponen, M.R.A., Hagggar, J.P., Edwards-Jones, G., Healey, J.R., Intensification of coffee systems can increase the effectiveness of REDD mechanisms. *Agricultural Systems*.

4.1. Introduction

Agricultural production and land-use change (LUC) together can account for almost one-third of global emissions of greenhouse gases (GHG) (IPCC, 2007c). Climate change mitigation strategies in these areas have therefore become an integral part of sustainable development thinking and planning. Identifying GHG emission hotspots and finding appropriate reduction solutions is, however, not the only challenge: global population has more than doubled in the past 50 years and with it demand for food (FAO, 2011). Historically, food supply and demand have tracked each other (Kendall and Pimentel, 1994) but this is no longer the case with global crop yields increasing at a slower rate than global population growth (Trostle, 2008). The agricultural sector therefore needs to address these multiple needs aiming at the improvement of food security, productivity, climate change mitigation and the sustaining of livelihoods. Projections by the United States Department of Agriculture (USDA) on the development of food prices over the next decades predict no decline in the current high and this could incentivise farmers to convert additional non-crop land, such as secondary (or even primary) forests, into agricultural production (Trostle, 2008). Although increases in food production have raised the average global calorific per capita food supply, the pressures of increased food demand through dietary changes and population growth are rising, especially in low-income countries (FAO, 2011). In turn, pressure on land availability is mounting, leaving forests in tropical regions more vulnerable (IPCC, 2007c; Malhi et al., 2008). Recent studies have emphasised the importance of increasing agricultural yields through high intensity production systems, to meet continually increasing global demand for food and agricultural commodities and to reduce

carbon (C) loss through LUC (West et al., 2010). Moreover, global emissions from LUC for agricultural production are likely to outweigh those from agricultural intensification, which is estimated to have resulted in a net C emission reduction of 590 GtCO₂e globally since 1961 due to avoided land use conversions (Burney et al., 2010). Many stakeholders, however, consider standing forests (especially secondary forests) to be less valuable than alternative land uses and therefore they are under threat of deforestation through land conversion to agriculture (Murdiyarso et al., 2010).

The intricate link between agricultural production and deforestation has been a driver for programmes such as “Reduced Emissions from Deforestation and Forest Degradation” (REDD), where financial mechanisms are used as incentives for not converting forests to other uses. Although individual REDD projects are often seen as a potential source of income (Laurance, 2007; Tollefson, 2008), in their design it will be paramount to assess not only profitability but also the potential for indirect GHG emissions through so-called “leakage”. With the arrival of REDD+ programs as an all-encompassing framework under which many global efforts ranging from climate change mitigation to poverty alleviation are now being placed, the debate around trading C for agricultural commodities has gained new momentum. However, concerns about financial viability and competitiveness of REDD+ projects (Butler et al., 2009), and their potential to address drivers of deforestation, are being voiced. Their wider success (including aspects of sustainable development, biodiversity conservation and protection of existing forest lands) may depend on intensification of existing agricultural land coupled with explicit policy intervention (Ewers et al., 2009). Activities that address the causes of deforestation, at the same time as presenting a viable financial alternative within existing global markets and the right policy framework, will therefore greatly assist the success of REDD+ programs.

It has been suggested that coffee farming could be considered for qualification under REDD+ activities (Soto-Pinto et al., 2010). Perennial agricultural production systems, especially those including trees such as coffee systems, have the unique potential to sequester and store relatively large amounts of C in aboveground biomass and in soil organic matter (Albrecht and Kandji, 2003; Dossa et al., 2008; Kandji et al., 2006; Mutuo et al., 2005; Segura et al., 2006; Soto-Pinto et al., 2010; Verchot et al., 2007). The C sequestration potential of agroforestry systems has long been documented and is often seen as an attractive option to combine climate change mitigation with adaptation of agricultural production and poverty alleviation (Mutuo et al., 2005). For agroforestry products such as coffee and cocoa, gross C sequestration could even out-weigh GHG emissions, making them carbon-neutral or even carbon-negative systems throughout their

productive lifetime. Coffee production, however, depends on a combination of regional environmental variables such as temperature, precipitation, altitude and soil properties as well as more system-specific variables such as shade tree species, shade density and management inputs. Indeed, enhancing standing biomass stocks to increase biological C sequestration and thus enable benefit from verified C credits could adversely affect the performance of coffee production systems. Nevertheless, with over 10 million hectares of tropical land devoted to coffee production (FAO, 2011), the coffee supply chain is also an important contributor to global GHG emissions. Environmental performance of agriculture (e.g. when changing systems to reduce emissions) will have to be weighed against a number of other factors such as productivity, profitability and land availability.

This study evaluates the trade-off between profitability and climate change mitigation potential through a comparative analysis of a number of coffee production systems within a long-term experiment in Costa Rica, by comparing different management systems under a range of shade tree types. We further explore how intensification affects the overall C balance and profitability within shaded coffee production systems.

We firstly assess the impact of intensification on the relationship between system productivity and GHG emissions. Secondly, we investigate the extent to which C sequestration into biomass offsets the GHG emissions from agronomic management in determining the difference in overall C balance amongst the systems. We then calculate the price (in foregone revenue from coffee production) of avoiding GHG emissions by retaining existing shaded coffee systems rather than converting to more productive intensive systems excluding non-market costs and benefits. The final analysis investigates the implications of LUC between forest and agriculture for the net impact of intensification versus extensification of coffee production on GHG emissions. This is done by calculating the LUC emissions associated with extensification, caused by the expansion of a less productive coffee system onto currently non-agricultural, forested land to compensate for the shortfall in profitability due to retaining lower productivity coffee systems. The net impact of these two components on GHG emissions is calculated. This study hereby aims to inform the debate around the role of agricultural production in climate change mitigation strategies with implications for current C market mechanisms.

4.2. Methods and materials

4.2.1. Site description

The research was conducted at a 3-ha field site at Centro Agronómico Tropical de Investigación y Enseñanza (CATIE), Turrialba, Costa Rica (9°53'44"N, 83°40'7"W) at 685 m above sea level, chosen to represent the low altitude coffee growing region.

4.2.2. Experimental design

The experiment was set up to compare organic and conventional coffee production systems under various types of shade. The main-plot treatments are full sun (FS) and four different individual species (*Erythrina poeppigiana* (E); *Chloroleucon eurycyclum* (C); *Terminalia amazonia* (I)) or combinations (*E. poeppigiana* + *T. amazonia* (ET)) of shade tree. The tree species were selected from those most commonly grown in association with coffee production in the region. The four sub-plot treatments combine different types (conventional and organic) and levels (intensive and moderate) of nutrient and pest management inputs (Tables 3.1 and 3.2 in Chapter 3). An incomplete factorial design comprising 14 of the potential 20 main-plot/sub-plot treatment combinations was chosen (Table 3.3 in Chapter 3), as some combinations are not representative of real farming systems (e.g. FS with organic management). The design is a randomized block with three blocks and one replicate of each treatment per block. The experiment was monitored for nine years (2000-2009).

4.2.3. Carbon footprint

As the aim of this study is to compare emissions from different farming methods, the system boundaries were drawn at the farm gate, including only those emissions directly associated with the production and management of a particular system. At the time of this study, the Publicly Available Specification 2050:2011 (PAS 2050), developed by the British Standards Institute, was the only globally recognised, transparent and publically available product carbon footprint (CF) methodology published to-date and was therefore chosen here for all CF calculations. Empirical data were used to calculate biomass and coffee yield for individual production systems; recommended models and emission factors outlined in PAS 2050 were used to estimate all other components of net GHG emissions (BSI, 2011). We recognise the limitations and uncertainties attached to the use of the fixed IPCC tier 1 assumptions about carbon fluxes, emission factors and models under such standards but consider these acceptable for the purpose of this analysis.

Within PAS 2050, fluxes of the GHGs CO₂, N₂O and CH₄ are accounted for and converted into units of CO₂ equivalents (CO₂e) according to their global warming potential (GWP) over 100 years. Of specific relevance to agricultural CFs are non-CO₂ emissions from livestock, their manure and from soils, which must be included, calculated according to IPCC guidelines for national GHG Inventories (IPCC, 2006). Nitrous oxide emissions from soils are accounted for as both direct and indirect emissions resulting from N additions, deposition and leaching. Direct emissions from land use change (LUC) must be included if the land conversion took place on or after the fixed date of the 1st January 1990. As all land in the experiment was in agricultural production prior to 1990, no LUC emissions have been included. Changes in soil C, either as emissions, sequestration or in eroded material, are excluded from PAS 2050 unless they are a direct result of LUC activities. Carbon stored in living organisms such as trees or perennial crops is also excluded from the PAS 2050 method, however for this study, in a separate analysis, the mean annual above-ground C sequestration has been estimated as a separate variable from the CF in order to establish a more complete assessment of the true net C balance of individual treatments (Appendix 4, Table A4.1).

Carbon footprint calculations for each system were based on annualised averages of all inputs and yields since the second year of coffee production, to best represent the whole production system. To allow for a direct comparison between emissions of CO₂e and C sequestration, CF calculations were made on a per-hectare basis. In order to calculate the overall net C balance of systems and to allow for comparison with the GHGs emitted (CF per ha), annual C sequestration in above- and below-ground biomass and litter have been converted into units of CO₂e.

4.2.4. Estimation of above-ground and below-ground biomass

Above-ground biomass stocks (Appendix 4, Table A4.1) for all treatments were estimated by specific allometric equations which were developed for each shade tree species (Appendix 4, Table A4.2). Below-ground biomass for shade trees was estimated using a function developed by Cairns et al. (1997) and recommended by IPCC (IPCC, 2003). Above-ground coffee biomass stocks were calculated using an allometric equation developed by Segura et al. (2006) for shaded and un-shaded coffee systems (Appendix 4, Table A4.2). The equations of Dossa et al. (2008) for coffee growing in the open versus under shade were used to estimate coffee bush below-ground biomass (Appendix 4, Table A4.2). Leaf litter and deadwood C stocks were estimated using the IPCC Good Practice Guidance for Land Use, Land Use Change and Forestry (LULUCF) on

measuring and monitoring changes in C stocks (IPCC, 2003). For all sampled living above-ground biomass and pools such as deadwood and small-fraction litter, a stock-based approach was adopted in which an annualised average was derived by dividing the results from 2009 by the years since establishment assuming a linear sequestration rate and a start value of zero for all pools.

4.2.5. Calculation of land-use change emissions

LUC emissions and sequestration of CO₂ are consequences of changes in ecosystem C stocks. These emissions and sequestration were calculated using the IPCC guidelines for national greenhouse gas inventories for agriculture, forestry and other land use (IPCC, 2006) using inventory data from the experiment. Changes in C stocks for a given land-use category are calculated from fluxes into and out of the above-ground and below-ground biomass, dead-wood and small-fraction litter, and soil organic matter pools. Non-CO₂ GHG emissions derived from sources such as manure, deadwood, small-fraction litter and soils have also been included using gas- and source-specific emission factors. Although changes in C stocks, for example through LUC, often result in immediate C-balance alteration, IPCC specifies a period of 20 years in which the land remains in the conversion category before a new C stock equilibrium is expected (IPCC, 2006). Therefore, these C-stock changes are annualised for 20 years. Management and shade type for additional LUC area have been assumed to equal that of the tested case in the experiment.

4.2.6. Cost-benefit analysis

Cost benefit analysis (CBA) was carried out on the individual experimental treatments. All economic data were obtained for Costa Rica on an annual basis to reflect changes in economic conditions, such as price fluctuations with global coffee prices doubling since the establishment of the experiment (ICO, 2011) and fertiliser prices increasing fivefold in the period 2005-2008 (Foresight, 2011). Management and resource inputs were recorded since the onset of the experiment. Annualised averages of all inputs since the first year of coffee production (third year after planting) were calculated. The individual treatments were appraised as their annualised net present values (NPV). The NPV is expressed as the difference between the discounted present value of past benefits (PV_B) and the discounted present value of past costs (PV_C). Income from firewood and fencepost material has not been taken into account as no accurate data were available for individual treatments but is believed to be less important at this stage of timber tree

development, contributing less than 1 per cent to the NPV. In addition, the range of other non-market benefits of trees within coffee agroforestry systems were not included as this analysis was intended to focus only on direct farmer income and expenditure.

4.2.7. Land Use Change scenarios

4.2.7.1. Intensification scenario

Up till the present, the decision-making of most Central American coffee farmers under the past conditions of uncertainty indicates that they have adopted the approach of “maximising the minimum” (maximising return on a limited capacity to invest). The choice of this ‘maximin’ criterion under uncertainty, even if it leads to a lower average outcome, is rational if financial markets are inefficient (for a discussion of this criterion see, e.g., Petersen & Lewis (1986)). A strategy that provides the average gain may be shunned for a strategy that provides a better cushion if things go wrong (Backus et al. 1997). The choice of production techniques such as the shaded systems that provide lower average gain in favour of the seemingly more profitable (higher net income per ha) FS systems is observed in our study area. This is because shaded systems have greater resilience of coffee production than FS systems. The latter introduces greater potential fluctuation in income because of the need for the use of expensive agrochemical inputs while there are constraints on the availability of finance. Nonetheless, some farmers have already made decisions based on “maximising expected value” (maximising net income per ha) and so converted to more profitable high-input FS systems. These have tended to be larger producers better able to access the financial markets. This conversion previously occurred during the 1970s and 1980s when the international coffee agreements supported coffee prices (Goodman, 2008). If global commodity prices remain high, as is foreseen, it will stimulate more farmers to maximise expected value in their decision-making and convert to more profitable high-input systems. The opportunity costs of not converting could be expected to surpass the risk threshold which has stopped farmers converting to high-input FS systems before. However, we do accept that even if this price signal occurs, some farmers will not convert to more profitable systems, the decision making of many will still be dominated by an adversity to risk. Our approach is supported by a sensitivity analysis (see results section) based on the confidence interval values of coffee prices for the seven-year period of this study. Using data of the fluctuation of actual coffee prices over this seven-year period, the range of resulting NPV values was calculated on an annual basis for each treatment with all other costs held constant. The opportunity costs of the intensification and extensification scenarios were then calculated for

each treatment combination using the mean NPV and the upper and lower 95% CI values of NPV.

4.2.7.2. Extensification scenario

Many coffee farmers in Central America continue to use low input shaded coffee systems despite their lower yield and potential profitability compared with more intensively managed high input shade systems. These decisions reflect their response to the uncertainty of future prices of both coffee and expensive agrochemicals, and unavailability of necessary financial resources to intensify their production systems (Batz et al. 2005). If farmers decide to retain low levels of agrochemical inputs, rather than converting to a more intensive system, while this may have global benefits of maintaining a lower CF, it also risks reducing the potential contribution of their produce to the national economy and agricultural markets. Given the strong continuing global demand for coffee, the collective impact of these farmers' decisions is likely to increase pressure to convert additional land to coffee production (an example of "extensification") (Batz et al. 2005), in some cases forest land at the agricultural frontier with its associated LUC GHG emissions. With repeated cycles of expansion and contraction of land area under coffee farming in Central America, there are in many places areas of secondary forest available for reconversion, and at higher altitudes primary forest is being converted where the climate has become relatively more favourable for coffee production (Gay et al., 2006; Guhl, 2008; Tucker, 2008).

4.2.7.3. Scenario calculations

To enable both scenario analyses we firstly quantify the overall farm-level GHG emissions (in the form of CF per ha) associated with alternative coffee production systems in the nine-year experiment in Costa Rica. This establishes the order of intensification of the coffee management treatments (applied at the subplot-level) regardless of shade-type (main-plot-treatments). Throughout the text "intensification" refers to higher levels of inputs, resulting in increased coffee production, per unit area and time (Lambin et al., 2001). In the intensification scenario, by carrying out a cost-benefit analysis, we calculate annualised NPV to identify the most profitable coffee production system (it was FS with conventional intensive management). We then assessed the opportunity costs of avoiding LUC from each shaded system to this intensive system. By calculating the net GHG emissions that would result from these LUC's we determined the break-even price per tonne of avoided CO₂e emissions that would need to be paid to farmers as

compensation to offset their opportunity costs of retaining less profitable but lower emission shaded systems (Healey et al., 2000).

Taking the assumption, that farming with less productive systems requires a greater land area to produce a given quantity of coffee, we constructed an extensification scenario. For this we calculate how much forestland would need to be converted to coffee production under the same management and shade system to generate income sufficient to cover the opportunity cost of maintaining less productive and profitable coffee management systems (within each shade type) rather than intensifying production on the existing coffee farmland. We then assess the contribution of the GHG emissions associated with this LUC to the net impact of retaining a less productive system. The annual CO₂e balance after LUC is calculated by summing the C sequestration into above- and below-ground biomass and litter less the CF on the existing farmed area, less the deforestation LUC emissions and the CF of the additional land area converted from forest (and then farmed with the same management and shade type) (LUC+CF). The results are expressed per area of existing coffee cultivation. It is assumed that unconverted forest has zero net GHG emissions or C sequestration. For each shade type the scenario tests the net impact on CO₂e balance of retaining each of the less intensive coffee management systems with the required additional land converted to coffee farming as an alternative to converting the existing farmed land to the most profitable (Conventional Intensive (CI) or in two cases where this was excluded, Conventional Moderate (CM)) within each shade type.

For further details on the methods and materials of this study please refer to the supporting information tables and text in Appendix 4.

4.3. Results

4.3.1. Effect of system intensification on GHG emissions, C balance and profitability

There is a strong positive correlation between net GHG emissions (CF per ha) and NPV indicating a strong trade-off between reductions of GHG emissions and profitability (Figure 4.1). This effect is seen in the comparison of conventional and organic systems and within conventional systems comparing moderate and intensive management inputs: the highest GHG emissions were found in the high-input intensive conventional treatment and the lowest in the moderate-input organic treatment (Figure 4.1).

When the annual sequestration of C in biomass and litter is subtracted from the emissions encapsulated in the CF, CO₂e balance varies greatly between shade types (Figure 4.2). Systems shaded by the single timber tree species *C. eurycyclum* had significantly ($p < 0.05$) higher (net fixation) C balance (Mg CO₂e ha⁻¹ yr⁻¹) than that of the mixed shade (*E. poeppigiana*/*T. amazonia*), leguminous shade (*E. poeppigiana*) or full sun (FS) systems, and those with the single timber species *T. amazonia* had significantly higher fixation than the later two systems. However, whilst not all trends amongst coffee management systems are consistent across shade types, there was an important interaction. Although, overall, the most intensive coffee management system (CI) produces a significantly higher CF than all others, its C balance (relative to the other systems) is strongly dependent on shade type and tree management, from being the system with the largest positive (sequestration) balance under *T. amazonia* to being the lowest under *E. poeppigiana* (both $p < 0.05$). This difference is mainly due to the dramatically different tree managements applied. *T. amazonia* is left to grow with a minimal pruning regime and responds with increased growth

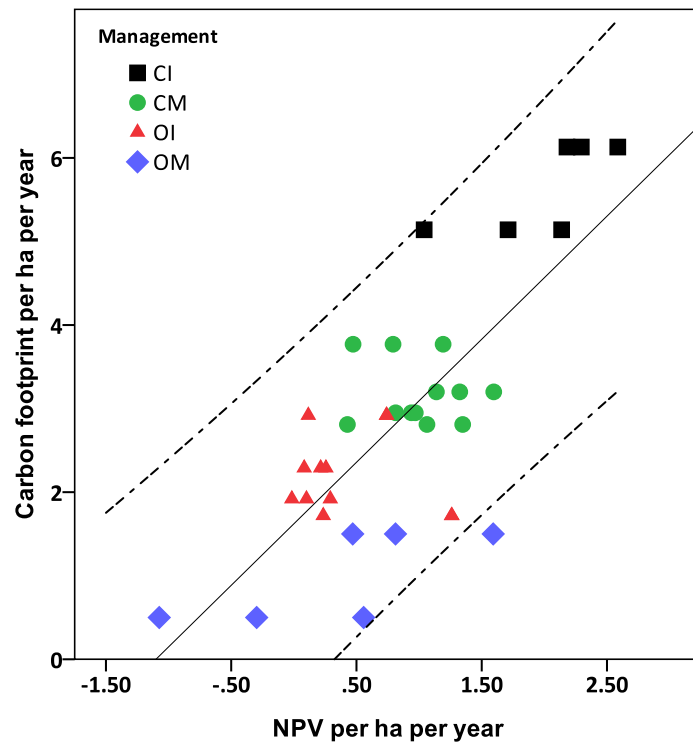


Figure 4.1 Relationship between mean CF (Mg CO₂e ha⁻¹ yr⁻¹) and mean NPV (1000 US\$ ha⁻¹ yr⁻¹) for four sub-plot coffee management treatments (conventional intensive (CI) $n=6$; conventional moderate (CM) $n=12$; organic intensive (OI) $n=12$; organic moderate (OM) $n=6$) across four main-plot shade treatments and three replicate blocks in Costa Rica. Fitted line, $r^2=0.57$; $CF_{ha} = 1.621 + 1.473 * NPV$; dashed lines indicate the upper and lower boundaries of the 95% confidence interval values.

accumulation of C in biomass when fertilized, while the leguminous shade tree *E. poeppigiana* was completely pruned (pollarded) at about 2 metres above ground level, twice a year to allow for higher light exposure at times of coffee flowering and maximum input to the soil of N-rich organic matter from the pruning residues (emulating the common practice throughout Costa Rica). No significant differences ($p < 0.05$) were found between conventional moderate (CM) and organic intensive (OI) management treatments across shade types except that the former had a more positive C balance under the mixture of *E. poeppigiana* and *T. amazonia*. Taking all of the results together, shade type had a significant ($p < 0.001$) impact on C balance (with a strikingly lower net fixation in the FS than the shaded systems) but the net effect of intensity of coffee management depended on the response of the shade trees to the higher inputs, whether additional C accumulation in biomass out-weighed the increased agronomic emissions (c.f. *T. amazonia*) or not (Figure 4.2). Therefore, in these agroforestry systems there is potential for higher emissions from intensification to be offset by greater C sequestration in tree growth.

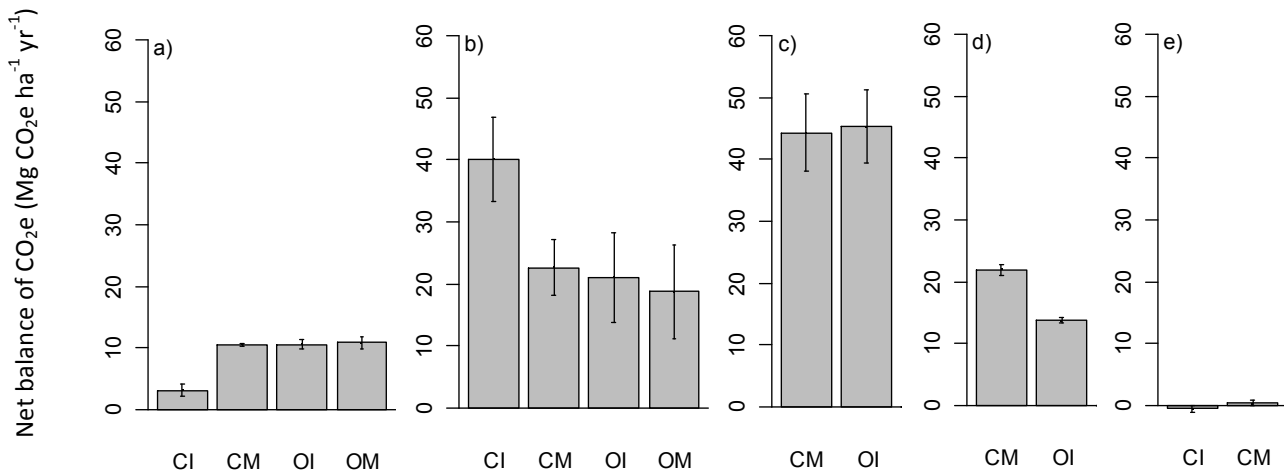


Figure 4.2 Mean annual system net C balance (sum of sequestration into above-ground and below-ground biomass and litter minus the CF, Mg CO₂e ha⁻¹ yr⁻¹) for the different shade types a) *Erythrina poeppigiana* (E); b) *Terminalia amazonia* (T); c) *Chloroleucon eurycyclum* (C); d) *E. poeppigiana*/*T. amazonia* (ET); e) full sun (FS), combined with the four coffee management sub-plot treatments (defined in Figure 4.1) which are arranged from the most intensive (left) to least intensive (right) in terms of quantity and quality of inputs. Whiskers indicate the upper and lower boundaries of the 84% confidence interval values (appropriate for judging significance of differences at $p < 0.05$).

4.3.2. Profitability and sensitivity to coffee prices of different production options

Net present values based on labor, material and other inputs, and coffee production outputs for the years 2003-2009 showed an increase from organic (mean 431 US\$ ha⁻¹ yr⁻¹) to conventional (mean 1425 US\$ ha⁻¹ yr⁻¹) and (in the conventional system) from moderate (mean 1075 US\$ ha⁻¹

yr⁻¹) to intensive (mean 2007 US\$ ha⁻¹ yr⁻¹) input management (Appendix 4, Table A4.4). For the CI management they were also higher under FS than under any shade type by at least an average of 100 US\$ ha⁻¹ yr⁻¹ (Appendix 4, Table A4.4). Analysis of the sensitivity of NPV for different production systems to coffee prices shows that with prices near the top end of the range experienced over the seven-year study period (corresponding to the upper 95% confidence interval of NPV for each production system) the opportunity cost of not converting to more intensive systems rises considerably. For the intensification scenario the mean opportunity costs to farmers across all shade types of not converting production systems dropped by an average of only 3% when the analysis is conducted using the lower 95% confidence interval value of NPV (for a 20% fall in coffee price) whereas it rose by 49% when using the upper 95% confidence interval value of NPV (for a 20% rise in coffee price). For the extensification scenario the deficit compared to intensifying production only fell by 6% with the lower coffee, price but rose by 49% with the higher coffee price (Appendix 4, Table A4.4).

4.3.3. Intensification

The avoided LUC emissions (Appendix 4, Table 4.3) from converting 1 ha of shaded to unshaded FS system ranged from 5.08 to 25.36 Mg CO₂e ha⁻¹ yr⁻¹ amongst shade types and showed a similar trend amongst shaded systems to their annual sequestration rates (Table 4.1) with the lowest and highest mean avoided LUC emissions associated with the leguminous tree species *E. poeppigiana* and the timber tree species *C. euryclum*, respectively. Similarly, significant differences ($p < 0.05$) were found under *E. poeppigiana* and *T. amazonia* between CI and all other subplot treatments with CI being the lowest under the former and the highest under the latter. The break-even C price required to compensate farmers for not intensifying ranged greatly from 9.3 to 196.3 US\$ per sequestered Mg CO₂e ha⁻¹ (Appendix 4, Table 4.3) because of the huge variation in profitability (NPV) under the different shade systems. The timber shade species (*T. amazonia* and *C. euryclum*), due to their relatively higher sequestration potential, had lower break-even prices on average than leguminous (*E. poeppigiana*) and mixed (*E. poeppigiana*/*T. amazonia*) systems, although no significant differences were found ($p < 0.05$) between the two groups. Break-even C prices were also significantly lower under conventional (mean 42.6 US\$ per sequestered Mg CO₂e ha⁻¹) than organic (mean 116.9 US\$ per sequestered Mg CO₂e ha⁻¹) management systems ($p < 0.01$).

4.3.4. Extensification

Without including the effects of extensification through deforestation LUC, all shade-type-coffee-management combination systems demonstrate a positive CO₂e balance (net sequestration) except for the most intensive FS CI system, in which the net CF just outweighed sequestration into biomass and litter (Table 4.1).

Table 4.1 Mean annual system net CO₂e balance (\pm SE based on variance amongst the three experimental blocks) for the LUC scenarios), for the five shade types (defined in Figure 4.2) under the four different management treatments (defined in Figure 4.1) after extensification.

Shade ¹	Management	CF ² (Mg CO ₂ e·ha ⁻¹ ·yr ⁻¹)	C sequestered in biomass and litter (Mg CO ₂ e·ha ⁻¹ ·yr ⁻¹)	Annual net CO ₂ e balance (Mg CO ₂ e·ha ⁻¹ ·yr ⁻¹) ¹	Annual net CO ₂ e balance of additional converted land (LUC + CF) (Mg CO ₂ e·ha ⁻¹ ·yr ⁻¹)	Annual net CO ₂ e balance after LUC (Mg CO ₂ e·ha ⁻¹ ·yr ⁻¹) ¹
E	CI	6.13	9.21 (\pm 1.28)	3.08 (\pm 0.7)	0	3.08 (\pm 1.3)
	CM	3.77	14.25 (\pm 0.37)	10.48 (\pm 0.2)	-30.31 (\pm 10.8)	-19.84 (\pm 10.5)
	OI	2.92	13.46 (\pm 0.95)	10.54 (\pm 0.5)	-100.32 (\pm 78.5)	-89.78 (\pm 78.5)
	OM	1.50	12.32 (\pm 1.27)	10.82 (\pm 0.7)	-19.42 (\pm 8.9)	-8.60 (\pm 8.2)
T	CI	5.14	45.24 (\pm 9.07)	40.10 (\pm 5.2)	0	40.10 (\pm 5.2)
	CM	2.81	25.43 (\pm 6.01)	22.63 (\pm 3.5)	-13.82 (\pm 10.5)	8.80 (\pm 7.1)
	OI	1.72	22.74 (\pm 9.51)	21.02 (\pm 5.5)	-11.07 (\pm 6.1)	9.96 (\pm 10.5)
	OM	0.5	19.24 (\pm 9.94)	18.74 (\pm 5.7)	³	³
C	CM	2.95	47.24 (\pm 8.22)	44.29 (\pm 4.7)	0	44.29 (\pm 4.7)
	OI	1.92	47.23 (\pm 7.84)	45.31 (\pm 4.5)	-147.63 (\pm 121.5)	-102.33 (\pm 122.1)
ET	CM	3.20	25.12 (\pm 1.23)	21.92 (\pm 0.7)	0	21.92 (\pm 0.7)
	OI	2.29	15.97 (\pm 0.58)	13.68 (\pm 0.3)	-62.12 (\pm 13.0)	-48.44 (\pm 13.1)
FS	CI	5.00	4.43 (\pm 0.45)	-0.57 (\pm 0.5)	0	-0.57 (\pm 0.5)
	CM	2.71	3.03 (\pm 0.35)	0.32 (\pm 0.4)	-5.32 (\pm 4.1)	-12.04 (\pm 9.8)

¹Abbreviations are defined full in Figure 4.2. ²Management inputs are considered the same across the three replicates and within the same sub-treatment and therefore show no SE. ³No data shown as the mean NPV was negative and therefore LUC emissions due to additional land requirements could not be calculated.

However, by including emissions from the deforestation LUC needed to provide the additional farmed area required to bring each less-intensive system up to the NPV of the most intensive management under that shade system, only the two coffee management systems under the *T. amazonia* shade type remained positive in their CO₂e balance. For all six other combinations of shade type and management system, the emissions caused by the forest

conversion LUC outweigh the sequestration in the existing and additional farmed area by at least 1.8 times, resulting in an overall net negative CO₂e balance (net emissions), up to 102 Mg CO₂e ha⁻¹ yr⁻¹ for the OI system under *C. eurycyclum* shade.

4.4. Discussion

4.4.1. C balance, NPV and intensification

We found that C sequestration in above- and below-ground biomass for all shaded systems far outweighed the GHG emissions resulting from the farming of the coffee crop for all management intensities, and in some cases intensification even had a positive effect on the net C balance during these first nine years of shade-tree growth through increased biomass accumulation (Table 4.1). The only negative net C balance was found in the intensively managed FS system. Similar results have been found in a previous study in Costa Rica comparing shaded and FS coffee systems, where the positive balance between C storage and non-CO₂ soil fluxes resulted in net storage of 11.93 and 2.67 Mg CO₂e ha⁻¹ yr⁻¹ respectively (compared to the corresponding values of +21.88 and -0.13 Mg CO₂e ha⁻¹ yr⁻¹ in the present study), on the assumption that initial above- and below-ground C biomass stocks were zero (Hergoualch, 2008). These results clearly indicate that coffee agroforestry systems can play an important part in climate change mitigation. This outcome will, however, depend on whether the starting C stocks are truly zero and the balance over the complete lifetime of the coffee production system as the rate of C sequestration into aboveground C pools will reduce as trees and coffee bushes mature. As such some divergence from these values of the first nine years of coffee and shade-tree growth can be expected during the full life cycle of a coffee cultivation system.

Net Present Value of coffee production (ha⁻¹ yr⁻¹) was positively correlated with CF (ha⁻¹ yr⁻¹) and thus economic benefits to the farmer are accompanied by greater global environmental costs. We found, however, that some forms of intensification in coffee agroforestry systems could mitigate climate change both through increased C sequestration and also reducing the pressure for further land conversion to agricultural production. This supports findings that agricultural intensification can lead to a net reduction in overall GHG emissions (Burney et al., 2010) and that, in particular, agroforestry systems can play an important role in mitigating GHG emissions without compromising agricultural yields (Palm et al., 2010). This outcome, however, is strongly dependent on the shade type, its management and the fate of the additional wood production. Additional benefits of agroforestry systems, such as the provision of firewood (sometimes substituting for forest degradation or for the use of fossil fuels), could actually

further increase their net positive contribution to climate change mitigation. Given the scale and effect of including the growth of standing biomass in calculation of the overall C balance of agricultural production systems, we conclude that current CF accounting methodologies should recognise this C sink in order to permit a more holistic representation of the footprint of entire supply chains.

4.4.2. LUC emissions and C markets

Our full economic analysis over the first nine years of production showed that, in this experiment, under high intensity management FS systems are more profitable than high intensity shaded systems (E CI and T CI) with 5-35 per cent greater NPV of coffee production (Appendix 4, Table A4.4). This supports previous research which showed that when optimal growing conditions of FS exposure and high fertilisation rates are altered by the inclusion of shade trees, coffee production is reduced by up to 33 per cent (Harmand et al., 2007a). Current mechanisms such as REDD+ that are aimed at protecting existing forests and reducing GHG emissions by avoiding deforestation and forest degradation could be expanded to include agroforestry systems such as shaded coffee, incorporating payments to farmers by C-market mechanisms (Albrecht and Kandji, 2003; Jong et al., 2004; Kandji et al., 2006; Soto-Pinto et al., 2010; Verchot et al., 2005; Verchot et al., 2007). In agriculture, these mechanisms are usually based on changes in C stocks that are associated with changing from lower C-sequestration systems (e.g. FS) to higher net C-sequestration systems (e.g. shaded).

Much coffee production in Central America, however, is already under shade which can store up to 100 Mg C ha⁻¹ above- and below-ground (Verchot et al., 2007). Could C-market mechanisms be extended to pay farmers not to convert shaded to FS systems? The answer is complex: our results suggest that break-even prices, based on C sequestration rates, to avoid LUC from shaded to FS systems span a wide range from 9.3 to 196.3 US\$ Mg CO₂e⁻¹ sequestered, depending on the existing shade system. The maximum C-market prices of 11 and 15 US\$ Mg CO₂e⁻¹ paid for REDD+ and agroforestry projects in 2009 respectively (Hamilton et al., 2010) would only be sufficient to offset the opportunity cost borne by shaded systems that are already the most intensively managed and productive. Therefore, current financial incentives to reduce GHG emissions through increased shade cover in coffee systems may only be able to compete economically with FS systems when combined with intensive production methods. Shade trees can provide other economic benefits from timber and fuelwood and we recognize that our NPV analysis only considered income from coffee.

Nevertheless, the summary of income from the tree component in coffee agroforestry systems by Idol et al. (2011) indicates that its income is rarely more than 20% of the value of the coffee harvest. Although much current coffee production is managed under shaded systems that may not maximize NPV, this could change with predicted future increased commodity prices, land scarcity and population growth while accepting that many risk-averse farmers will still decide to retain shaded systems. With economic opportunities and individuals' responses continuing to be one of the main drivers of LUC (Lambin and Meyfroidt, 2011), reducing emissions by avoiding further LUC will have to present viable financial alternatives.

The sensitivity analysis supports the key assumption for this scenario that higher coffee prices favour a conversion from shaded to FS coffee. Although this has not been the norm to date, farmers have shown a divergence of responses to price signals (Hill 2006), and recent increases in international coffee prices are likely to make FS systems even more profitable, with opportunity costs potentially surpassing the risk threshold which has stopped many farmers converting to this system before. Farmers' decision-making under uncertainty is heavily influenced by their perceptions of likely future changes in the market price of the commodities that they produce and inputs that they purchase (Batz et al. 2005). However, farmers know that these future prices are fundamentally unpredictable. Therefore farmers' perceptions of the future are heavily influenced by their recent past experience of levels and trends in prices (Hill 2006; Simelton et al. 2011). We consider this justifies our use of cost-benefit analysis based on the actual data of the past nine years as the basis for testing scenarios about potential future land use change by coffee farmers in the study area.

4.4.3. 'Leakage' through extensification

The potential for C-market payments to coffee farmers to avoid intensification discussed above is based on an analysis confined to the existing farm system. However, it ignores the potential for a wider environmental impact of limiting production in this way mediated by the coffee commodity market. We have shown that, if the modelled system is expanded to incorporate that effect through including the anticipated forest conversion LUC required to maintain the current profit from coffee production, the net effect on GHG emissions is strongly detrimental in approximately half the cases, i.e. it results in increased emissions. This illustrates how 'leakage' in the form of indirect land-use change through extensification can have a considerable impact on the overall net C balance resulting from limitation to agricultural productivity. In reality, a reduction in coffee production in one location is unlikely to result in an exactly equal increase

elsewhere (the degree of leakage will depend on the elasticities of both supply and demand for coffee), but some leakage is highly likely. Leakage has already been identified as one of the main constraints to the success of REDD+: discontinuation or avoidance of economic activities in a project area being likely to cause the initiation or intensification of those activities in other areas (Dargusch et al., 2010; Martello et al., 2010).

The present study shows why it is important that the effects of leakage should also be realistically incorporated into the planning of projects to reduce GHG emissions from current agricultural land. The continuing high prices of inputs such as fertilisers are a constraint on the alternative of agricultural intensification, which is more likely to succeed if financial incentives are viable. However, without this, there is also an increased risk that leakage from agricultural GHG emissions reduction projects will be in the form of displaced deforestation (resulting in a potential net increase in GHG emissions and abrogation of the objectives of REDD+). Burney et al. (2010) argue that the improvement and increase of crop yields can play a vital role in helping mitigate climate change within this wider land use context, and Fisher et al. (2011) suggest specifically that REDD+ payments could help finance the targeting of underlying drivers of deforestation by subsidising fertiliser, seed and agricultural training to increase yields on existing crop land. If successful, this strategy could, therefore, not only contribute to mitigating climate change but at the same time keep pace with the increase in global demand for coffee. Therefore, a logical extension of REDD+ mechanisms to aid the success of climate change-mitigating agroforestry systems could be found in what we term 'reduced emissions through avoided land-use change' (REAL). Adequate financial incentives through mechanisms such as REAL could therefore play an important role, not only in climate change mitigation, but also in helping to meet the millennium development goals of eradicating poverty and hunger.

We do recognise that this study is limited to the trade-off in the ecosystem service provisions of climate-change mitigation and agricultural commodities provisioning. We recommend that future studies should assess the trade-offs resulting from the impact of intensification on a wider range of provisioning, regulating and cultural ecosystem services. Whilst our results clearly indicate the benefits of conventional intensive shaded systems over FS systems in terms of climate change mitigation potential on currently farmed land, other drivers such as global demand for coffee and resulting financial incentives and policy development will determine farmers' decision-making over production system. This further highlights the need to combine efforts such as REDD+ with intensification or yield improvements in agricultural production.

Chapter 5

Sink or source – the potential of coffee agroforestry systems to sequester atmospheric CO₂ into soil organic carbon

Submitted as:

Noponen, M.R.A., Healey, J.R., Edwards-Jones, G., Haggard, J.P., Sink or source – the potential of coffee agroforestry systems to sequester atmospheric CO₂ into soil organic carbon. *Agriculture, Ecosystems and Environment*.

5.1. Introduction

Soils are the greatest terrestrial C stock and hold an estimated 1462-1548 Pg of organic C to 1 m depth (Batjes, 1996). However, surface soils (0-30 cm depth), which store almost half of soil organic carbon (SOC) and up to three times the C stored above-ground in vegetation, are considered to be the most vulnerable to loss as CO₂ emissions due to climatic and land-management change, highlighting a major threat to climate regulation (Powlson et al., 2011a). At the same time, it has been widely recognised that practices which maintain SOC stocks are important in ensuring the sustainability of soil functions (Lal, 2004; Nair et al., 2009a; Powlson et al., 2011a). Identifying how different agricultural management practices or changes in land-use create SOC sinks (accumulating additional C), act as C sources (emitting C) or maintain stocks at current levels are imperative in identifying effective strategies for land-based climate change mitigation. Agriculture that is established on land depleted in SOC will have potential to sequester C. However, some practices such as addition of organic matter that may increase SOC can also increase N₂O emissions. In addition, it is not always clear how farm annual GHG flux may be altered by change in SOC stock, as this tends to occur slowly and with an uncertain trajectory. Therefore, assessment of how best to achieve climate change mitigation through agriculture needs to consider both short-term changes in GHG emissions from soil and longer-term changes in SOC stocks (Lal, 2004; Smith et al., 2008). To get a whole-system perspective

this should be combined with assessment of changes in other C pools, such as above- and below-ground biomass and litter (e.g. of shade trees or crops such as coffee).

Agroforestry systems (AFS) have been recognised for their potential to sequester large amounts of C above ground (and in some cases below ground into SOC) (Albrecht and Kandji, 2003; Nair et al., 2009a; Soto-Pinto et al., 2010; Verchot et al., 2007). Nair et al. (2009a) have suggested an area of more than 1000 million (M) ha globally to be currently managed under AFS, including silvopastoral systems, with 630 M ha more estimated to be suitable for conversion of unproductive croplands and grasslands to AFS (IPCC, 2000). This suggests a great potential for further above- and below-ground C sequestration. It is commonly believed that AFS enhance SOC stocks compared with tree-less annual crop systems (Nair et al., 2009b). However, much of this evidence is based on changes in the SOC of surface soils and little has been published on the effects of trees on stocks deeper in the soil. Understanding of the soil processes involved is still limited, making it difficult to predict accurately changes in SOC over time (Nair et al., 2009b). Much evidence of increases in SOC stocks after changes in agricultural management is based on extrapolation from rates of C sequestration by growing plants using weak evidence about the processes by which this might influence SOC stocks (which can be positive or negative (Sanderman and Jeffrey, 2010)). As a result of the complexity of assessing long-term SOC change, it had until recently been largely excluded from carbon accounting within land-based projects for international carbon markets, which tended to focus only on above-ground C as it is relatively easy to measure and model (IPCC, 2006). Recently, SOC has been included as a C pool within respected accounting methodologies, e.g. in four out of the seven used for small-scale afforestation and reforestation under the CDM pool (UNFCCC, 2011b). However, all except one use a default value of an increase in SOC of $0.5 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$ for a C accounting period of 20 years following afforestation or reforestation of land. Similarly, the UNFCCC (2011b) methodology specifies accounting by means of an assessment tool which is based on climatic default values that only allow for an increase in SOC, with a maximum value of $0.8 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$. Although initial losses of SOC through site preparation are recognised, the potential for reduction of SOC due to tree establishment is not accounted for. Use of these default values is rarely replaced by monitoring of actual changes in SOC stocks ex post, which might, in fact, reveal longer-term decreases in SOC (Bashkin and Binkley, 1998).

Coffee production systems occupy over 10 million ha globally (FAO, 2011) so their design and management have potentially major importance for land-based C flux and storage. The aim of this study is to advance understanding of the extent to which producing coffee with shade trees (coffee agroforestry systems - CAFS) change SOC stocks and whether this provides a

viable climate change mitigation strategy. Major variables in CAFS as implemented by farmers in Central America that we hypothesized would affect SOC stocks are: (i) the use of shade trees versus full-sun, (ii) amongst shade trees the use of timber species (unpruned, therefore predominantly providing only a litter input above-ground) versus nitrogen-fixing species that are frequently and heavily pruned; (iii) conventional chemical fertilisation versus organic fertilisation. By using experimental comparison of these specific variations amongst types of CAFS, this study seeks to improve our understanding of the C cycle, the effects of coffee shade management on sequestration of C in soil relative to that in above-ground biomass, and the extent to which SOC should be taken into account in coffee-farm C projects considering the relative merits of alternative land-use C-accounting methods. The specific objectives are to investigate (a) how the addition and management of trees to agricultural systems change total SOC stocks through the soil profile and (b) how agronomic management affects SOC stocks in comparison with the effects of the trees. We evaluate these by assessing the differences in SOC firstly between shaded and un-shaded (full sun) coffee farming systems, and the effect that tree pruning has within shaded systems, and secondly between conventional and organic management, each with different input levels.

5.2. Methods & materials

5.2.1. Site description

The research was conducted at two 3-ha field sites, in Costa Rica and Nicaragua, chosen to represent low altitude coffee growing regions, both managed by the ‘Centro Agronómico Tropical de Investigación y Enseñanza’ (CATIE). Experiments were established in both sites at the end of 2000. The Costa Rica site is located in Turrialba (9° 53’ 44” N, 83° 40’ 7” W) at 685 m above sea level. The climate is humid tropical with no marked dry season: annual precipitation is 2600 mm yr⁻¹ and mean annual temperature is 22 °C (Haggar et al., 2011). The soils have been classified as Inceptisols (Typic Endoaquepts) and Ultisols (Typic Endoaquults) under the USDA Soil Taxonomy classification system (Soil Survey Staff, 1999) and a water table that fluctuated up to 50 cm depth (prior to drainage of the site at the time of establishing the experiment). The former land-use was sugar cane cultivation. The cultivar *Coffea arabica* L. ‘Caturra’ was then planted in 2000.

The Nicaragua site is located in Masatepe (11° 53’ 54” N, 86° 08’ 56” W) at 455 m above sea level. The climate is semi-dry tropical with a distinct rainy season between May and November: mean annual rainfall is 1386 mm and mean annual temperature is 24 °C (Haggar et al., 2011).

At the Costa Rican site Ultisols were present in two of the three experimental blocks (1 and 3); are were distinguished by the accumulation of clay in the B-horizon. Inceptisols were present in the third experimental block (2); they are distinguished by an absence of clay. High cation-exchange capacity ($> 30 \text{ cmol}(+) \text{ kg}^{-1}$) was common throughout the site.

The soils of the Nicaraguan site are commonly associated with low bulk densities, high amorphous mineral content, high retention of phosphorus, high organic matter content and high water retention. A particular feature of the soils in this region is the presence of a material locally known as ‘talpetate’. This is a horizon of indurated volcanic tuff, which occurs between 15 cm and 1 m depth and can pose difficulties for agriculture due to its durability and the associated difficulties of water flow and root penetration. For the experiment, all of the existing coffee plants were uprooted and removed and the shade trees were felled and all trunk and branch material removed. Remaining leaf and fine branch material and root systems of the shade trees were left on-site to decompose.

5.2.2. Experimental design

The experiments were set up to study the ecological basis of efficiency in coffee production. A main aim was to compare organic and conventional coffee production systems under various types of shade. The main-plot treatments at each site are full sun (not agroforestry) and agroforestry with four different individual species or species combinations of shade tree (Table 3.1, Chapter 3) and were allocated at random. The four sub-plot treatments are coffee management systems combining the two different types (conventional and organic), each with two different levels of nutrient and pest management inputs (intensive and moderate) (Table 5.1) and were allocated at random. The design is a randomized block with three blocks per site, each containing one replicate of each main-plot/sub-plot treatment combination; not all sub-plot treatments are represented within main-plot treatments as some combinations are not representative of real farming systems (e.g. full sun with organic management, Table 3.1, Chapter 3).

Shade trees were planted in 2000 at a density of 416 and 667 trees per ha^{-1} in Costa Rica and Nicaragua respectively but have since been progressively thinned and managed to achieve a uniform shade level (Table 3.1, Chapter 3). The tree management regime varied according to species; *Erythrina poeppigiana* in Costa Rica and *Inga laurina* in Nicaragua (both Leguminosae) were pruned for the management of shade level and to provide organic matter (including N) input to the soil. All *E. poeppigiana* trees were heavily pruned twice per year and their prunings left as a

mulch on the ground. In Nicaragua, *I. laurina* was pruned to create a homogeneous canopy cover of approximately 40%, through annual pruning of branches at any height. The timber tree species were managed primarily by thinning to reduce tree density.

5.2.3. Estimation of soil organic carbon stocks

A total of 18 soil samples for soil C were collected in each sub-plot using a 7.6 cm diameter metal auger with each sample divided into three depths (0-10, 10-20, and 20-40 cm) in August to October 2001 and in February and March 2010 (10 years after the start of the experiment). The sampling design is described in more detail in Appendix 5. To measure bulk density, an undisturbed core of soil 5 cm diameter and 5 cm deep was collected in 2010 in the centre of each of the sub-plots for each of the three designated sampling depths and oven dried to constant dry mass at 105 °C, sieved to separate the fine fraction from the stones (> 2 mm), and then both fractions were weighed (Appendix 5). Due to a lack of bulk density data for the year 2001 (in Costa Rica baseline data were only available for the 0-10 cm soil layer at the subplot level whereas in Nicaragua none were available) C stock calculations on a per ha basis were carried out using the 2010 data (Table A5.1) collected in both countries. This is justified by a t-test between 2001 and 2010 bulk density data in Costa Rica (where land-use changed from sugar cane to shaded coffee), which showed no significant changes ($p = 0.41$) in mean bulk density across the experiment (0.84 to 0.86 g/cm³). Similarly, in Nicaragua where the land-use (shaded coffee) did not change we expect an even smaller change in mean bulk density values.

5.2.4. Statistical analysis

To test the effect of main-plot shade and sub-plot coffee management treatments on the changes in SOC stocks 2001-2010 we fitted separate linear mixed effects models for each country using R (R Development Core Team, 2010) with the lme4 package (Bates et al., 2011). Main-plot/sub-plot treatment combinations were fitted as a factor with 15 levels for each country. Results were assessed using the Akaike Information Criterion (AIC) (Burnham and Anderson, 1998), and the model presenting the smallest AIC selected. This analysis was carried out on the measured SOC stocks between the three sampled depths (0-10, 10-20 and 20-40 cm) and depth was included as a term in the model as the different depths are not independent. To elucidate specific treatment effects an ANOVA was carried out on changes in SOC stock for the main-plot/sub-plot combinations for each depth and country separately using INFOSTAT (InfoStat, 2004). Specific contrasts within the ANOVA were developed based on shaded versus non-shaded main-plot

treatments, heavily versus lightly pruned treatments, organic versus conventional sub-plot treatments and a contrast between the two intensities of sub-plot treatment. Bivariate correlation analyses using Pearson's correlation coefficient for parametric data (data that have met the assumptions of being normally distributed and homogeneity of variance (Table A5.4)) and Kendall's tau correlation for non-parametric data (data that have not met the above mentioned assumptions) were carried out (separately for each depth) between all combinations of SOC stocks, SOC stock changes, above-ground biomass C stocks, pruning inputs and organic fertiliser inputs. These correlation tests were carried out separately for each country using each individual sub-plot as a replicate using SPSS (vers. 19). Statistical significance is judged as $p < 0.05$ unless otherwise stated in the text. The results are presented graphically as SOC stocks in Mg C ha^{-1} because this is the form that is of most relevance for carbon accounting, and for assessing the net impact of treatments on ecosystem carbon storage and thus their potential for climate change mitigation.

Table 5.1 Mean organic matter inputs (\pm SE) ($\text{Mg ha}^{-1} \text{yr}^{-1}$) in experimental sub-plot coffee-management and main-plot shade-tree treatments in the sites in Costa Rica and Nicaragua.

Name of sub-plot treatment	Organic Moderate (OM)	Organic Intensive (OI)	Conventional Moderate (CM)	Conventional Intensive (CI)
Soil amendments¹ (organic-coffee pulp)	Costa Rica: 4.42	Costa Rica: 2.5	None	None
	Nicaragua: 9.33	Nicaragua: 7.5		
Soil amendments¹ (chicken manure)	None	Costa Rica: 8.75	None	None
		Nicaragua: 9.24		
Organic matter inputs² (in form of leaf litter and prunings in Costa Rica)	<i>E</i> : 10.95 (\pm 0.19)	<i>E</i> : 11.40 (\pm 0.78)	<i>E</i> : 9.85 (\pm 0.72)	<i>E</i> : 10.40 (\pm 1.78)
	<i>ET</i> : n/a	<i>ET</i> : 6.50 (\pm 0.26)	<i>ET</i> : 5.85 (\pm 0.31)	<i>ET</i> : n/a
	<i>C</i> : n/a	<i>C</i> : 2.65 (\pm 0.03)	<i>C</i> : 2.54 (\pm 0.05)	<i>C</i> : n/a
	<i>T</i> : 2.34 (\pm 0.06)	<i>T</i> : 2.73 (\pm 0.03)	<i>T</i> : 2.67 (\pm 0.08)	<i>T</i> : 2.75 (\pm 0.12)
	<i>FS</i> : n/a	<i>FS</i> : n/a	<i>FS</i> : 2.23 (\pm 0.01)	<i>FS</i> : 2.29 (\pm 0.06)
Organic matter inputs² (in form of prunings in Nicaragua)	<i>ILSG</i> : n/a	<i>ILSG</i> : 6.95 (\pm 0.47)	<i>ILSG</i> : 7.35 (\pm 0.29)	<i>ILSG</i> : n/a
	<i>ILSS</i> : 5.86 (\pm 0.39)	<i>ILSS</i> : 6.26 (\pm 0.13)	<i>ILSS</i> : 6.30 (\pm 0.33)	<i>ILSS</i> : 5.58 (\pm 0.31)
	<i>SGTR</i> : 4.37 (\pm 0.25)	<i>SGTR</i> : 4.30 (\pm 0.11)	<i>SGTR</i> : 4.37 (\pm 0.14)	<i>SGTR</i> : 4.91 (\pm 0.13)
	<i>SSTR</i> : n/a	<i>SSTR</i> : 4.49 (\pm 0.36)	<i>SSTR</i> : 4.45 (\pm 0.07)	<i>SSTR</i> : n/a
	<i>FS</i> : n/a	<i>FS</i> : n/a	<i>FS</i> : 2.21 (\pm 0.02)	<i>FS</i> : 2.23 (\pm 0.07)

¹Quantities of soil amendments are shown as mean values of known amounts applied annually over seven years (2004–2010); ²Quantities of organic matter inputs are shown as mean values of leaf litter (Costa Rica) and pruning samples (Costa Rica and Nicaragua) collected in 2009. Abbreviations are given in Table 3.1, Chapter 3.

5.3. Results

5.3.1. Changes in soil organic carbon (SOC) stocks

Overall, during the first nine years of coffee establishment total 0-40 cm depth SOC stocks decreased by an average of 12.4% in Costa Rica and 0.13% in Nicaragua. The best fitting mixed effects model for predicting changes in total SOC stocks for both the experiment in Costa Rica and that in Nicaragua is based on sub-plot treatments (management type), depths, and the initial C content as fixed effects with random slope effects of the replicate blocks and of main-plot treatments nested within the replicate blocks (the AIC values of this model for Costa Rica and for Nicaragua were respectively 47.2 and 327.8) although for Nicaragua a model based on main-plot treatments instead of sub-plot treatments was equally as good (AIC = 326.3). Effects of the individual main-plot and sub-plot treatments and of soil depth are presented below. The inclusion of initial SOC concentrations led to a considerable improvement in the models' prediction: in those sub-plots with a higher initial SOC concentration there was a greater subsequent reduction in concentration (Costa Rica) or smaller increase (Nicaragua) during the experiments (this result is also addressed below in more detail).

There was a difference between the experiments in the two countries in the effects of main-plot (shade) and sub-plot (coffee management) treatments on total SOC stocks (Mg C ha^{-1}). In Costa Rica the ANOVA showed significant ($p < 0.01$) overall effects of both on the change in SOC stock at 0-10 cm depth over the 9-year period. However, in deeper soil only the shade treatment effect remained significant with an additional significant ($p < 0.01$) effect of initial C content at the 20-40 cm depth. In contrast, in Nicaragua the ANOVA showed no significant effects of main-plot treatment or sub-plot treatment or initial C content at any soil depth.

5.3.2. Differences between pruned and un-pruned shade tree systems

The ANOVA contrast of the main-plot full-sun treatment versus all the shaded treatments as a group showed no significant differences in change of SOC stocks at each depth in each country. However, in Costa Rica the pruned-legume (E, ET) shade treatments showed significantly different changes in SOC stock compared with the un-pruned shade systems (C, T, FS), at each of the three sampling depths. Across the treatments there were differences in trend of SOC stocks amongst the soil depths in both countries. In Costa Rica, for every shade type there was an increase in SOC at 0-10 cm (average $2.14 \text{ Mg C ha}^{-1}$ or 8.5%), a decrease at 10-20 cm (average $-2.48 \text{ Mg C ha}^{-1}$ or 11.4%) and a large decrease at 20-40 cm (average $9.65 \text{ Mg C ha}^{-1}$ or 28.6%)

(Figure 5.1, Appendix 5, Table A5.2). At 0-10 cm the greatest increase was for the two pruned shade types (E, ET) (which (by chance) had lower initial average SOC stocks at the start of the experiment), whereas at both 10-20 and 20-40 cm depth the E shade type showed the greatest decreases. Therefore, over the whole 0-40 cm soil depth there was a similar mean decrease in SOC stock between the two pruned and two un-pruned shade types (9.9 and 9.7 Mg C ha⁻¹ respectively); thus the average SOC stock increased across all treatments by 8.5% in the top 10 cm of soil and decreased by 21.8% in the 10-40 cm depth. In contrast, the surrounding fields in which sugar cane cultivation had continued over the study period lost on average 11% of SOC in the top 10 cm of soil but gained around 42% (from 47.3 to 67.3 Mg C ha⁻¹) in the 10-40 cm depth.

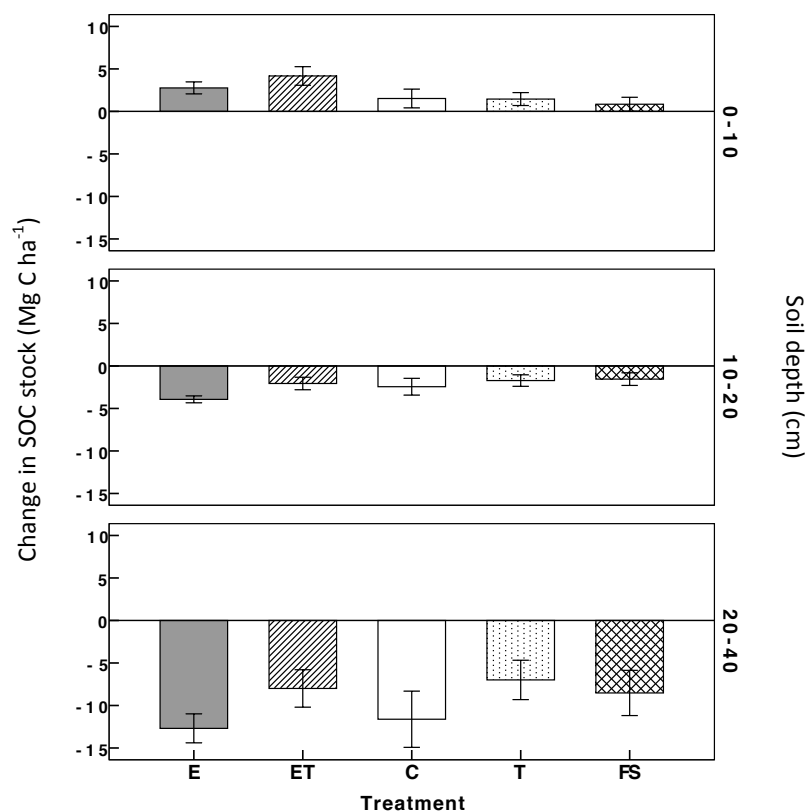


Figure 5.1 Change in mean total SOC stock (\pm SE) (Mg C ha⁻¹) between 2001 and 2010 for three soil depths (cm) of five shade treatments in a coffee agroforestry experiment in Costa Rica. The shade treatment abbreviations are given in Table 3.1, Chapter 3.

In Nicaragua, similar to the results in Costa Rica, in the top 10 cm of soil there was an increase in mean SOC stock for every shade treatments (average 1.26 Mg C ha⁻¹ or 2.8%) (Figure 5.2, Appendix 5, Table A5.3). However, in contrast to Costa Rica at 10-20 cm depth every shade type

showed an increase in mean SOC stock (average 1.38 Mg C ha⁻¹ or 3.8%). At 20-40 cm depth, the same as Costa Rica, across shade treatments average SOC stock generally decreased (by -2.85 Mg C ha⁻¹ or 4.6%), however this trend was only shown in four out of the five shade treatments. Over the whole 0-40 cm soil depth there was a decrease in SOC stock during the experiment for three and an increase in two of the shade treatments. Therefore, across all the shade treatments there was an overall average decrease in SOC stock in both countries, but it was much smaller in Nicaragua (0.13%) than in Costa Rica (12.4%).

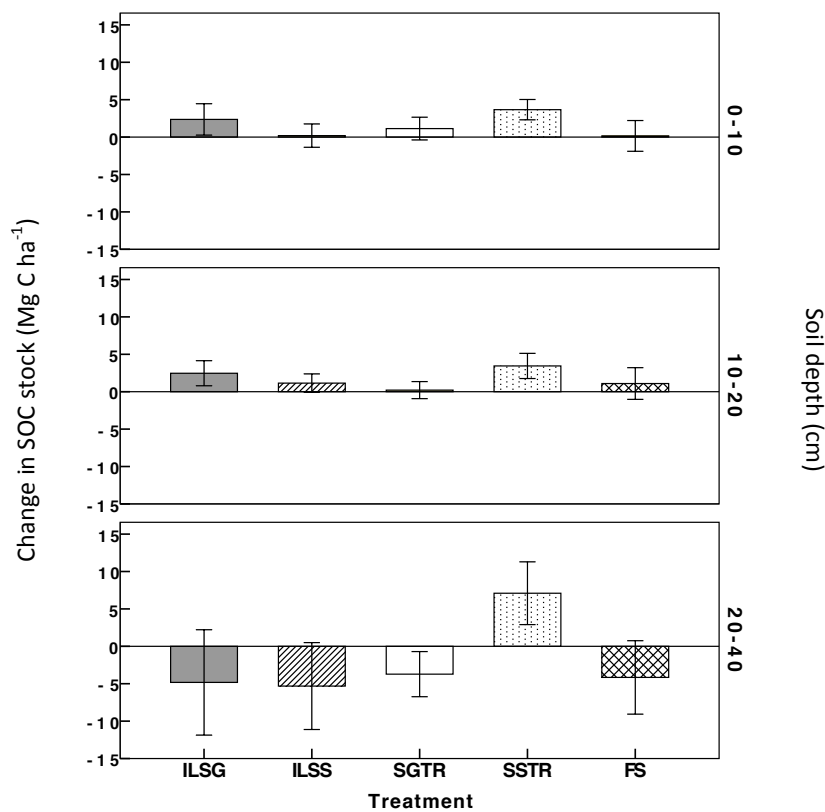


Figure 5.2 Change in mean total SOC stock (\pm SE) (Mg C ha⁻¹) between 2001 and 2010 for three soil depths (cm) of five shade treatments in a coffee agroforestry experiment in Nicaragua. The shade treatment abbreviations are given in Table 3.1, Chapter 3.

5.3.3. Changes in soil organic carbon (SOC) stocks with management type (conventional versus organic)

When the mixed effects model is restricted to the 0 - 10 cm soil layer, the results for the best fitting models in both Costa Rica and Nicaragua include the coffee management (sub-plot) treatments and the initial C concentration as fixed effects with random slope effects of the replicate blocks and of main-plot treatments nested within the replicate blocks; AICs were 18.2

and 97.7 respectively (compared with 33.0 and 105.6 for models including main-plot treatment and sub-plot treatment as fixed effects and 37.0 and 99.8 for models based on main-plot treatments only). The contrasts within the ANOVA for 0-10 cm soil depth SOC stock changes for Costa Rica further support the findings of the mixed effect models, showing a significantly greater increase in SOC stock in the organic than the conventional management treatments ($p = 0.0001$) (Figure 5.3).

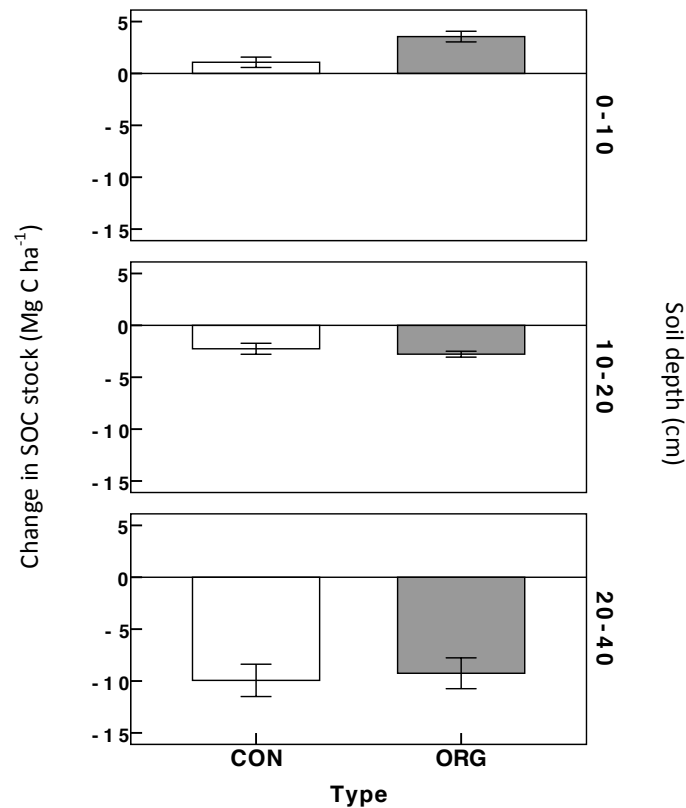


Figure 5.3 Change in mean SOC stock (\pm SE) (Mg C ha^{-1}) between 2001 and 2010 for three soil depths (cm) of conventional (CON) ($n = 72$) and organic (ORG) ($n = 54$) coffee management treatments in a coffee agroforestry experiment in Costa Rica.

The difference between management treatments is likely to be due to the application of organic fertilisers (at up to $11.25 \text{ Mg ha}^{-1} \text{ yr}^{-1}$), as no significant differences were found between these sub-plot treatments for total inputs of above-ground biomass to the soil in the form of senescent leaf litter and pruned material ($p = 0.24$). Further, there was a positive correlation between the mass of organic fertiliser inputs and changes in 0-10 cm depth SOC ($r = 0.42$, p (one-tailed) < 0.01 , Table 5.2). Both conventional and organic managements showed a consistent decline in SOC stocks at the two lower soil depths with no significant between-treatment differences

(Figure 5.3). Changes in total 0-40 cm depth SOC stock showed no significant correlations with either pruning or organic fertiliser inputs.

In Nicaragua no significant differences in changes of SOC stock between the organic and conventional treatments were detected for any soil depth (Figure 5.4). Nevertheless, the trends were generally similar to Costa Rica, with a greater increase of SOC stock at 0-10 cm depth in the organic compared with the conventional treatment and in the 20-40 cm depth a similar decrease in SOC stock between them. In Nicaragua, like Costa Rica, there was a positive correlation between the mass of organic fertiliser inputs and changes in 0-10 cm depth SOC ($r = 0.26$, p (one-tailed) < 0.05 , Table 5.2).

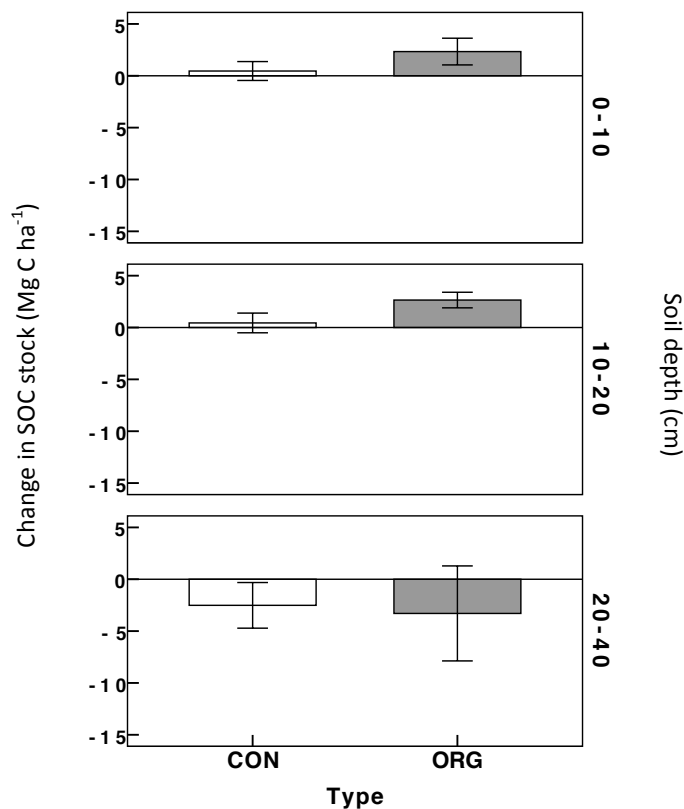


Figure 5.4 Change in mean SOC stock (\pm SE) (Mg C ha^{-1}) between 2001 and 2010 for three soil depths (cm) of conventional (CON) ($n = 72$) and organic (ORG) ($n = 54$) coffee management treatments in a coffee agroforestry experiment in Nicaragua.

5.3.4. Relationships between above-ground biomass and soil organic carbon stocks

In Costa Rica there was a highly significant ($p < 0.001$) negative correlation between SOC stocks in 2001 and the change in SOC stocks between 2001 and 2010, however there was no significant

correlation between above-ground C (AGC) stocks and SOC stocks in 2010 (Figure 5.5). In contrast, in Nicaragua there was a weaker, though still significant, negative correlation between SOC stocks in 2001 and the change in SOC stocks between 2001 and 2010 but a highly significant ($p < 0.01$) positive correlation between AGC and SOC stocks in 2010 (Figure 5.5). Changes between 2001 and 2010 in 0-10 cm depth SOC stock were not significantly correlated with 2010 AGC in either country (Table 5.2). However, increases in the 0-10 cm depth SOC stock were significantly positively correlated with the quantity of organic inputs in every form (fertiliser, prunings and litter (except for pruning inputs in Nicaragua which were non-significant)), the strongest correlation being with organic fertiliser inputs (Table 5.2).

Table 5.2 Pearson and Kendall's correlation coefficients (r) and probability values (one-tailed test, p) between above-ground carbon stocks in 2010, changes in soil organic carbon stocks (2001-2010) and mean annual organic dry matter inputs in the form of organic fertilisers, prunings and leaf litter in 2009 in Costa Rica (grey cells) and Nicaragua (white cells).

Correlation	AGC 2010	SOC change in 0-10cm	Pruning inputs	Organic fertiliser inputs
AGC 2010	-	$r = 0.11$ $p = 0.25$	$r = 0.58$ $p < 0.001$	$r = 0.30$ $p < 0.05$
SOC change in 0-10 cm	$r = -0.09$ $p = 0.29$	-	$r = -0.08$ $p = 0.31$	$r = 0.26$ $p < 0.05$
Pruning inputs	$r = -0.41$ $p < 0.01$	$r = 0.29$ $p < 0.05$	-	-
Organic fertiliser inputs	$r = 0.08$ $p = 0.30$	$r = 0.42$ $p < 0.01$	-	-
Litter inputs	$r = 0.45$ $p < 0.01$	$r = 0.26$ $p < 0.05$	$r = -0.03$ $p = 0.42$	-

- Not applicable or measured.

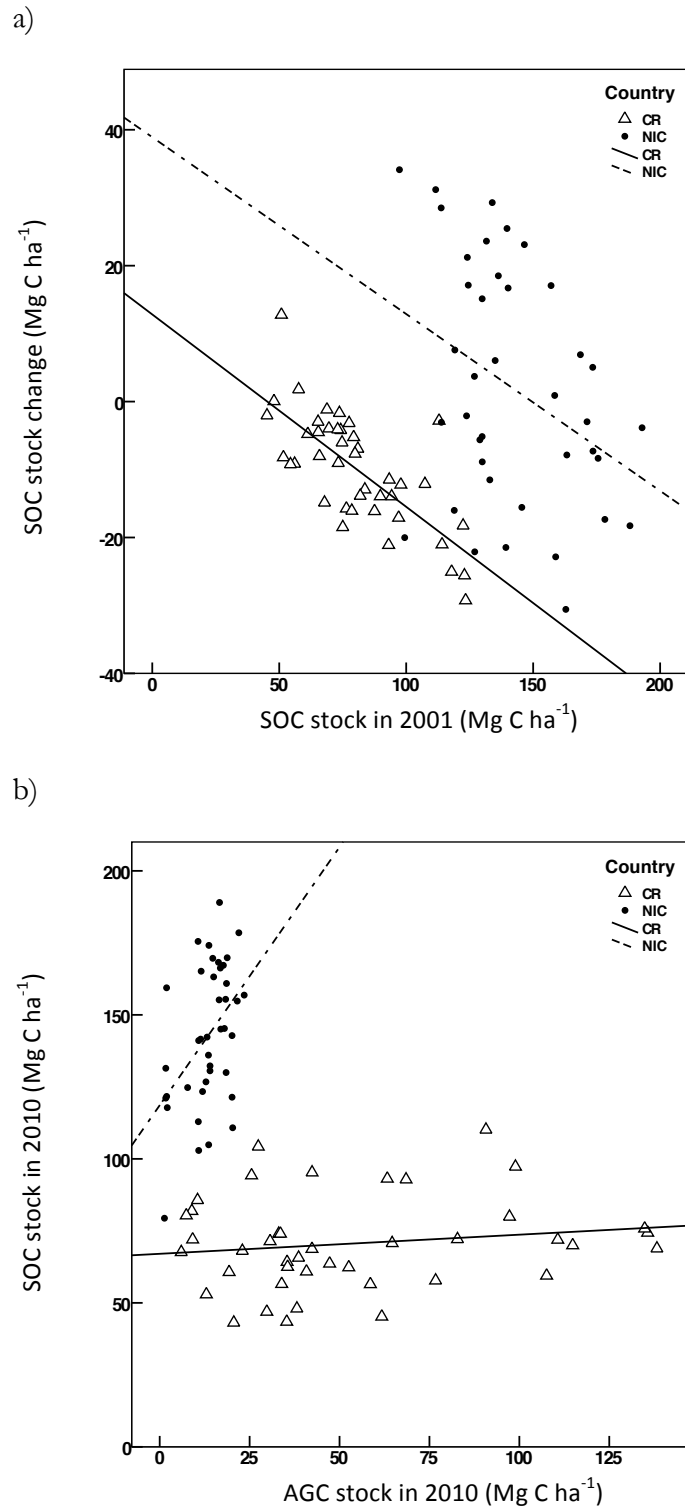


Figure 5.5 Correlation between a) AGC and 0-40 cm depth SOC stocks (Mg C ha^{-1}) in 2010 and b) 0-40 cm depth SOC stocks in 2001 (SOC_{01}) and SOC stocks in 2010 (SOC_{10}) (Mg C ha^{-1}) for all replicate main-plot sub-plot combinations in Costa Rica (CR) and Nicaragua (NIC), plotted as individual points. Fitted lines: a) $\text{SOC}_{\text{CCR}} = 12.5 - 0.281 * (\text{SOC}_{01})$ [$r^2 = 0.52, p < 0.001$]; $\text{SOC}_{\text{CNIC}} = 49.7 - 0.346 * (\text{SOC}_{01})$ [$r^2 = 0.17, p < 0.05$] and b) $\text{SOC}_{\text{CR}} = 67.2 + 0.067 * (\text{AGC})$ [$r^2 = 0.02, p = 0.34$]; $\text{SOC}_{\text{NIC}} = 119.9 + 1.743 * (\text{AGC})$ [$r^2 = 0.20, p < 0.01$].

5.4. Discussion

5.4.1. Do trees help to sequester more C in soil?

It is important to understand the effects on SOC of change in land use systems or agricultural practices when assessing their potential environmental impact. It is widely acknowledged that shifting from natural to managed ecosystems, such as arable cropping, results in a loss of SOC (Powlson et al., 2011b). In the present study, the plots with initially higher SOC stocks tended to have greater SOC losses (or smaller gains) during the observed period of coffee system establishment, notwithstanding the major difference between them in shade tree and coffee management treatments (Figure 5.5). This indicates that these systems, with biomass dominated by woody plants and limited soil disturbance after crop establishment, are in a transition towards a new equilibrium between inputs of organic matter and SOC stocks. Specifically, in Costa Rica the change in land-use from long-term arable sugar cane agriculture to an agroforestry system with perennial coffee and shade trees does not lead to an increase in SOC stocks over the first nine years, which is contrary to the widely held expectation (Powlson et al., 2011b). In fact, we found a nine-year decrease in SOC stocks over 0-40 cm depth by an average, across all shade types, of 9.99 Mg C ha⁻¹ (12.4%) in Costa Rica, whereas in Nicaragua (where the long-term land use before the experiment had been the same as afterwards, shaded coffee) there was a much smaller decrease in average 0-40 cm depth SOC stock of 0.2 Mg C ha⁻¹ (0.14%).

The direction of change in SOC stocks varied with soil depth in a similar way between the two countries. In both countries there was an increase in 0-10 cm depth SOC stocks which was positively correlated with the input mass of organic fertiliser (and in Costa Rica of prunings and litter too). This shows that, although their long-term development is influenced by soil type, climate, management and the SOC-storage capacity of the soil (Fließbach et al., 2007), SOC stocks in the surface do also depend on the quantity of above-ground organic matter inputs (Carter et al., 2002; Parton et al., 1996). This is further supported by the significant differences in SOC stock changes between the treatments with pruned and un-pruned trees in Costa Rica, though all treatments showed a huge contrast in trends of SOC stock with soil depth between an increase at 0-10 cm and a decrease at 20-40 cm.

Despite the huge variation in above-ground biomass between the shade treatments (between an average of 9.1 Mg C ha⁻¹ for full sun, 22.6 Mg C ha⁻¹ for pruned leguminous shade systems and 115.8 Mg C ha⁻¹ for unpruned timber shade systems (Chapter 4), there were no significant differences in SOC stock changes between the shaded and full-sun systems at any depth. As the above-ground biomass was entirely represented by trees and coffee bushes planted at the start of

the experiment, the 2010 biomass standing stock directly corresponds to biomass growth rate. There was a difference between the two experiments in the relationship between above-ground biomass and SOC stocks. In Nicaragua SOC stocks were correlated with above-ground biomass C stocks (though r^2 was only 0.20) but there was no such correlation in Costa Rica. This lack of universality in relationships between above-ground biomass and soil carbon stocks indicates the potential for introduction of a large error into calculations of total ecosystem C stocks when they include estimates of SOC stocks based simply on an assumed linear correlation with above-ground biomass as is commonly used in some of the small-scale afforestation and reforestation C accounting methodologies described in the introduction (UNFCCC, 2011b). Therefore, it is just as essential that soil be adequately sampled and SOC measured directly, as it is for an adequate inventory of above-ground biomass.

5.4.2. Do tree-based systems sequester more C in deeper soil layers?

In both the Nicaraguan and Costa Rican experiments during the nine years of coffee and tree establishment, SOC stocks in 20-40 cm depth soil generally decreased (and this also occurred in 10-20 cm depth soil in Costa Rica, giving an average loss over 10-40 cm of 12.1 Mg C ha⁻¹). The stocks of SOC in deeper soil are generally considered to be more stable than in the surface layer, reacting more slowly to changes in the land-use system (Jenkinson and Coleman, 2008). There are strong limitations to the rate of incorporation of organic material from the soil surface into deeper soil layers, where SOC stocks are predominantly controlled by mechanisms mediated by root systems (both direct inputs of organic matter through root turnover, exudation, mycorrhizas and herbivory, and indirect effects, e.g. due to the effect of the root sink on soil water relations). In the Costa Rican experiment reduction in average SOC stocks in 10-40 cm depth soil occurred in all shade and management treatments. This SOC decomposition might have been stimulated by an increase in aeration which could in turn have accelerated the effect of labile C from root systems priming the soil microbes to accelerate their depletion of existing SOC stocks (33-35). Such aeration could have been due to greater transpiration of coffee bushes/trees compared with the previous annual crop of sugar cane (Dunne and Leopold, 1999; Richter et al., 1999; Richter et al., 2007) and/or to the drainage carried out as part of the site preparation for the experiment, although the redox zone in the soil profiles would suggest that the previous high water level was below 50 cm (Haggar, unpublished data). In the Nicaraguan experiment the previous land use had been coffee with shade trees and no drainage was carried out, and its reduction in average SOC stock in deeper soil had been much less (only 2.85 Mg C

ha⁻¹ at 20-40 cm soil depth). Nonetheless, a reduction did occur in all four management treatments and four out of the five shade treatments, therefore (on balance) the present study does provide some evidence of the generality of this phenomenon to the development phase of coffee systems after replanting and during the rapid early growth during shade tree establishment. It cannot just be attributed to the particular conditions at the Costa Rican site. A similar result was found in a long-term forest re-establishment experiment in South Carolina where, over the 50 years of loblolly pine establishment after previous arable land use under cotton, SOC stocks increased in the surface soil but decreased in the soil deeper than 35 cm (Richter et al., 2007).

In order to compare SOC stock changes between coffee cultivation and the previous land use at the site in Costa Rica (sugar cane cultivation), SOC was also monitored in the surrounding fields, which continued to be used to grow sugar cane without additional drainage. SOC stocks in the sugar cane fields showed an opposite trend to that in the experiment at each depth: decreasing by 11% in the 0-10 cm depth soil, but increasing greatly at 10-40 cm (by 42%), giving an overall increase of 16.0 Mg C ha⁻¹ (19%) over the nine year period. Here, fields are annually fertilised primarily with N-based fertilisers, burned before harvest and periodically tilled before replanting (the latter is likely to be a major factor in the loss of SOC from the surface soil). Similar results have been found by other studies where the long-term cultivation of sugar cane that is burnt before harvesting resulted in a decrease in SOC stocks at 0-10 cm depth (Galdos et al., 2009) and an increase in SOC stocks at 20-40 cm to levels near those of natural forest (Silva et al., 2007). Grass species such as sugar cane are known to input carbon into deeper soil layers quicker than some tree species (Bashkin and Binkley, 1998). Changes in SOC in an experiment in Hawaii in which land formerly under sugar cane cultivation was afforested with a fast growing eucalyptus plantation showed remarkably similar results. Measured using stable isotope ratios to examine changes in soil organic C derived from cane (SOC₄) and eucalyptus (SOC₃), 10-13 years after establishment SOC in the top 10 cm had increased by 11.5 Mg ha⁻¹ in the eucalyptus plantation but decreased by 10.1 Mg ha⁻¹ in the 10-55 cm depth soil (Bashkin and Binkley, 1998). These losses in deeper soil were indicated by losses of SOC₄ derived from sugar cane being much greater than the gains of SOC₃ in this layer attributed to the growth of the eucalyptus. Similarly in the present study's experiment in Nicaragua, although the prior land-use was a coffee agroforestry system, the accumulation of organic matter inputs to the soil was disrupted by its clearance and the subsequent re-establishment of new coffee and shade trees. As a result, the levels of organic matter input of the previous system will have only been reached after several years. In addition, the penetration of roots into the deeper soil, and thereby the deposition of C

at that depth (which showed the greatest decrease in SOC stocks) would have been delayed during the establishment of the new trees and coffee bushes. Thus, although tree-based systems might have a greater potential to sequester C into more stable stocks in deeper soil than some treeless systems (Haile et al., 2010), this is strongly influenced by other site- and land use change-specific variables.

5.4.3. Organic versus conventional management

The results of the present study showed that coffee production systems under organic management increased SOC stocks in the top 10 cm of soil more than did conventional production systems in Costa Rica (with a highly significant ANOVA test result), but not in Nicaragua. However evidence for the generality of this result was provided by the more powerful mixed effects model which showed that management system had a greater effect on changes in 0-10 cm depth SOC concentration than did shade type in both countries. The mixed effects model applied to all three soil depths also showed that management system was an important factor influencing changes in SOC concentration (as well as depth itself) in both countries.

In the last decade much attention has centred on the management of SOC and its potential for climate change mitigation through increased C sequestration into soils. Proponents of organic systems have often claimed that they sequester more C into the soil than do conventional systems (Freibauer et al., 2004; Scialabba and Müller-Lindenlauf, 2010). Recent studies (Sanderman and Jeffrey, 2010; Powlson et al., 2011a; Powlson et al., 2011b), however, have warned of the shortcomings of many field trial results and of current C-accounting methodologies that can over-estimate the net sequestration of C into soil. The term sequestration is often used simply to describe an increase in SOC stocks over time following a change in land-use system or practice. Powlson et al. (2011b), however, argue that these changes only contribute to climate change mitigation if they do actually result in a net additional transfer of C from atmospheric CO₂ to soil or vegetation, which is not necessarily the case. At the centre of this argument lies the issue exemplified by the question of how the fate of organic C input would have differed were it to have an alternative use. For example, management practices that increase SOC through application of manure and other organic materials such as crop residues or pruning inputs are often only a transfer of C from one terrestrial pool to another (Powlson et al., 2011b). If alternative uses would have stored the C for longer (e.g. in solid wood products or through conversion of the organic material to biochar) or would have substituted for fossil fuel emissions (e.g. from domestic cooking) then they may have had a more positive effect on climate

change mitigation. Even restricting assessment to the soil itself, changes in land management that increase SOC stocks could still have a detrimental net climate change impact by increasing emissions of non-CO₂ greenhouse gases (GHG) such as CH₄ and N₂O which have much higher global warming potentials (25 and 298 times respectively over 100 years) compared with CO₂. For example, in Chapter 3 we estimated that the coffee management systems of the present experiments produced non-CO₂ GHG emissions from soil ranging between 0.66 and 2.24 Mg CO₂e ha⁻¹ yr⁻¹ for the conventional and 0.55 and 2.02 Mg CO₂e ha⁻¹ yr⁻¹ for the organic treatments. Especially in the organic systems, which have additional organic matter inputs in the form of manures and coffee pulp, the climate change mitigation potential of the gains in SOC stock in the 0-10 cm depth soil equate to an average of 1.45 Mg CO₂e ha⁻¹ yr⁻¹ in Costa Rica and 0.88 Mg CO₂e ha⁻¹ yr⁻¹ in Nicaragua, both of which lie well within the range of estimated non-CO₂ GHG emissions from soil resulting from the inputs of organic matter. Therefore, the organic management may lead to no net mitigation of global warming via the soil and may even cause net GHG emissions. This calculation, however, does not include the GHG emissions associated with the transport of the organic material, or consider which of the emissions would also occur if the organic material is subject to alternative uses or fates, while analysis of conventional coffee management also needs to include the emissions associated with the production and transport of the agrochemicals that are used (Powlson et al., 2011b). Incorporation of some of the chicken manure and coffee pulp applied to coffee farms into the soil might result in lower GHG emissions than their decomposition in open air, should the soil have a capacity to absorb some of the CH₄ and N₂O emissions, which would be a priority for future research.

Through their increase in the SOC content of upper soil layers, organic amendments can improve physical soil properties that are beneficial for crop production (Powlson et al., 2011a). This improvement in soil growing conditions might achieve equivalent yields to those obtained with higher applied nutrient contents in inorganic fertiliser, thereby reducing the net GHG emissions (especially of N₂O) of the farming operation. Increased biomass growth rates of perennial crops and shade trees resulting from improved soil properties will further contribute to a real reduction of atmospheric CO₂ concentration while the biomass remains intact. The existing condition of the soil is also an important consideration. The results of the present study show that where agroforestry systems are established on soils more depleted in SOC content they provide a greater potential for climate change mitigation through higher SOC stocks, at least until a new equilibrium in SOC content is reached (Johnston et al., 2009). Therefore, despite the detailed measurement of these experiments, covering many aspects of C stocks and GHG

emissions, it remains difficult to answer the question of the extent to which organic management is more favourable to mitigating global warming compared with conventional management, such as the complexity of processes involved.

The diversity of net changes in SOC stocks amongst treatments found in the present study in Nicaragua and in Costa Rica illustrate the complexity of predicting which changes in existing coffee production systems will have a net positive or negative impact, especially where they involve soil-disturbing agronomic operations. The long timescale for changes in SOC stocks to become manifest also presents a challenge for the evidence. There was an overall mean decrease of 0-40 cm depth SOC stocks in eight of the ten shade treatments over the nine years after system establishment. However, positive effects of shade tree growth might be realised over the longer term. As already reported in many previous studies (Bashkin and Binkley, 1998; Binkley et al., 2004; Poulton et al., 2003; Resh et al., 2002; Richter et al., 1999) the benefits of shade trees in terms of sequestration of C into aboveground biomass are already apparent. For Costa Rica there was a range of mean sequestration rates per shade treatment of 3.3-12.9 Mg C ha⁻¹ yr⁻¹ (chapter 4), more than five times the rates of loss of 0-40 cm depth SOC (with a range of 0.65-1.54 Mg C ha⁻¹ yr⁻¹ per shade treatment) reported in the present paper. In Nicaragua, mean above-ground C sequestration rates ranged between 1.73 and 2.70 Mg C ha⁻¹ yr⁻¹ per shade treatment (Nojonen unpublished data) which are again higher than the loss or gain of 0-40 cm depth SOC reported here (ranging from 0.44 Mg C ha⁻¹ yr⁻¹ loss to 1.58 Mg C ha⁻¹ yr⁻¹ gain). Overall the results of this nine-year study show that the C stock changes down to 40 cm soil depth were greatly outweighed by the C gains in the above-ground biomass. While loss of SOC below 40 cm depth probably also occurred, it is improbable that it matched the increases in above-ground biomass. This further emphasises the importance of both conservation of tree biomass in established forest and agroforestry systems and avoiding practices that reduce stocks of SOC.

Land use decisions designed to take into account impacts on climate change mitigation should be based on analyses that include all of the major components. For example assessment of alternative agricultural soil management systems that change SOC stock should take into account not only carbon sequestration in the soil, but also emissions of all GHGs, impacts on biomass growth rate of all system components and impacts on crop yield (with its potential effect on future farmer management decisions).

Chapter 6

Carbon and socio-economic performance: trade-offs in coffee agroforestry systems in Costa Rica and Nicaragua

6.1. Introduction

Research into the functioning of forestry systems and agroforestry systems (AFS) as carbon sinks has been an integral part of efforts to reduce emissions of greenhouse gases (GHG) from land use. The agriculture and forestry sectors account for up to a third of global emissions and deforestation and degradation of mostly tropical forests alone are estimated to contribute 17.4 % of global emissions (IPCC, 2007c). Consequently, the management and protection of carbon stores in tropical forests is an imperative

It has been widely acknowledged that AFS have the potential to contribute to climate change mitigation. Through the inclusion of trees, these agricultural production systems not only have the capacity to sequester large amounts of carbon in living biomass and soil (Albrecht and Kandji, 2003; Dossa et al., 2008; Kandji et al., 2006; Mutuo et al., 2005; Segura et al., 2006; Soto-Pinto et al., 2010; Verchot et al., 2007) but also, through the provision of other ‘goods and services’ such as wood fuel and building material, can indirectly reduce emissions from forest degradation and deforestation. The management inputs and the difference in shade, and their interaction, will determine both the net GHG flux of the system and its profitability, but in both cases this will be moderated by the natural environment and socio-economic context in which the farming is being carried out.

In addition to their climate change mitigation potential, AFS can sustain and diversify agricultural production, providing and enhancing social, economic and environmental benefits (Nair et al., 2009a). Accordingly, AFS are often considered to bridge the gap between natural forests and treeless agricultural monocultures, conserving biodiversity and providing a range of ecosystem services whilst at the same time supplying significant economic returns (McNeely and Schroth, 2006; Perfecto et al., 2005; Verchot et al., 2007). The profitability of these systems, however, depends on a host of management, biological and climatic factors. These make it difficult to generalise about what is the “optimal” agroforestry system when balancing climate change mitigation and socio-economic performance. Nevertheless, efforts have been made to quantify and compare the carbon sequestration performance (Dossa et al., 2008; Payán et al.,

2009) and profitability (Lyngbæk et al., 2001) of different coffee agroforestry systems (CAFS) for various regions in order to identify favourable systems locally. Furthermore, assessments have been made of these trade-offs in different agroforestry shade systems under various types of management. For example, in Chapter 4 of this thesis I have argued that the intensification of CAFS can help to reduce emissions from forest degradation and deforestation by reducing the need for further conversion of forested land to less productive coffee systems in order to meet market demand for coffee. That study based on an experiment also showed that different highly intensified shaded CAFS could be made financially viable if payments for avoided emissions could be received through C-market mechanisms similar to those that are currently promoted under REDD (reducing emissions from deforestation and forest degradation). The break-even payment levels needed to equal the benefits from converting coffee production from shaded to un-shaded (with greatly reduced C stocks in living biomass) varied greatly between systems: 9 to 196 US\$ Mg CO₂e⁻¹ (Chapter 4). So far, however, little evidence has been published of the success of AFS within C-market mechanisms and, indeed, few such case studies exist. Although there are a number of mechanisms within the compliance and voluntary C markets which could enable CAFS projects to benefit from C-offset payments, as a whole land-based C sequestration projects have had a relatively minor role in those markets, especially within the dominating compliance market (UNFCCC, 2012a).

Due to their diverse forest-like structures and relatively long rotation times, it has recently been suggested that CAFS could be considered for qualification under REDD (+) activities (Soto-Pinto et al., 2010). This will depend, however, on the current C status of the farm system; farms with comparatively lower levels of stored C may be more suited to C enhancement projects such as ‘improved (agro) forest management’, with C payments to cover the costs of project implementation (tree-planting) activities and possible resulting reduction in coffee yield. The suitability of different farm types for different C project types therefore needs to be considered.

Within the coffee industry there has already been a high level of uptake of voluntary certification schemes as marketing mechanisms that variously aim to increase social welfare, economic stability of farmers and environmental performance. Although climate change issues have recently been taken into consideration by some certification bodies such as the Rainforest Alliance, who have been promoting the increase of C stocks in coffee systems in order to benefit from verified C credits (Gibbon et al., 2009), little scientific evidence has been published that identifies the trade-offs between climate change mitigation and socio-economic performance of coffee farms. It is thus important that these trade-offs are examined to ensure that the

consequences of improvement in one area (e.g. increase in biomass stocks) for success in another (e.g. economic condition of the farmer) are well understood in the design of policy and market mechanisms.

Here, we aim to assess the potential synergies and trade-offs between profitability, C storage and GHG emissions associated with CAFS in Costa Rica and Nicaragua under various types of shade and coffee management. In particular we aim to address whether differences exist between conventional and organic farms in these trade-offs. Further, by quantifying C storage and the net profit of the individual farms we assess the importance of shade type in overall system performance and how this is affected by management (e.g. of density of shade or fertilisation intensity). Through this research we aim to inform the debate around the suitability of different farm types to different C market mechanisms (REDD+ versus C enhancement activities) and to further enhance climate add-ons to existing product certification schemes in order to achieve the dual goals of environmental and economic sustainability.

6.2. Methods and materials

6.2.1. Study regions and site characteristics

Farms were studied in two clusters, one in Costa Rica and one in Nicaragua (Figure 6.1). The Costa Rican farms are located within a radius of 20 km of the Tropical Agricultural Research and Higher Education Center in Turrialba (9°53'44"N, 83°40'7"W) between 598 and 1400 m above sea level. The climate of the region is humid tropical with no marked dry season: annual precipitation is 2600 mm yr⁻¹ and annual mean temperature is 22 °C (Hagggar et al. 2011). The soils are very fertile which developed in volcanic materials and have been classified under the two major soil orders Inceptisols in the Turrialba valley and Andosols on the slopes of Volcan Turrialba including Andic Eutropepts and Umbric Andosols (Kass et al., 1995).

The Nicaraguan farms are located within a radius of 20 km of the community of Masatepe (11°54'39"N, 86°08'42"W) between 400 and 700m above sea level. The climate of the region is semi-dry tropical with a distinct rainy season between May and November: mean annual rainfall is 1386 mm and mean annual temperature is 24 °C (Hagggar et al. 2011). The soils of the area have been classified as Andisols or Andosols, Humic Durustands and Humic Haplustands under the USDA Soil Taxonomy classification system (Soil Survey Staff, 1999).



Figure 6.1 Map of Costa Rica and Nicaragua with pins representing the study regions within each country.

6.2.2. Sampling design and frame

To analyse the differences between farming systems in profitability, C storage and GHG emissions, the range of coffee farms in the two study areas were stratified according to their tree components (four types of shade) and coffee management (conventional versus organic). Individual sampled farms were defined as a unit of land under the same coffee management, shade type and ownership. Production areas that were under a single ownership but had different types of management or shade type were considered as separate farms for this research.

A preliminary survey of coffee farms was carried out in the two study areas to determine the range of conditions of farms within each stratum. A sampling frame was created of climatic conditions, soil type and altitude within which each stratum was well represented. Within this frame a sample of farms was chosen to be representative of the range within each stratum.

The four shade types were:

- i. Full sun, farms with no shade cover
- ii. Leguminous shade, farms with shade cover of leguminous trees that are mostly managed for their ‘services’ such as N fixation and organic matter inputs of high N content

- iii. Timber shade, farms under a shade cover of timber trees that are managed for their timber value
- iv. Mixed shade (leguminous and timber shade mixture), farms under a mixture of the two systems described above.

The two coffee management types were:

- i. Conventional, farms that use agrochemicals as part of their agronomic measures for fertilisation and pest control
- ii. Organic, farms that only use organic compounds and soil amendments (however, to be included in this category farms did not have to be registered under an official organic certification scheme).

6.2.3. Data collection

6.2.3.1. Farm surveys

As the aim of this study was to compare profitability, C storage and GHG emissions from different coffee farming systems, the system boundaries were drawn at the farm gate, including only those costs, benefits and emissions directly associated with the production and management of a particular farming system. In total 910 and 1014 hectares under coffee cultivation were surveyed in Costa Rica and Nicaragua respectively. This included 47 farms in total with 21 in Costa Rica and 26 in Nicaragua. Of those, 16 and 20 for Costa Rica and Nicaragua respectively were under conventional management whereas the remaining farms were under organic management.

We carried out structured interviews with each farm owner or farm manager responsible for the day-to-day running of the coffee farm. The questionnaire (Appendix 2) consisted of socio-economic and biophysical aspects of the management of the farming system. Questions relating to the socio-economic aspects covered coffee yields and revenues, and management and material inputs and their costs. Questions related to the biophysical aspects were designed to provide some of the data from which above-ground carbon (AGC) stocks and fluxes could be calculated, e.g. species and densities of shade trees and coffee bushes, the level of their pruning and their use, and average shade tree age of different tree species present. In the majority of cases farmers had kept a detailed account of management inputs; where prices were not available for past inputs historical data of corresponding inputs from on-going CAFS experiments in the same area of each country (Chapter 4) have been used.

The price of coffee and any additional products from the farming area, such as firewood or fruits, were recorded for each production year for the past three years. Coffee prices were distinguished between regular and premium prices, the latter of which can be obtained for certified and/or organic management.

6.2.4. Estimation of carbon stocks

Within each farm, three sampling blocks each of 500 m² (25 x 20 m) were established in stratified random locations; each farm was surveyed before the sampling to assess any variation in the structure and the current management cycle (i.e. pruning stage) to ensure a representative sample of C stocks for the farms. The sampling blocks were then established randomly in the stratified areas of the farm with the first corner of the sampling plot being marked within a coffee row. From there the sampling plot was laid out 25m along the coffee row and 20m across the coffee rows. Trees that fell outside the coffee rows within the sampling block were not included in the assessment. The following variables were then recorded: diameter at breast height (DBH), height (h_T) and species (SP_T) of all shade trees over 5 cm in diameter, diameter of the widest stem at 15 cm above ground (D_{15}) and height (h_C) of 30 randomly-selected coffee bushes, total number of coffee bushes within the sampling area (n_C), the number of coffee bushes that had been pruned within the last three years (n_{prun}), and the average distances between coffee bushes within (d_w) and between (d_b) rows.

Above-ground biomass stocks for each farm were then estimated using allometric equations. A number of allometric equations have been developed for the main shade tree species associated with coffee farming in the region (Appendices 1 and 4). If species-specific equations were not available, default allometric functions as recommended by IPCC (IPCC, 2003) were used. Basal area (BA) was calculated according to the IPCC specification (IPCC, 2003).

Below-ground biomass for shade trees was estimated using a function developed by Cairns et al. (1997) and recommended by IPCC (2003). Above-ground coffee biomass stocks were calculated using the allometric equations developed by Segura et al. (2006). Similarly, the equations of Dossa et al. (2008) for coffee in shaded and unshaded systems were used to estimate coffee bush below-ground biomass.

Soil C stocks were assessed by taking soil samples from three different sampling positions relative to shade trees in each sampling block: (a) within 1 m of the tree stem; (b) half way between two shade trees within the same coffee row; (c) half way between positions (a) and (b). For each of these sampling positions three sub-samples were taken at different points within

coffee rows: (i) within the row; (ii) between rows; (iii) half way between points (i) and (ii). At each point soil samples were collected at three different depths: 0-10, 10-20 and 20-40 cm. Samples collected in each block were thoroughly mixed and then a single composite sample was taken for analysis of C content. The composite samples for each depth for each block were air dried on the same day as collection from the field. They were then ground and sieved through a 2-mm sieve to remove larger pieces of root material and the stone fraction. An additional soil sample to determine bulk density was also collected from the centre of each block for each of the three depths by inserting a 5 x 7.5 cm metal tube horizontally into the middle of the depth horizon in a dug soil pit located between coffee rows. The samples were then oven dried to constant dry mass at 105 °C, sieved to separate the fine fraction from the stones (> 2 mm), and then both fractions were weighed. The soil samples from the two countries were analysed for bulk density at the Universidad Nacional Agraria (UNA) in Managua, Nicaragua and at the Soil Laboratories of the Centro Agronómico Tropical de Investigación y Enseñanza (CATIE) in Turrialba, Costa Rica.

6.2.5. Costs and benefits of farming systems

A cost benefit analysis (CBA) was carried out for each farm. All economic and management data were obtained for the three years 2007, 2008 and 2009 to reflect changes in economic conditions, such as coffee price fluctuations, the increase in fertiliser prices and the biennial yield pattern of coffee. To enable CF calculation the material inputs were divided into the following categories: (a) organic and inorganic fertilisers, (b) pesticides, (c) fuels and (d) materials and sundries, including coffee seedlings for replacement or restoration. Labour and management were divided into categories of tasks commonly associated with coffee farming. Income from additional products obtained from the farming area, such as firewood, fencepost material, timber and fruits, was taken into account, as well as coffee, in the calculations as these, according to PAS 2050 (BSI 2011), have to be apportioned a part of the CF according to their overall financial value. Annualised averages of management and resource inputs, and then the annualised net benefit (NB) of each farm, were then calculated. The NB is expressed as the difference between the present value of benefits (PV_B) and the present value of costs (PV_C). No discounting of PV_B or PV_C has been carried out for the purpose of calculating the NB.

6.2.6. Calculation of carbon footprints

PAS 2050 (BSI, 2011) is the only transparent and publically available product CF methodology published to-date and has therefore been chosen here for all CF calculations. Within this method, all GHGs (including CO₂, N₂O and CH₄) are accounted for and converted into units of CO₂-equivalents according to their global warming potential (GWP) over 100 years. All GHG emissions associated with the provision and use of raw materials and energy are included in the calculation. Capital goods, human energy inputs such as manual labour, transport of employees to and from the workplace and animals providing transport are excluded from PAS 2050.

Of specific relevance to agricultural CFs are non-CO₂ emissions from livestock, their manure and soils, which must be included, calculated according to IPCC guidelines for national GHG inventories (De Klein et al., 2006). Nitrous oxide emissions from soils are accounted for through including direct and indirect emissions resulting from N additions, deposition and leaching. As all land under study here was verified as being under agricultural production prior to 1990 in the interviews with the farmers, no direct emissions from land use change (LUC) have been included. Changes in soil C stocks, due to losses in emissions or eroded material, or due to sequestration, are excluded from PAS 2050 unless they are a direct result of LUC activities. Carbon stored in living organisms such as trees or perennial crops is excluded from the PAS 2050 method. A more detailed description of the methodology and calculations used are described in Chapter 3. All CF calculations have been carried out using the calculation tool CAFCA described and shown in detail in Appendix 1.

Carbon footprint calculations for each system were based on annualised averages of all inputs and yields for 2007-2009, to best represent the different production systems. The functional unit (unit of production) was set at 1 kg of non-processed fresh coffee cherries.

For all coffee managed with conventional systems, emissions from the production of inorganic fertilisers and pesticides were extracted from the Ecoinvent database (Nemecek et al., 2007). Only commercial fertiliser and pesticide products were assigned production emissions; PAS 2050 states that emissions should be assigned according to a product's economic value rather than its mass, thus the production emission from one industry (e.g. chicken farming) should be partitioned between its products (e.g. chicken meat and manure) according to their respective commercial values. In the case of these coffee production systems, however, organic fertilisers such as chicken manure and coffee pulp were assumed to be waste products of another industry with no economic value, and thus were assigned no production emissions. Although data on GHG emissions from production of poultry manure can be found within the

Ecoinvent database, we considered these values excessive for this study as the database values include processing emissions from drying, granulation and packaging (Nemecek et al., 2007) which are not part of the manure production process in Costa Rica or Nicaragua.

Emissions were calculated for the transportation of materials and fertilisers from their place of purchase to the farm sites; to allow for comparability a default transport distance of 10 km was chosen for all farms. Emissions arising from the production and use of fuels such as gasoline and lubricants, used mostly for weed control, and materials and sundries used in farm management were also included in the calculations. Emission factors for the production and manufacturing processes of individual inputs were obtained from the publically available database of the Renewable Fuels Agency (RFA) and Ecoinvent (Althaus et al., 2007; Classen et al., 2009). Costa Rica-specific EFs for diesel and gasoline were sourced from a report used in the Costa Rican national GHG inventory (MINAET, 2007) and used for both countries' footprints. No electricity was consumed in the on-farm operations. For calculating N₂O emissions from soil we followed IPCC recommendations and chose a regional-specific EF established by Hergoualc'h et al. (2008) for N fertiliser application of 1% (kg N₂O-N(kg N)⁻¹) for timber-tree and full-sun coffee production systems and 1.2% for leguminous-shade systems respectively, and the value 0.3% for pruning inputs.

6.2.7. Statistical analysis

Independent sample t-tests of the differences between conventional and organic farms and analysis of variance of the difference between the four shade types (GLM procedure SPSS vers. 19) were carried out separately for each country for the following outcome variables: above-ground carbon in living biomass (AGC), soil organic carbon (SOC), total carbon stocks (TC), greenhouse gas emissions associated with the farming of coffee (also known as the carbon footprint, CF), the economic net benefit of the individual farm (NB), and coffee yield. A post hoc pairwise comparison was performed using the Games-Howell multiple comparison test at a risk level of $\alpha = 0.05$ (Field, 2009). Further, bivariate correlation analyses using Pearson's correlation coefficient for parametric data and Spearman's correlation for non-parametric data (Table A6.1) were carried out between yield, CF, AGC, SOC, TC, BA and NB. These correlation tests were carried out combining all farms in both countries using SPSS (vers. 19). Statistical significance is judged as $p < 0.05$ unless otherwise stated in the text.

6.3. Results

Shade systems in Nicaragua were much more diverse with up to 19 shade tree species within one farm compared with five in Costa Rica. However, greater tree densities (mean of 249 (± 41 SE) trees ha^{-1}) were recorded in Costa Rica compared with an average tree density of 218 ha^{-1} (± 17 SE) in Nicaragua. Nevertheless, significantly lower basal area ($p < 0.01$; 10.6 $\text{m}^2 \text{ha}^{-1}$ (± 2.11) and 20.8 $\text{m}^2 \text{ha}^{-1}$ (± 2.59)) and AGC for shaded systems ($p < 0.001$; 29.00 Mg C ha^{-1} (± 3.87) and 67.96 Mg C ha^{-1} (± 5.90)) were recorded for Costa Rica compared to Nicaragua respectively.

Most of the farms sampled in Costa Rica had significantly higher ($p < 0.01$) densities of coffee (mean 4798 (± 174 SE) ha^{-1}) under a single species of shade tree or a two-species two-storey shade tree structure; in comparison mean coffee density in Nicaragua was 3886 (± 191 SE) ha^{-1} and the shade tree structure usually much more complex. The only exceptions in Costa Rica were a number of small organic farms which had diversified their shade to include a number of fruit tree species. The average tree age on coffee farms in Nicaragua (74 (± 5.6 SE) years) was significantly higher ($p < 0.01$) than in Costa Rica (40 (± 7.6 SE) years). In addition, we found that shade tree density was significant negatively correlated with SOC. Similarly, AGC was significant negatively correlated with yield ($p < 0.001$).

6.3.1. Conventional versus organic farming systems

In Costa Rica a significant difference was found between conventional and organic for the coffee yield being twice as large in conventional farms ($p < 0.01$, Table 6.1) and basal area in conventional farms being significantly lower than in organic farms. Despite the significant difference ($p = 0.004$) in CF per ha between organic and conventional systems (1.26 and 2.78 $\text{Mg CO}_2\text{e ha}^{-1} \text{yr}^{-1}$ respectively) in Costa Rica, absolutely no difference was found between these systems in the CF per kg of yield (Table 6.1) due to the significantly lower yields of organic systems. In contrast, in Nicaragua coffee yield ($p = 0.01$), SOC ($p = 0.03$), CF_{kg} ($p < 0.01$) and CF_{ha} were all significantly greater in the conventional than the organic farms; basal area was found to be higher for organic farms but with no significant difference (Table 6.1).

Nitrogen inputs varied considerably between farms due to the differences in management type (conventional *versus* organic) and in the quantity and quality of pruning inputs from shade trees and coffee bushes. The steeper regression slope of coffee yield – total N input of conventional than organic farms across both countries (Figure 6.2) suggests a greater positive impact of chemical than organic fertiliser on coffee yield, i.e. conventional farms had a higher efficiency of use of applied N than did organic farms.

Table 6.1 Mean (\pm SE) above-ground carbon (AGC), soil organic carbon (SOC), total carbon stocks (TC), carbon footprint per coffee yield and hectare (CF_{kg} , CF_{ha}), coffee yield, economic net benefit (NB) and tree density (TD) in conventional and organic coffee farms in a) Costa Rica and b) Nicaragua, and t-test results for the differences between them.

a) Costa Rica

		Conventional (n=16)	Organic (n=5)	p-value
AGC	(Mg C ha ⁻¹)	23.62 (\pm 3.61)	29.51 (\pm 8.43)	0.47
SOC	(Mg ha ⁻¹)	142.79 (\pm 13.14)	100.48 (\pm 19.67)	0.12
TC	(Mg C ha ⁻¹)	166.4 (\pm 13.48)	130.0 (\pm 13.75)	0.17
BA	(m ² ha ⁻¹)	8.48 (\pm 2.10)	19.27 (\pm 4.70)	< 0.05
CF_{kg}	(Mg CO ₂ e kg ⁻¹ yr ⁻¹)	0.39 (\pm 0.03)	0.39 (\pm 0.05)	0.94
CF_{ha}	(Mg CO ₂ e ha ⁻¹ yr ⁻¹)	2.78 (\pm 0.25)	1.25 (\pm 0.29)	< 0.01
Yield	(t ha ⁻¹ yr ⁻¹)	7.06 (\pm 0.60)	3.38 (\pm 0.71)	< 0.01
NB	(US\$ ha ⁻¹ yr ⁻¹)	491.36 (\pm 196.9)	-123.87 (\pm 299.1)	0.13
TD	(ha ⁻¹)	183 (\pm 31)	342 (\pm 103)	0.07

b) Nicaragua

		Conventional (n=20)	Organic (n=7)	p-value
AGC	(Mg C ha ⁻¹)	59.95 (\pm 7.60)	73.72 (\pm 6.47)	0.32
SOC	(Mg C ha ⁻¹)	196.32 (\pm 8.79)	156.29 (\pm 14.61)	0.03
TC	(Mg C ha ⁻¹)	256.27 (\pm 11.98)	230.00 (\pm 16.61)	0.26
BA	(m ² ha ⁻¹)	18.71 (3.11)	27.07 (3.79)	0.17
CF_{kg}	(Mg CO ₂ e kg ⁻¹ yr ⁻¹)	0.55 (\pm 0.08)	0.12 (\pm 0.02)	< 0.01
CF_{ha}	(Mg CO ₂ e ha ⁻¹ yr ⁻¹)	1.75 (\pm 0.34)	0.25 (\pm 0.06)	< 0.05
Yield	(t ha ⁻¹ yr ⁻¹)	3.09 (\pm 0.37)	1.99 (\pm 0.21)	< 0.01
NB	(US\$ ha ⁻¹ yr ⁻¹)	270.77 (\pm 88.03)	244.19 (\pm 39.71)	0.86
TD	(ha ⁻¹)	210 (\pm 20)	237 (\pm 35)	0.48

6.3.2. Differences in shade types

In both Costa Rica and Nicaragua shade type had a significant effect on AGC and coffee yield ($p < 0.05$) (Table 6.2). Carbon stored above ground was significantly higher under mixed shade than in full sun systems in both countries (and higher than under legume shade in Nicaragua only) ($p < 0.05$) (Table 6.2). Similarly, coffee yield in mixed shade systems was significantly lower than under other shade types ($p < 0.05$). In Costa Rica TC was significantly higher under timber

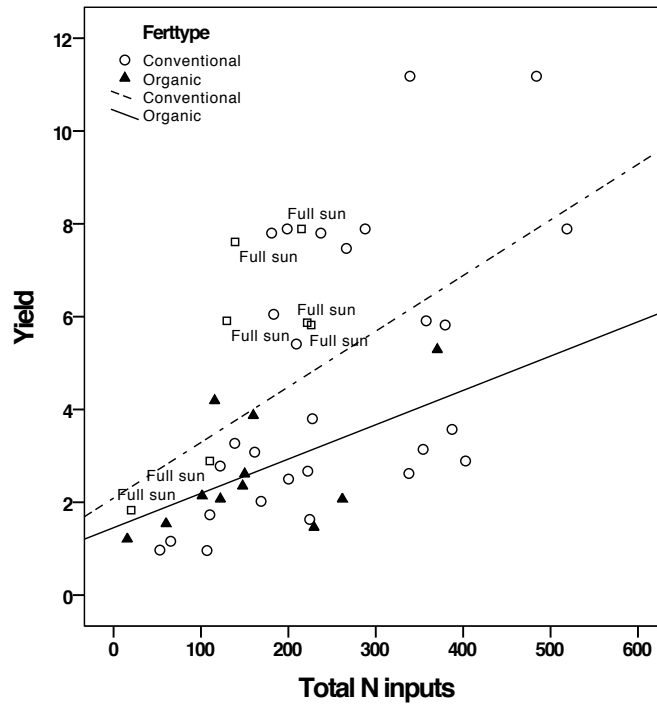


Figure 6.2 Relationship between total organic and inorganic N inputs (TN, kg N ha⁻¹ yr⁻¹) and coffee yield (t ha⁻¹ yr⁻¹) for (a) conventional and (b) organic coffee farms in Costa Rica and Nicaragua. Regression model fit: y (a) = 2.09 + 0.012 * TN ($r^2 = 0.25$, $p = 0.002$); y (b) = 1.45 + 0.007 * TN ($r^2 = 0.32$, $p = 0.06^a$). ^aAlthough r^2 is higher in organic compared with conventional farms p for organic farms remains not significant due to a smaller sample size.

tree shade than in the other shade types ($p < 0.05$). For emissions of greenhouse gases associated with the cultivation of coffee, the highest CFs were found in mixed (0.43 (± 0.04 SE) and 0.73 (± 0.34 SE) kg CO₂ e kg⁻¹ fresh coffee cherries in Costa Rica and Nicaragua respectively) and leguminous (0.43 (± 0.05 SE) and 0.58 (± 0.14 SE) kg CO₂ e kg⁻¹ fresh coffee cherries in Costa Rica and Nicaragua respectively) shade types in both countries although none of the differences amongst types were significant.

6.3.3. Cost-benefit analysis and economic net benefit

There was a strong correlation of total economic benefits with total costs amongst farms in Costa Rica and Nicaragua combined ($r^2 = 0.64$). However NB varied greatly amongst individual farms (Figure 6.3) and there was only weak evidence of difference in NB between conventional and organic farms in Costa Rica ($p = 0.13$) and a very low probability of a difference in Nicaragua ($p = 0.86$) (Table 6.1). Even though the mean values of NB varied greatly amongst shade types, the differences were not significant in either country (Table 6.2). Nevertheless, in Costa Rica (but not Nicaragua) I found a significant positive correlation between NB and total N

input (the sum of different forms of organic and inorganic inputs) as well as between total N input and yield per hectare ($p < 0.05$).

Table 6.2 Mean (\pm SE) above-ground carbon (AGC), soil organic carbon (SOC), total carbon stocks (TC), carbon footprint per coffee yield (CF), coffee yield and economic net benefit (NB) in coffee farms in a) Costa Rica and b) Nicaragua with differing shade types.

Country	Shade type	n	AGC (Mg C ha ⁻¹)	SOC (Mg C ha ⁻¹)	TOC (Mg C ha ⁻¹)	BA (m ² ha ⁻¹)	Yield (t ha ⁻¹ yr ⁻¹)	CF (Mg CO ₂ e kg ⁻¹ yr ⁻¹)	NB (US\$ ha ⁻¹ yr ⁻¹)
Costa Rica	Full sun	5	12.3 ^a	132.5 ^a	144.8 ^a	0.00 ^a	5.8 ^{ab}	0.32 ^a	92.7 ^a
	Mixed	8	35.0 ^b	104.7 ^a	139.6 ^a	18.09 ^b	4.2 ^a	0.43 ^a	43.5 ^a
	Legumes	4	14.5 ^{ab}	138.8 ^a	153.3 ^a	13.52 ^{ab}	8.2 ^b	0.43 ^a	740.0 ^a
	Timber	4	31.6 ^{ab}	183.0 ^a	214.6 ^b	8.01 ^b	8.7 ^b	0.36 ^a	867.7 ^a
Nicaragua	Full sun	2	13.5 ^a	189.5 ^a	203.0 ^a	0.00 ^a	4.4 ^a	0.37 ^a	610.8 ^a
	Mixed	18	77.5 ^b	177.5 ^a	255.1 ^a	26.58 ^b	2.3 ^b	0.73 ^a	212.5 ^a
	Legumes	7	41.8 ^a	206.6 ^a	248.3 ^a	12.39 ^c	3.7 ^a	0.58 ^a	296.9 ^a

For each outcome, different letters between rows indicate statistical significance at $p < 0.05$.

6.3.4. Trade-offs amongst carbon footprint, total carbon stocks and economic net benefit for conventional and organic farms

For organic farms across both countries there was a significant negative correlation between CF and NB ($p = 0.008$) and between CF and TC ($p = 0.048$) (Figures 6.3 and 6.4). However, no significant correlation was detected between NB and TC (Figure 6.5). For conventional farms across both countries no significant correlations were detected amongst CF, TC and NB (Figures 6.3, 6.4 and 6.5). Furthermore, inspection of the regression plot shows no evidence that the conventional farms were showing the same trend of a negative correlation between CF and TC that was found for the organic farms (Figure 6.4).

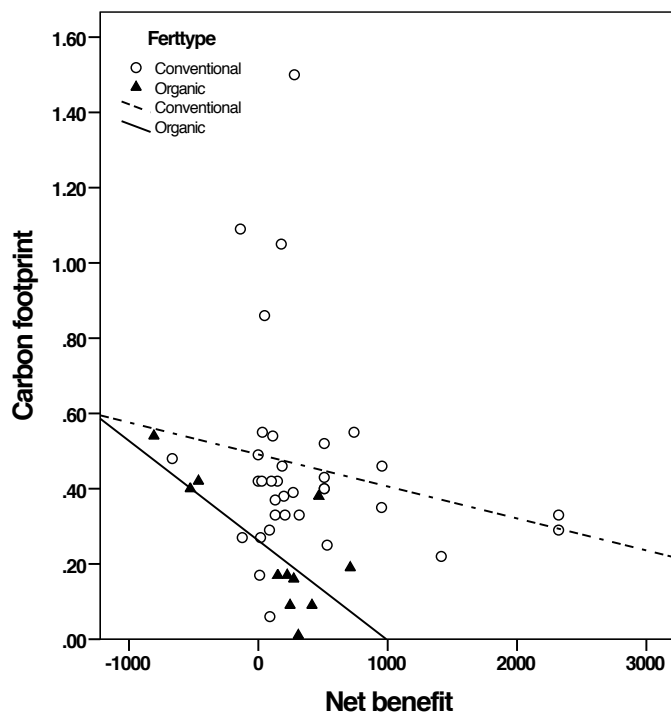


Figure 6.3 Relationship between carbon footprint (CF_{kg} , $Mg\ CO_2e\ kg^{-1}\ yr^{-1}$) and economic net benefits (NB, US\$ $ha^{-1}\ yr^{-1}$) for (a) conventional and (b) organic farms in Costa Rica and Nicaragua. Regression model fit: y (a) = $0.491 - 0.008 * NB$ ($r^2 = 0.04$, $p = 0.28$); y (b) = $0.262 - 0.001 * NB$ ($r^2 = 0.56$, $p = 0.008$).

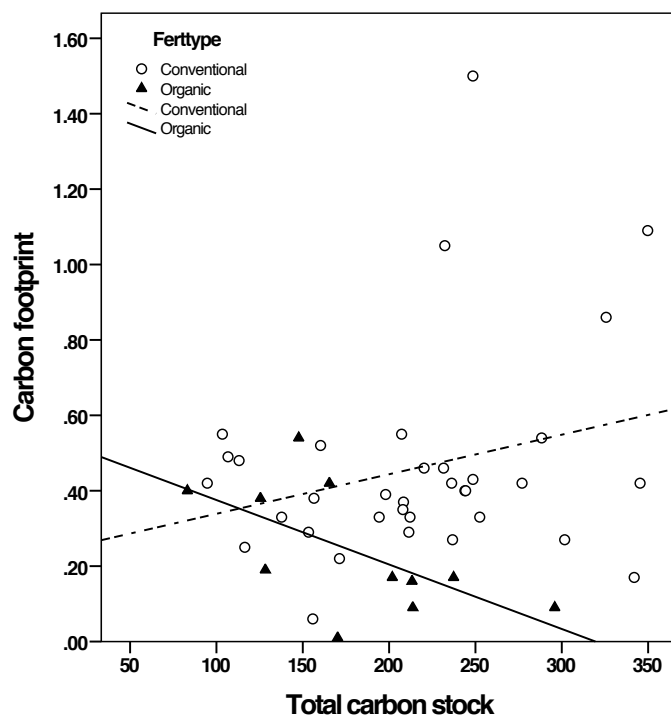


Figure 6.4 Relationship between carbon footprint (CF_{kg} , $Mg\ CO_2e\ kg^{-1}\ yr^{-1}$) and total carbon stocks (TC, $Mg\ C\ ha^{-1}\ yr^{-1}$) for (a) conventional and (b) organic coffee farms in Costa Rica and Nicaragua. Regression model fit: y (a) = $0.234 + 0.001 * TC$ ($r^2 = 0.07$, $p = 0.12$); y (b) = $0.546 - 0.002 * TN$ ($r^2 = 0.37$, $p < 0.05$).

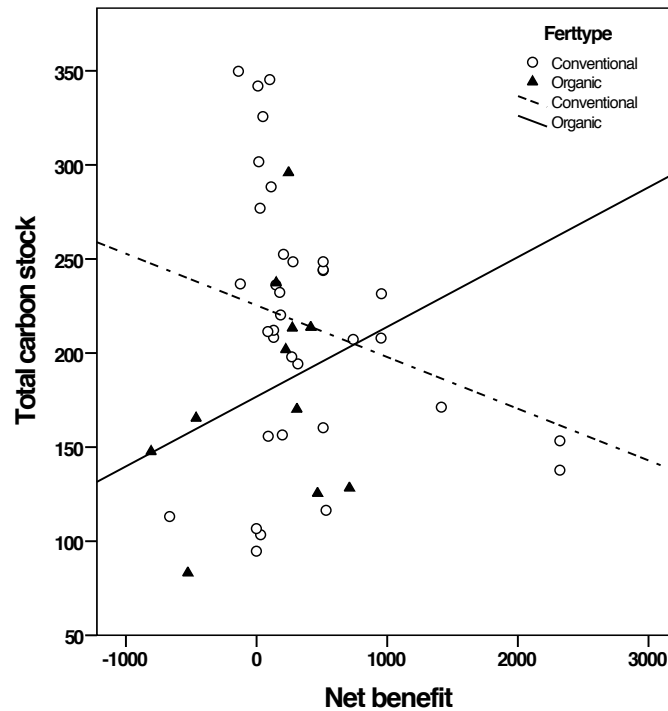


Figure 6.5 Relationship between total carbon stocks (TC, Mg C ha⁻¹ yr⁻¹) and net benefits (NB, US\$ ha⁻¹ yr⁻¹) for (a) conventional and (b) organic coffee farms in Costa Rica and Nicaragua. Regression model fit: y (a) = $225.4 - 0.027 * TN$ ($r^2 = 0.06$, $p = 0.17$); y (b) = $176.8 + 0.037 * TN$ ($r^2 = 0.09$, $p = 0.38$).

6.4. Discussion

6.4.1. Assessment of carbon and socio-economic trade-offs

For organic coffee production there was clear evidence that the sampled farms which were more profitable (producing a greater net benefit) tended to have a lower carbon footprint (CF) per kg of fresh coffee cherries, which is a win-win economic and environmental outcome. In contrast, on the sampled conventional farms there was very weak evidence for this relationship between net benefit and CF, which showed huge variation in both due to the interaction of many site and management factors. Here higher yields are not associated with lower CF.

For conventional farms there was no significant correlation between total carbon stocks (TC) and either CF or net benefit, and for organic farms only the (negative) correlation between TC and CF was significant. Although large differences in mean values were found between shaded and un-shaded systems for the tested variables, apart from the obvious BA and AGC, most were not significant due to their large variances.

Mean AGC across all shade types was significantly higher in Nicaragua than in Costa Rica which is due to the higher basal area of shade trees in Nicaragua and the fact that commercially valuable trees have been left to grow to large dimensions in some cases for hundreds of years on some farms creating huge C reserves. Further differences amongst farms occur due to the management applied to the shade trees and its purpose. In both countries, leguminous trees showed the lowest AGC amongst shaded coffee systems. These leguminous 'service' trees are predominately managed for their high N-rich organic matter inputs; they can be pruned up to three times a year and are often kept at a low height of around two metres to allow maximum sunlight exposure of the coffee bushes at times of flowering, thereby maintaining fairly low system AGC levels. Although in Costa Rica no significant differences between shaded systems were detected, this is attributable to the large variation in management applied between farms of each type. Estimates of mean AGC for the leguminous shade farms in Costa Rica were similar to the value of 15.6 Mg C ha⁻¹ measured by Polzot (2004) in *Erythrina poeppigiana* shaded coffee farms in southern Costa Rica but lower than that of Fournier (1996) who reported stocks of 24.2 Mg C ha⁻¹ for these systems in central Costa Rica; variation in tree density and intensity and type of pruning are likely to have been a major factor in this variation in reported AGC stocks. In timber shade systems, conversely, the trees are usually left to grow to greater heights to achieve higher financial returns from harvested timber. While the mean AGC value for the timber shade system in Costa Rica in the present study is notably lower than those reported elsewhere (Fassbender et al., 1991) this is likely to be due to a relatively young age of the shade trees on the sampled farms. Mixed systems, which fall between these two shade categories, often represent a multi-layered shade structure that allows higher shade-tree stocking densities (supported by the higher basal area found in both countries under mixed systems in this study) than monoculture timber shade systems. A study by Soto-Pinto et al. (2010) on C sequestration through agroforestry systems in Mexico found similar quantities of AGC (39.4 Mg C ha⁻¹) in mixed shade systems of coffee as were found in the present study in Costa Rica.

No significant variation in CF was found amongst the shade types within each country. However, for the sampled farms the lowest mean CF per kg of coffee production was found in full sun systems in both countries. In Nicaragua, the full sun farms produced a higher mean coffee yield and lower CF compared with those using other shade systems. Although the full sun farms in Costa Rica produced a lower mean yield than those using leguminous and timber shaded systems, taken as a whole the results indicate that, with their lower CF per kg of coffee, the full sun farms tend to make more efficient use of N inputs, considering that the majority of GHG emissions making up the CF stem from N inputs to the systems.

The results showed a very mixed picture in terms of variation between organic and conventional management types. Contrary to common assumptions, I found higher mean SOC in the conventional than in the organic farms, significantly so for Nicaragua. However, the explanation for this difference may not simply be the effect of management on SOC. Although high organic matter inputs associated with organic farming systems can be expected to maintain high SOC (or even increase it after depletion by previous farming practice) over long periods of time, processes that affect C fluxes in soil are highly variable and depend on a multitude of mechanisms (Sanderman and Jeffrey, 2010). The net balance of soil C will depend not only on newly gained C often found in the top soil layers, but also on C losses due to previous land management (Bashkin and Binkley, 1998; Powlson et al., 2011b). An alternative explanation for this relationship between SOC and management type could therefore be that farmers establish their farms on better soil (characterised by higher SOC) and farm these more intensively, while those farmers with poor low-SOC soils are more likely to switch to organic production, with its high organic matter inputs, or to plant a higher density of shade trees, rather than rely on costly high agrochemical inputs in a conventional management system. Indeed, we found a significant negative correlation between greater tree densities and SOC in both Costa Rica and Nicaragua.

With reference to climate change mitigation, although application of N-rich fertiliser to CAFS may increase SOC stocks by increasing crop yields and tree growth, and therefore return higher rates of organic C in roots and residues, emissions associated with the manufacturing and use of the fertiliser might outweigh the net gains achieved (Powlson et al., 2011b). In Chapters 3 and 5 of this thesis, for example, in an experiment in Costa Rica the average net increase of SOC in the top 10 cm of soil over nine years of CAFS establishment accounted for $0.87 \text{ Mg CO}_2\text{e ha}^{-1} \text{ yr}^{-1}$ of sequestration whereas the average CF across all treatments averaged $3.04 \text{ Mg CO}_2\text{e ha}^{-1} \text{ yr}^{-1}$ of emissions. In addition, whilst it is often believed that a change in AGC may also affect below-ground C stocks, evidence from the CAFS experiments in Costa Rica and Nicaragua suggests that this might not always be the case (Chapter 5); despite large variation in AGC amongst the treatments (which varied from full sun to leguminous, timber and mixed species shade), no significant differences in SOC changes (up to 40 cm depth) were seen between them over the nine years of system establishment following tree-planting.

The coffee yield of the organic farms was significantly lower than that of the conventional farms in both countries in the present study, on average by 44%. This is twice the difference found in a previous study of farms in Costa Rica which showed that the mean yield of organic farms was 22% lower than that of conventional farms, which would require a 38% higher price for organic certified coffee to equal the net income from growing coffee using conventional

management (Lyngbæk et al., 2001). Evidence from coffee farms in Nicaragua is more contradictory. Beuchelt and Zeller (2011) concluded that although all had insufficient net income from coffee to cover basic needs, organic farmers were more often beneath the absolute poverty line and had become poorer relative to conventional farmers. This led these authors to conclude that existing prices for certified coffee are not able to compensate for the constraints imposed by available land, labour and low productivity. However, Hagggar et al. (2012) found that organic farmers could obtain the same income as conventional farms for a lower investment. Similarly, in the present study in Nicaragua the net benefit obtained by the organic farms was very similar to that of the conventional farms. Although organic farms achieved the highest farm gate prices for their certified coffee, in the opinion of the farmers interviewed, achieving high prices was mostly dependent on the quality of the coffee cherries and not necessarily on the type of certification or management intensity employed. In order to analyse the impacts of management on profitability further a sensitivity analysis on price premiums such as those for organically certified coffee should be carried out in future studies.

In considering whether credits for climate change mitigation can provide an alternative source of income to organic or low-input coffee farms, it is important to relate the influence of these management variables to both coffee yield and CF. However, while CF was 78% lower for organic than conventional farms in Nicaragua, there was no difference between them in Costa Rica. Across both countries, both conventional and organic farms showed evidence of a positive correlation between coffee yield and total N inputs, but the response was clearly greater for conventional farms. Nitrogen inputs contribute strongly to the CF and, combining these linkages, while organic farms showed a significant negative correlation between NB and CF, there was very weak evidence for any such correlation for conventional farms. This provides good evidence that, for organic farms they can both increase their profitability and reduce their carbon footprints through management changes (including reducing excessive N-inputs). In doing so they may also be able to earn additional income from carbon credits. However, for conventional farms there is a huge variation in CF which is not closely correlated with their profitability. Therefore, there is good scope for at least some of these farms to increase their profitability without increasing their CF through management changes, including the potential to use high yielding systems which do not have an excessive CF, again focussing on the careful targeting of N-rich fertilizer inputs to ensure efficiency of its utilization, for which the interaction with shade management may be critical.

6.4.2. Participation of coffee agroforestry system farms in current carbon market mechanisms

Currently there seems to be no clear pathway for the inclusion of CAFS in C accounting methodologies due to the inherent complexities and variability of these systems. On sites where trees have been newly established or are still sequestering large amounts of C, the GHG emissions associated with the farming of coffee will, in most cases, be counterbalanced or even outweighed by C sequestration (Chapter 4). However, on many of the existing and long-established coffee farms, such as those presented in this study, net sequestration into trees would most likely have reached a level close to equilibrium (though subject to stochastic changes as trees are and coffee bushes are heavily pruned, thinned or harvested). When assessed over a sufficient time period to buffer such stochastic changes, I believe that existing long-established agroforestry systems managed to maintain a similar shade tree and crop cover, such as the shaded coffee systems studied here, can be considered to be more or less stable in their C stock. However, little published evidence to support this exists. Whilst there is good evidence of current net sequestration in old-growth tropical forests, connected with the direct and indirect effects on productivity of elevated atmospheric CO₂ concentrations (Grace et al., 1995; Luyssaert et al., 2008; Phillips et al., 1998) it is unlikely that this effect over-rides the influence of tree harvesting, management and establishment of replacement trees in managed forests and agroforestry systems.

Under the current compliance and voluntary accounting methodologies for tree C sequestration, however, only annually sequestered C is recognised and qualifies for offset payments (with the exception of REDD(+)). Therefore, the baseline emissions from, and sequestration into, all C pools must be calculated at the project start (UNFCCC, 2011b). All additional C sequestration or reduced GHG emissions which are projected to take place can then be compared against the C stock baseline to determine the volume of C credits which will be generated. Therefore, existing CAFS which have already reached shade levels that favour highest coffee yields would not be able to benefit greatly from these mechanisms. Nevertheless, in view of the high C stocks found on the farms of the present study, the climate change mitigation potential of CAFS is evident in that the conversion to other land use options would result in the release of large amounts of GHGs. Therefore, as suggested in chapter 4, some types of CAFS should be included under mechanisms that are similar to those of REDD and REDD+. For example, in the mixed shade systems studied here, AGC comprised 25 and 30 % of TC in the Costa Rican and Nicaraguan farms respectively, compared with just 9 and 17 % in the

leguminous shade systems in Costa Rica and Nicaragua respectively. Systems that have higher AGC will be more suited to REDD-type C projects, where the emphasis is put on maintaining C stocks and to a lesser extent on their enhancement (UN-REDD, 2012). In contrast, systems with lower AGC, such as the full sun systems in both countries and the leguminous only shade system in Costa Rica, would benefit from financial payments to enhance C stocks, so-called ‘improved forest management’ activities, with payments compensating for the investment needed to enhance C stocks (VCS, 2008).

Key to determining the best strategy and methodology in this area will be evidence of the relationships between carbon stocks, greenhouse gas fluxes (e.g. as captured by the carbon footprint) and economic performance of coffee farms, as presented in the current paper. In particular, in terms of farmer decision-making and the costs of potential climate change mitigation measures, the potential negative effects on coffee yield of enhancing AGC stocks supported by a significant negative correlation between AGC and yield in this study, need to be considered. A reduction in yields could result in indirect land-use change as other areas of land are diverted to coffee production (Chapter 4). In fact, the present study provides good evidence that trade-offs amongst coffee farm economic performance, CF and total carbon stocks are often weak and the dominant pattern is, instead, high uncorrelated variability amongst the farms in each of these three variables. While this will partly be explained by inherent site differences, given the relative small sample areas used, this is more likely to be due primarily to differences in management amongst the farms. This, then, indicates the great scope for management innovation or improvement in CAFS. Thus, if there is a general increase in the availability to farmers of payments for ecosystem services (e.g. from carbon credits), farmer decisions are not likely just to be determined by the relative financial value of their product or environmental outputs, which they must simply trade off. Instead, there will be good potential for farming system improvement and farmer innovation that can achieve valuable win-win outcomes.

In previous chapters, I demonstrated that intensification of existing coffee systems can potentially result in both improved net C benefits and profitability. Beyond this, for farms that are already at the upper end of the scale for coffee productivity, ‘improvement’ of C stocks might best be achieved by creating ‘conservation islands’ on formerly degraded lands or the establishment of windbreaks and live fences that can harbour significant amounts of AGC (Gibbon et al., 2009) without necessarily affecting the productivity of the coffee, rather than altering the management of coffee shade. In all cases, however, generalised prescriptions must be resisted and, instead, potential system improvements must be assessed on an individual farm basis taking into account its specific environmental and socio-economic factors.

6.5. Conclusion

With global population rise creating a greater demand for food, there is a stark policy choice between increasing productivity of existing farmland (through intensified agricultural systems) and increasing the land area used for agricultural production. The present study shows that in both countries organic coffee farms produced lower coffee yields than the conventional ones but had no advantages in terms of higher C stocks or profitability. Also, they only had an advantage of lower net GHG emissions in Nicaragua, not in Costa Rica. If their lower yields result in additional forest area being converted to coffee farming to meet global coffee demand, then the disadvantage of the organic systems studied here for the global environment would be still greater. The results of this study suggest that there are not strong general trade-offs between coffee farm socio-economic performance, C stocks and climate change mitigation potential (especially for conventional farms). Therefore, there is likely to be high potential for improvements in management to meet the new climate change agenda on an individual farm basis (and not on the basis of promotion of general prescriptions). There is no doubt about the potential for CAFS to play a role in helping to mitigate climate change but fitting this into existing carbon market mechanisms presents a challenge. I recommend that more research and development work is required to identify suitable agronomic methods to improve system performance based on local assessment of the environmental and socio-economic factors limiting productivity and profitability. Furthermore, because of the important role that CAFS play in maintaining current C stocks, at the same time as providing a wide range of products and services to local communities, development of mechanisms to allow their participation in the C market, e.g. through REDD+, is an urgent priority.

Chapter 7

Discussion and conclusions

7.1. Context

As one of the most traded commodities in the world, over 10 million hectares of land area are devoted to coffee production, largely within tropical regions (FAO, 2011), sustaining the livelihoods of up to 25 million people globally (FAO, 2004). Traditionally grown under a diverse range of shade, coffee continues to be one of the most widely grown cash crops in Central America. With a global increase in coffee consumption, especially of speciality coffees, and the rise of new markets such as China the export of coffee has reached a historical record volume for the harvest year 2010/11 (International Coffee Organization (ICO), 2011)

As a result of their scale, coffee farming systems play a crucial role in maintaining and providing ecosystem services at a local and national level and therefore actively contribute to climate change mitigation and adaptation. Nevertheless, agricultural landscapes vary in their design and management with consequential effects on their relative mitigation and adaptation potentials. The trade-off between climate change impacts and livelihoods, however, is of great importance, as global climate change policies must not negatively affect the livelihoods of coffee-producing communities in order to fulfil the Millennium Development Goals (UN, 2012). This dichotomy has long been a hard fought battle. On one hand, it is argued that an increase in industrialised agriculture is causing negative impacts such as biodiversity decrease, water and soil contamination, soil erosion, and the loss of farmers' agronomic knowledge (Altieri, 2004). On the other hand pressure on land availability is mounting due to global population increase, leaving forests in tropical regions more vulnerable to agricultural expansion (IPCC, 2007c; Malhi et al., 2008). Based on the original idea of Norman Borlaug, which identified low land productivity as a main driver of tropical deforestation (Gockowski and Sonwa, 2011), more recent studies have again emphasised the importance of increasing agricultural yields, through high intensity production systems, to meet continually increasing global demand on food and other agricultural commodities and to reduce C emissions through land use change (LUC) (West et al., 2010). Others such as Pirard and Treyer (2012), however, coin this hypothesis as uncertain and highlight the fact that intensification, although a key variable in long term forest

conservation, in itself does not seem to result in land sparing, unless accompanied by specific policies and measures.

At the same time, many ecosystem services have been degraded due to activities undertaken to increase the supply of goods such as food, timber or fuel. “Sustainable” coffee production systems that guarantee the provision of ecosystem goods (natural products harvested or used by humans) and ecosystem services (processes that support and sustain human and other life) must therefore be identified. With the degradation of ecosystem services predicted to have particular impact on the rural poor in developing countries, greater understanding of their interaction and appropriate management is an imperative.

Emerging mechanisms such as payments for *reduced emissions from deforestation and forest degradation* (REDD), a strategy used, if successful, for its all-encompassing framework ranging from climate change mitigation to poverty alleviation (Angelsen, 2008; Brown et al., 2008), therefore need to be re-evaluated to incorporate agricultural landscapes. Debate around the potential success of REDD has gained new momentum and concerns about the financial viability and competitiveness of REDD projects, and their potential to address drivers of deforestation, have been voiced (Butler et al., 2009). Their wider success may therefore depend on the design and management of projects that include aspects of sustainable development, biodiversity conservation, protection of existing forestlands and agricultural production and sustainability. It follows that intensification of existing agricultural land coupled with explicit policy intervention (Ewers et al., 2009), will contribute to reducing deforestation and forest degradation elsewhere. In particular seed-fertiliser technologies (Gockowski and Sonwa, 2011) and improved seeds and more efficient fuel use (Fisher et al., 2011) are emphasised in helping to increase crop yields and so reduce greenhouse gas (GHG) emissions. However, the relevance of these specific approaches for perennial woody crops such as coffee is unclear.

It is therefore important to develop and design REDD projects around activities which address the drivers of deforestation. By providing a wide variety of ecosystem services such as regulation of water and of climate (through carbon sequestration), provisioning of timber, fuelwood and non-timber forest products (NTFPs) including fodder, food and medicinal resources, and supporting and cultural services linked to biodiversity, agroforestry systems offer good potential to meet this need. In coffee-growing landscapes, carefully planned agricultural intensification may be a win-win solution, but its coupled effects on local and regional ecosystem services and livelihoods need to be determined further.

In the following sections I will examine the main contributions (7.2) of this research in providing the evidence needed to address this challenge: how to design and manage coffee agroforestry systems to mitigate climate change. This is followed by an assessment of the limitations (7.3) of this research and recommendations (7.4) for future research.

7.2. Contributions

In order to evaluate the C performance of alternative coffee agroforestry systems (CAFS) defined here as whole farm including its financial and human capital, a variety of overstorey shade and farm management types were studied in Costa Rica and Nicaragua. The overall conclusion was that there is no single rank order of performance of these systems in terms of either profitability or GHG emissions as there is so much interaction amongst the main system variables. The key interacting variables (which vary from farm to farm) are climatic and environmental conditions and type of shade tree and agronomic management in interaction with socio-economic differences. Despite this, a number of conclusions can be drawn on the relative merits of differing CAFS for climate mitigation within the agricultural sector.

7.2.1. GHGs from the cultivation of coffee

This research found that carbon footprints of coffee production systems mostly depend on organic and inorganic fertiliser inputs (Chapter 3). Although in general organic systems had lower footprints, this was dependent on the amount of organic fertilisers such as chicken manure and coffee pulp applied. One should also remember that in organic systems no emissions have been accounted for the production of its fertiliser which if industrially produced could further increase the overall CF of these systems. Also, organic fertilisers are often applied in large quantities and therefore would have a greater effect if these would have to be transported over a larger distance.

The type of shade did not play a crucial role in determining the overall CF. However, for shade systems with high levels of nitrogen-rich pruning residues from leguminous trees, the relative contribution of GHG emissions attributed to these can be significantly higher compared with other shade types. The major emission hotspots were found to be the production of fertilisers and enhanced non-CO₂ emissions from soil, which are dependent on the amount of organic and inorganic N applied to the system, which has also been found to be the case in many other tested agricultural systems (Hillier et al., 2009). It is therefore advised that nutrient

deficiencies and optimal application timings are identified within individual farming systems in order to maximise the N-use efficiency of crops, thereby minimising over-use of N.

7.2.2. Intensification of coffee

In Chapter 4 I found that in CAFS the increase in GHG emissions from production intensification can be compensated for, or even outweighed by, the increase in C sequestration into above-ground and below-ground tree biomass. However, whilst ‘full-sun’ systems completely lacking shade trees had the highest coffee yields and greatest profits, these systems had the least favourable C balance. Thus, the most profitable systems had the least potential for C sequestration. By evaluating the trade-offs between intensification, profitability and net GHG emissions, I found that the break-even C price to compensate for the coffee production revenue foregone which would need to be paid to farmers to offset the opportunity cost of not converting to full sun systems varies widely from 9.3 to 196.3 US\$ per Mg CO₂e of emissions reduction amongst different shaded CAFS.

I also found that if maintenance of less productive, lower intensity coffee production systems resulted in extension of coffee production onto the area of currently forested land required to compensate for the shortfall in profitability, this land-use change causes additional GHG emissions > 5 Mg CO₂e ha⁻¹ yr⁻¹ resulting in net emissions > 8 Mg CO₂e ha⁻¹ yr⁻¹ for the whole system for the majority of shade types tested. I therefore conclude that instead, by intensifying the productivity of shaded systems, mechanisms similar to REDD that are based on reducing emissions through avoided land-use change (REAL) could play a major role in increasing the climate change mitigation success of agroforestry systems at the same time as aiding REDD through reducing pressure for further forest conversion to agriculture. Therefore, integrating the policies that currently address agriculture and forestry separately is an imperative when designing sustainable climate change mitigation strategies.

7.2.3. Impacts on SOC

Current C accounting methodologies often assume a direct correlation between stocks of above- and below-ground C, with little consideration of the effects of land management on that relationship. As a result, it is commonly assumed that increasing above-ground carbon stocks (AGC) by planting trees or perennial crops will result in a proportional increase in below-ground carbon (BGC). In Chapter 5 I investigate the effects on soil organic carbon (SOC) of planting

coffee, under a range of shade and management type treatments, on land previously under sugar cane production (Costa Rica) and coffee production (Nicaragua). Here, I show that during the first nine years of coffee establishment, total 0-40 cm depth SOC stocks decreased by 12.4% in Costa Rica and 0.13% in Nicaragua although across treatments this differed consistently amongst soil layers; at 0-10 cm, SOC increased by 2.14 and 1.26 Mg C ha⁻¹ in Costa Rica and Nicaragua respectively, however a much greater reduction occurred at 20-40 cm (9.65 and 2.85 Mg C ha⁻¹ respectively).

Further, organic management caused a greater increase in 0-10 cm SOC than did conventional management but did not influence its reduction at depth. Effects of shade type, on the other hand, were smaller with heavily-pruned legume shade trees producing a greater increase in 0-10 cm SOC than unpruned timber trees. Interestingly, no significant differences in SOC stocks were found between shaded and unshaded (full sun) systems at any depth and SOC was poorly correlated with AGC highlighting the poor validity of “expansion factors” currently used to estimate SOC. Moreover, SOC stock changes were significantly negatively correlated with initial SOC stock per plot (before the establishment of the experimental CAFS), providing evidence that during establishment of these woody-plant-dominated agricultural systems SOC stocks tend to converge on a level determined more by site environment. I therefore conclude that it cannot be assumed that tree-based agricultural systems necessarily lead to increases in soil C stocks compared with perennial agricultural systems. While high inputs of organic fertiliser/tree pruning mulch increased surface-layer SOC, this did not affect stocks in deeper soil, where decreases generally exceeded any gains in surface soil.

7.2.4. The ‘real’ world

Replicated experiments are a perfect way to compare the effects of treatments. In agriculture, however, it is often difficult to categorise individual farms, or even fields, according to a rigid set of characteristics (such as those which could be tested as treatments in an experiment). Similarly here, although the coffee farms studied in this research were stratified according to a number of key attributes (shade type and farm management), much variation was found to exist within each stratum making it difficult to draw clear-cut conclusions on their comparative performance. Nevertheless, this research has shown that there are a number of common trends that occur amongst the two experiments and the sampled farms.

The greatest variation between coffee farms in their C performance is caused by the C stored in above-ground biomass (Chapter 4) and GHG emissions stemming from the cultivation

of the coffee (Chapter 3), with changes in SOC (Chapter 5) probably playing a lesser role. Although changes in SOC on farms could not be assessed, overall net losses of SOC were found for almost all shade types in the experimental systems, further highlighting the importance of site-specific accounting of C (Chapter 6) and bringing into question current accounting methodologies that by default credit tree establishment with an increase in SOC. A similar result might be observed during the establishment of other tree-based agricultural systems, e.g. cacao agroforestry systems in Central America, and therefore merits further investigation. In order for improved management of CAFS to contribute to a real reduction of atmospheric CO₂ concentrations, detailed information on site-specific characteristics and wider environmental influences is therefore required. Changes in GHG emissions that are caused by changes in farm management have the potential to negate the apparent benefits of any SOC increase (Chapters 4 and 5). The real climate change mitigation benefits of CAFS might therefore be dominated by the enhancement of C sequestration into above-ground biomass (Chapter 3). Therefore, greatest success in net GHG emission reductions may result from incremental improvement in current agronomic practice and, especially, a focus on the management of trees in CAFS (maximising their economic value and minimising their potential negative impact on coffee productivity, rather than more novel approaches guided by measures targeted at reduction in the more narrowly defined CF per se (Chapter 3).

In order to make meaningful recommendations for C management, a high degree of accuracy in on-farm data collection must be achieved that is based on site- and system-specific sampling. Further, a common methodology, which can be applied to the whole supply chain even across countries and continents, should be established. Finally, data analysis, according to a standardised methodology, should be consistent, rapid, cost-effective and accurate. To facilitate this process, an important advance has been made through this research, enabling the consistent, yet rapid and cost-effective assessment of AGC and GHG emissions in CAFS in Costa Rica and Nicaragua (Chapter 3), by utilising the large volume of data collected in this PhD to develop an excel-based calculator tool (Appendix 1) that estimates the GHG emissions and C storage potential of individual CAFS. Whilst other carbon footprint practitioners have critically appraised calculations using this tool, the next step will be for its peer-review and publication. By making this tool more widely accessible, it is anticipated that GHG assessments on coffee farms can be carried out rapidly and economically whilst ensuring scientific rigour and a common methodology. This is particularly well-aligned with current national climate change mitigation policies of Costa Rica that aim to reduce the CF of agricultural systems by identifying their emission hotspots and evaluating alternative farming approaches.

It then follows that coffee farms which have the potential to sequester more C would be suited to C projects that focus on increasing C stocks whereas coffee systems already high in C stocks would benefit from the participation in mechanisms more similar to “forest protection” type projects as promoted under mechanisms such as REDD and REDD+. Nevertheless, in order for C projects to be financially viable pathways for coffee farmers, C prices will need to be able to compete with other agricultural land use options as shown in Chapter 4 to enable these to offset any opportunity costs associated with the management of the shade within coffee systems for C. However, evidence from Chapter 5 demonstrates that the methods for estimating future C sequestration levels must not assume SOC levels will increase in-line with AGC. Rather, I have shown that a soil equilibrium level is likely to be reached, thus a conservative, fixed level of SOC should be estimated and included in C assessment methods.

It has thus become evident throughout this research, both during the interviews with coffee farmers and the data analysis, that the strong potential for CAFS to be included in C market mechanisms is coupled with interest from farmers, C project developers and not least buyers of C credits. Therefore it is hoped that the evidence presented in this thesis will carry forward their participation in order for CAFS to become a respected alternative of land-based C projects based on accurate accounting methodologies.

7.3. Limitations and future research

This research quantified and evaluated aspects of the climate change mitigation performance of CAFS. Focus was therefore placed on the trade-off between delivery of the ecosystem service climate change regulation, and the provisioning of an agricultural commodity in the form of coffee productivity and its associated farm profitability at the plot level. The research did not address impacts on other ecosystem services. It is recognised that the effects on externalities such as biodiversity, soil conservation, water quality etc. will most likely be higher for intensively compared to extensively managed agricultural systems (T'scharntke et al. 2005) and therefore need to be taken into account in future studies. In particular, before policy recommendations based on findings presented in this thesis are taken forward, impacts in particular on livelihoods at the household and regional level including those of cultural ecosystem services provided by CAFS need to be considered. Further, in order to guarantee the success and the appropriateness of actions implemented, recognition of local knowledge, local circumstances, traditions and perspectives in land use and natural resource management need to be taken into account through

the involvement of farmers, to successfully combine conservation and local development objectives (Cerdan et al. 2012; Leach et al. 2012; Scoones 2009).

Further research is needed in particular on the impacts of systems that combine profitability of agricultural commodities with climate change mitigation, on a wider range of important provisioning, regulating and cultural ecosystem services as well as adaptation to climate change. As such, the results presented here aim to give a starting point for the wider discussion around future food security and its challenges which, to be successfully achieved, need to combine efforts and contributions from all stakeholders.

The experimental sites and farms used in this study cover only a limited range of biophysical and socio-economic conditions and it is therefore advisable to expand future studies to other agro-economic coffee-growing regions in order to test the generality of the presented results. For example such the soil types presented in this research might not be representative of other coffee growing regions and therefore future research should expand to include a variety of soil types in order to draw further conclusions. In addition, in particular two topics are in need of further research to allow for more broad application of accounting methodologies and tools such as the one described and developed in this research: (a) broadening the allometric functions or models to a wider range of tree species associated with CAFS in other geographical regions and farming situations to allow its more accurate use for case-specific accounting of above-ground C sequestration and (b) improve the accuracy and breadth of data available on emissions factors associated with the rates of N₂O emissions from the soil caused by the addition of inorganic and organic N-rich material, in order to ensure that GHG emissions are accurately accounted for and efficient GHG reduction strategies can be identified.

In addition it should be mentioned that the methodologies applied throughout the thesis focus on an evaluation per unit of economic good e.g. per kg of fresh coffee cherries. Although this is currently the most common form of evaluating climate change mitigation potentials especially within agricultural commodities, other more holistic forms of evaluation such as the calculation of emissions per capita, calorific value or bio-productive area to sequester the emitted GHGs are being advocated (Pathak et al. 2010; GFN 2012). As such, depending on the objectives of future research, applying these more holistic forms of GHG evaluations might provide a much needed social component, although for this research in evaluating the carbon and economic potential for mitigating climate change the current methodology is thought to be more appropriate.

7.4. Conclusions

When making recommendations on climate change mitigation strategies for CAFS, it is important to first make accurate GHG balance estimates. I conclude that although some generalisations can be made across the investigated production systems on the impact of agronomic management and shade type on AGC and GHG emissions, site-specific data are still critical if valid claims of improved GHG performance and increased C stocks are to be made. At the same time, assessments need to be made cost- and time-efficient to enable GHG accounting methods to be accessible to locally-focused institutions and individual farmers as a basis for recommendations and decision-making on improved management. This can be achieved with a common methodology and accounting tools such as CAFCA, developed here.

Although organic production systems have been found in the present study to contribute positively to climate change mitigation through greater soil C sequestration rates and in some circumstances smaller production GHG emissions, these often come at the price of coffee productivity and profitability. In a world facing increasing demands for natural resources, food and other agricultural commodities in combination with decreasing land availability, evaluating the trade-off between climate change mitigation potential and farm productivity and profitability is of great importance. I therefore conclude that the intensification of less-productive CAFS could not only prove beneficial for climate change mitigation through avoiding conversion of forest to less productive agricultural systems (extensification) but also increase their profitability through the increased productivity. Finally, although full sun coffee systems can be more profitable in the right circumstances, by using payments through mechanisms similar to REDD that are aimed at halting forest degradation and deforestation, intensification of shaded CAFS could be financed as a more efficient alternative. This could protect large areas of already-stored AGC and BGC by reducing emissions through avoided land use change.

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Appendix 1

CAFCA – Calculator tool to estimate farm-level greenhouse gas emissions in coffee agroforestry systems

1. Introduction

The carbon agroforestry calculator (CAFCA) for coffee production systems has been developed to not only quantify on-farm GHG emissions but at the same time to be used as a simple tool in assessing above- and belowground biomass C stocks. Although originally designed for coffee agroforestry systems, CAFCA could easily be adapted to other tree-based or perennial agricultural systems such as cacao or tea. The GHG calculations in the tool are based on the PAS 2050 (BSI, 2011) carbon footprint methodology which draws on the IPCC methodologies for national greenhouse gas inventories to calculate soil and direct land use-change emissions related to agriculture (IPCC, 2006). In addition, CAFCA combines a number of empirical models on biomass and pruning residue calculations based on data from two long-standing experiments. These allow for an overall estimate of emissions depending on tree species and shade type. As such, the majority of sub-models operate according to IPCC tier 2 specification³, based on regional-specific EF and sub-models. Currently the calculation tool is calibrated for the Central American regions of Costa Rica and Nicaragua. For farms outside these regions the calculations are based on IPCC default values and functions and reach a tier 1 level. Although this will still conform to PAS 2050-specification, calculations will not necessarily be representative at the farm-scale; for greater accuracy, peer-reviewed data or field measurements should be sought.

2. Materials and Methods

2.1. Calculation of carbon footprints

PAS 2050 (BSI, 2011) is the only transparent and publically available PCF method published to-date and has therefore been chosen here for all CF calculations. Within this method, all GHGs (including CO₂, N₂O and CH₄) are accounted for and converted into units of CO₂-equivalents according to their global warming potential (GWP) over 100 years. All GHG emissions associated with the provision and use of raw materials and energy are included in the calculation.

³ Tier 1 are simple methods that use global default values; Tier 2 use country specific values and other regional data; Tier 3 are more complex models and approaches often based on experimental site-specific data (IPCC, 2006).

Capital goods, human energy inputs such as manual labour, transport of employees to and from the workplace and animals providing transport are excluded from PAS 2050. Of specific relevance to agricultural CFs are non-CO₂ emissions from livestock, their manure and soils, which must be included, calculated according to IPCC guidelines for National GHG Inventories (De Klein et al., 2006). Non-CO₂ emissions from soil are accounted for through including direct and indirect emissions resulting from N additions, deposition and leaching. Direct emissions from land use change (LUC) must be accounted for if the land conversion took place on or after 1st January 1990.

2.2. Structure

CAFCA is divided into four main sections and several sub-models which can be used independently. The system boundaries for the calculator tool start at input to farm and currently end at farm gate, excluding emissions from further processing or transport. Later versions are likely to include other life cycle stages in the supply chain such as wet and dry processing, shipping and storage. The functional unit for which the CF is reported as a default is 1 kg of fresh coffee cherries. Due to the variability of weight and sizes in fresh coffee beans between regions and altitudes local conversion factors for weight and volume have been added to allow for comparability between different regions. Results for CF per area rather than by weight can also be obtained.

Where PAS 2050 has referred to IPCC methodologies to calculate emissions, tier 2 data have been sourced from National Greenhouse Gas Inventories unless data from local studies were available. This was of particular importance when calculating non-CO₂ soil emissions through organic and synthetic nitrogen inputs to the farming system. More detail on this will be given in the sub-section on non-CO₂ soil emissions.

PAS 2050 specifies that multiple outputs of the production system, or co-products, must be allocated emissions on an economic basis (i.e. according to their proportional economic value). In relation to coffee farming systems, emissions within CAFCA have been allocated to co-products that have been sold. Such co-products include other agricultural products e.g. citrus fruit, timber for construction and fence material, and pruned material that has been sold for firewood.

The following is a breakdown of input requirements and calculations based on the individual sub-models described above.

3. Data requirements

3.1. General information

The first sub-model requires general information on aspects such as climate, farm and soil variables (Figure A1.1). These are important in determining the correct choice of emission factors within the subsequent sub-models. In addition, country-specific units of measure of weight, volume or length, specific to the coffee sector, are determined automatically through the choice of economic region and country. Information on the type of shade and management enables the correct choice of EFs when calculating soil N₂O emissions from organic and inorganic N based fertilisers at the same time as differentiating between allometric functions to calculate above and belowground biomass of coffee plants based on their shade cover.

3.2. Crop and farm management

3.2.1. Fertiliser production

Emission factors (EF) for the calculation of GHG emissions associated with the production, storage and distribution of common commercially-available fertilisers have been obtained and calculated through the popular life cycle software SimaPro, based on data from the Ecoinvent

	Coffee	Other products	
Main product	Coffee	Other products	[Select]
Economic region	[Select]		
Country	FSU Eastern Europe China Other Asia India Middle East Latin America Africa		
Region			
Farm name			
Production area		[Select]	
Total harvested yield	0.00	[Select]	
No. years under coffee production	[Select]	yrs	
Distance between coffee rows	[Select]	[Select]	
No. plants	0	ha	
Climate	[Select]		
Land use type	[Select]		
Soil type	[Select]	Shade type	Shaded
Soil fertility	[Select]		
Soil drainage	[Select]	Type of farm	Legumes chemical

Figure A1.1 Input of general farm information such as location, climate and soil variables

database (Althaus et al., 2007), combinations of elements of fertilisers based on the nutrients N, P, K, Mg and B have been estimated, allocating emissions according to their percentage share within a particular product. Other commercial products have been researched and their emissions been calculated based on their active ingredient. Organic fertilisers such as chicken manure and coffee pulp have been assigned production emissions according to their estimated average economic value as a co-product of the poultry and coffee sector, within their specific geographic regions. Emission factors from the SimaPro database are based on European circumstances and include process emissions such as transportation and storage to a regional distribution centre. Circumstances are likely to be different for the countries under investigation but the data used here are the best estimates available at present.

3.2.2. Pesticide production

GHG emissions from pesticides have been calculated using the same approach as for fertilisers. GWP for average fungicides, herbicides and insecticides were obtained from SimaPro. GWPs for a range of common pesticides were then calculated based on estimates of their active ingredient using data available through the Ecoinvent database (Althaus et al., 2007). GWPs of active ingredients include process emissions such as transportation and storage at a regional distribution centre.

3.2.3. Fuels

Emission factors are taken from the DEFRA 2010 (DEFRA, 2010) database or where available, from national greenhouse gas inventory reports as in the case of Costa Rica.

3.2.4. Materials/sundries

Emission factors for all other consumables used within the coffee production process were calculated based on Ecoinvent databases (Althaus et al., 2007; Classen et al., 2009).

3.2.5. Transport

Transport emission factors have been taken from the Renewable Fuels Agency (RFA) (2010) and are Latin America-specific except in the case of Costa Rica where country-specific emission factors for fuels have been taken from Costa Rica's National Greenhouse Gas Inventory (Ministerio de Ambiente y Energia , Costa Rica, 2007).

4. Soil emissions

According to PAS 2050 (BSI, 2011), non-CO₂ emissions from soil must be calculated according to the highest tier approach set out in the IPCC guidelines for National Greenhouse Gas Inventories (De Klein et al., 2006). N₂O emissions from soils are accounted for as both direct and indirect emissions resulting from N additions, deposition and leaching. The following gives an overview of the generic methodologies and equations used within the calculation of N₂O emissions from managed soils including CO₂ emissions from lime and urea application within the IPCC guidelines for national greenhouse gas accounting.

4.1. N₂O emission from managed soils

The calculation methodology for N₂O emissions from managed soils is based on assumptions around the availability of inorganic nitrogen a controlling factor within the processes of nitrification and denitrification. The calculations are therefore based on a) human-induced net N additions to soils which include organic and inorganic (synthetic) fertiliser, organic manures and crop residues and b) activities or management such as drainage on organic soils or land-use change on mineral soils that alter the mineralisation of N in organic matter. N₂O emissions include direct and indirect pathways such as volatilisation of NH₃ and NO_x and leaching and runoff mainly in the form of NO₃⁻ and are calculated separately. Where available, differences in land cover, soil type, climatic conditions and management practices are taken into account. The IPCC default (tier 1) value for calculating N₂O emission from soils assumes a rate of 1% of all N applied. In CAFCA, tier 2 data have instead been sourced as follows: the EF for calculating N₂O emissions from soil is based on a study in Costa Rica (Hergoualc'h et al., 2008) which measured N₂O and CH₄ emissions from four different coffee systems: a full sun monoculture chemically managed, a legume shade (*Inga laurina*) system chemically managed, an organic full sun monoculture and an organic legume shade system (*Erythrina poeppigiana*). The EF for N₂O emissions resulting from organic (chicken manure, coffee pulp etc.) and inorganic (chemical) fertiliser range from 1 % to 1.2 % of applied N depending on the shade tree system. For pruning residues from shade trees and coffee bushes, an EF of 0.3 % of N is used (Hergoualc'h, pers. comm.).

4.2. Direct N₂O emissions

The following N sources have been included in estimating direct N₂O emissions from managed soil and are in accordance with IPCC guidelines for national GHG inventories (De Klein et al., 2006):

- Synthetic N fertilisers (F_{SN})
- Organic N applied as fertiliser (e.g. animal manure, compost, sewage sludge) (F_{ON})
- N in crop residues (above-ground and below-ground) (F_{CR})
- N mineralisation associated with loss of soil organic matter resulting from change of land use or management of mineral soils (F_{SOM});
- Drainage and management of organic soils (F_{OS}).

Direct N₂O emissions from managed soils are calculated according to the following equation (De Klein et al., 2006):

$$N_2O_{Direct} - N = N_2O - N_{N\ inputs} + N_2O - N_{OS} + N_2O - N_{PRP}$$

$$N_2O - N_{N\ inputs} = [(F_{SN} + F_{ON})_i \cdot EF_{1i} + (F_{CR} + F_{SOM}) \cdot EF_{1i}]$$

$$N_2O - N_{OS} = \left[\begin{array}{l} (F_{OS} \cdot EF_{2CG,Temp}) + (F_{OS,CG,Trop} \cdot EF_{2CG,Trop}) + \\ (F_{OS,F,Temp,NR} \cdot EF_{2F,Temp,NR}) + (F_{OS,F,Temp,NP} \cdot EF_{2F,Temp,NP}) + \\ (F_{OS,F,Trop} \cdot EF_{2F,Trop}) \end{array} \right]$$

Where:

$N_2O_{Direct} - N$ = annual direct N₂O–N emissions produced from managed soils, kg N₂O–N yr⁻¹

$N_2O - N_{N\ inputs}$ = annual direct N₂O–N emissions from N inputs to managed soils, kg N₂O–N yr⁻¹

$N_2O - N_{OS}$ = annual direct N₂O–N emissions from managed organic soils, kg N₂O–N yr⁻¹

$N_2O - N_{PRP}$ = annual direct N₂O–N emissions from urine and dung inputs to grazed soils, kg N₂O–N yr⁻¹

F_{SN} = annual amount of synthetic fertiliser N applied to soils, kg N yr⁻¹

F_{ON} = annual amount of animal manure, compost, sewage sludge and other organic N additions applied to soils, kg N yr⁻¹

F_{CR} = annual amount of N in crop residues (above-ground and below-ground), including N-fixing crops returned to soils, kg N yr⁻¹

F_{SOM} = annual amount of N in mineral soils that is mineralised, in association with loss of soil C from soil organic matter as a result of changes to land use or management, kg N yr⁻¹

F_{OS} = annual area of managed/drained organic soils, ha (Note: the subscripts CG, F, Temp, Trop, NR and NP refer to Cropland and Grassland, Forest Land, Temperate, Tropical, Nutrient Rich, and Nutrient Poor, respectively).

EF_{ii} = emission factors developed for N₂O emissions from synthetic fertiliser and organic N application under conditions i (kg N₂O-N (kg N input)⁻¹); i = 1, ...n. (Table A1.4)

EF_2 = emission factor for N₂O emissions from drained/managed organic soils, kg N₂O-N ha⁻¹ yr⁻¹; (Table A1.4)

For reporting purposes all N₂O-N emissions are converted in to N₂O emissions by multiplying the former by 44/28.

To estimate the amount of pruning residue inputs for a number of individual shade trees and coffee bushes, two separate sub-models were developed using empirical data from two long-standing experiments in Costa Rica and Nicaragua. These are described in more detail in the next section.

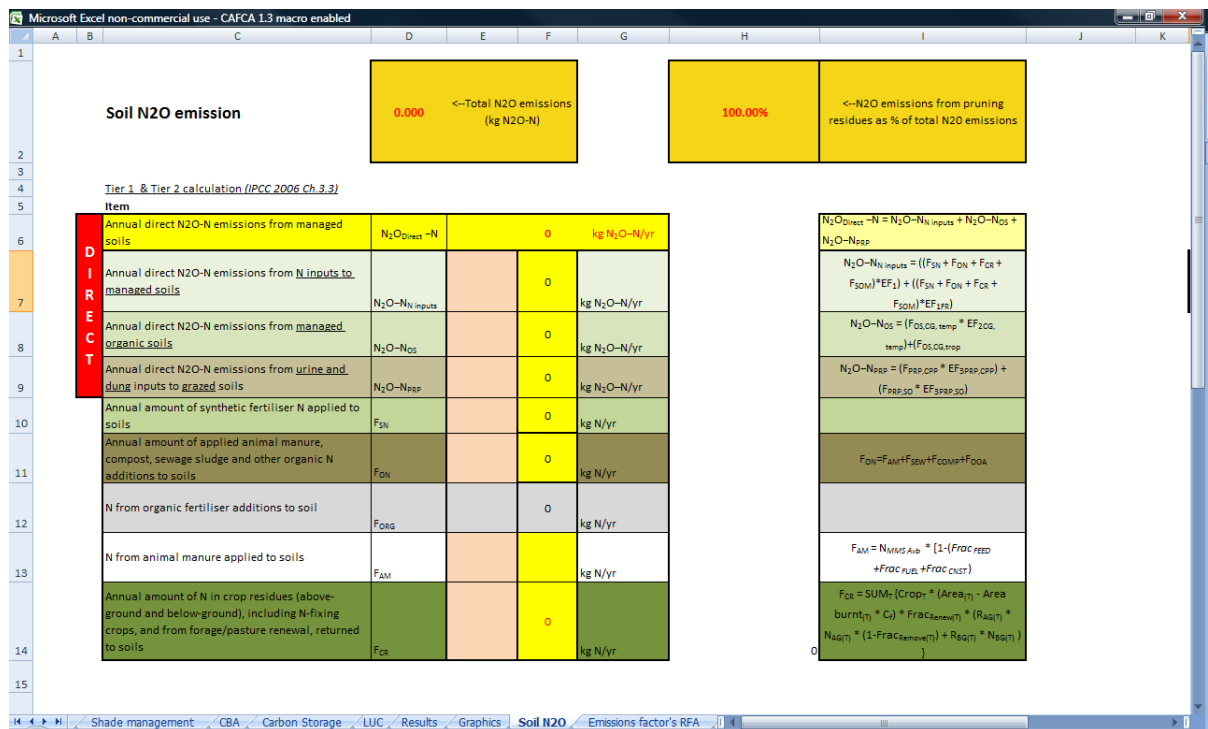


Figure A1.2 Tier 1 & 2 direct soil N₂O emission calculations window

4.3. Indirect N₂O emissions

Indirect N₂O emissions are calculated by estimating the emissions from two pathways, volatilisation and leaching or run-off of N, and are based on IPCC tier 1 methods used to estimate aggregated total indirect N₂O emissions dependent on total N additions to managed soils (De Klein et al., 2006). Emissions are based on the same N sources as for the emission estimates of direct N₂O emissions.

Section	Parameter	Symbol	Value	Unit	Description
EMISSIONS	Annual amount of N in mineral soils that is mineralised, in association with loss of soil C from soil organic matter as a result of changes to land use or management	F_{SOM}	n/a	0 kg N/yr	(equ. 11.8, p.11.16) $\Delta C_{Mineral, LU}$ $LU =$ annual change in carbon stocks in mineral soils for each land-use type (LU) see Chapter 2, Equation 2.25, tC; $F_{SOM} = \sum_{LU} \{ (\Delta C_{Mineral, LU}) \cdot R \}$, R = C:N ratio of SOM
	Annual change in carbon stocks in mineral soils,	$\Delta C_{Mineral, LU}$		0 tC/yr	$\Delta C_{Mineral, LU} = (SOC_{CG} - SOC_{(0-T)}) /$ Other Land Use, Ch.2 p. 2.30 equ. 2.25 CG = cropland & grassland; F = forest land;
	Annual area of managed/draind organic soils	F_{OS}	CROP AREA, if Organic soil, if mineral value should be zero	0 ha	temp = temperate; trop = tropical; NR = nutrient rich; NP = nutrient poor
FACTORS	Annual amount of urine and dung N deposited by grazing animals on pasture, range and paddock	F_{PRP}	not relevant here	0 kg N/yr	CPP = cattle, poultry & pigs; SO = sheep & other animals see IPCC (2006) Vol 4, Agriculture, Forestry and Other Land Use, p.11.13
	Emission factor for N ₂ O emissions from N inputs (synthetic and organic N applications to soils, including crop residue and mineralisation of soil organic carbon in mineral soils due to land-use change or management)	EF_1		0.012 kg N ₂ O-N/kg N input	See lists for EF's
	Emission factor for N ₂ O emissions from N inputs from pruning or crop residues	EF_{1PR}		0.003 kg N ₂ O-N/kg N input	See lists for EF's
	Emission factor for N ₂ O emissions from drained/managed organic soils	EF_2	organic soil, temperate cropland	0 kg N ₂ O-N/ha/yr	CG = cropland & grassland; F = forest land; temp = temperate; trop = tropical; NR = nutrient rich; NP = nutrient poor Table 11.1
	Emission factor for N ₂ O emissions from urine and dung N deposited on pasture, range and paddock by grazing animals	EF_{3PRP}		0 kg N ₂ O-N/kg N input	CPP = cattle, poultry & pigs; SO = sheep & other animals Table 11.1

Figure A1.3 Emission factors for direct soil emission calculations window

Indirect N₂O emissions through volatilisation from managed soils are calculated according to the following equation (De Klein et al., 2006):

$$N_2O_{(ATD)} - N = [(F_{SN} \cdot Frac_{GASF}) + ((F_{ON} + F_{PRP}) \cdot Frac_{GASM})] \cdot EF_4$$

Where:

$N_2O_{(ATD)} - N$ = annual amount of N₂O-N produced from atmospheric deposition of N volatilised from managed soils, kg N₂O-N yr⁻¹

F_{SN} = annual amount of synthetic fertiliser N applied to soils, kg N yr⁻¹

$Frac_{GASF}$ = fraction of synthetic fertiliser N that volatilises as NH_3 and NO_x , kg N volatilised (kg of N applied)⁻¹ (Table A1.5)

F_{ON} = annual amount of managed animal manure, compost, sewage sludge and other organic N additions applied to soils, kg N yr⁻¹

F_{PRP} = annual amount of urine and dung N deposited by grazing animals on pasture, range and paddock, kg N yr⁻¹

$Frac_{GASM}$ = fraction of applied organic N fertiliser materials (F_{ON}) and of urine and dung N deposited by grazing animals (F_{PRP}) that volatilises as NH_3 and NO_x , kg N volatilised (kg of N applied or deposited)⁻¹ (Table A1.5)

EF_4 = emission factor for N_2O emissions from atmospheric deposition of N on soils and water surfaces, [kg N- N_2O (kg NH_3 -N + NO_x -N volatilised)⁻¹] (Table A1.5).

Conversion of emissions into N_2O = N_2O -N * 44/28

Indirect N_2O emissions through leaching and run-off from managed soils are calculated according to the following equation (De Klein et al., 2006):

$$N_2O_{(L)} - N = (F_{SN} + F_{ON} + F_{PRP} + F_{CR} + F_{SOM}) \cdot Frac_{LEACH-(H)} \cdot EF_5$$

Where:

$N_2O_{(L)}-N$ = annual amount of N_2O -N produced from leaching and runoff of N additions to managed soils in regions where leaching/runoff occurs, kg N_2O -N yr⁻¹

F_{SN} = annual amount of synthetic fertiliser N applied to soils in regions where leaching/runoff occurs, kg N yr⁻¹

F_{ON} = annual amount of managed animal manure, compost, sewage sludge and other organic N additions applied to soils in regions where leaching/runoff occurs, kg N yr⁻¹

F_{PRP} = annual amount of urine and dung N deposited by grazing animals in regions where leaching/runoff occurs, kg N yr⁻¹

F_{CR} = amount of N in crop residues (above- and below-ground), including N-fixing crops, and from forage/pasture renewal, returned to soils annually in regions where leaching/runoff occurs, kg N yr⁻¹

F_{SOM} = annual amount of N mineralised in mineral soils associated with loss of soil C from soil organic matter as a result of changes to land use or management in regions where leaching/runoff occurs, kg N yr⁻¹

$Frac_{LEACH-(H)}$ = fraction of all N added to/mineralised in managed soils in regions where leaching/runoff occurs that is lost through leaching and runoff, kg N (kg of N additions)⁻¹ (Table A1.5)

EF_5 = emission factor for N₂O emissions from N leaching and runoff, kg N₂O-N (kg N leached and runoff)⁻¹ (Table A1.5)

Conversion of emissions into N₂O = N₂O-N * 44/28

Parameter	Default	Unit	Reference
INDIRECT			
INDIRECT N2O EMISSIONS: (1) volatilisation of N as NH3 and oxides of N (NOx), and the deposition of these gases and their products NH4			
(1) N2O emissions from atmospheric deposition of N volatilised from managed soil		0 kg N ₂ O-N/yr	$N_2O_{(ATD)}-N = [(F_{SN} * Frac_{GASF}) + ((F_{ON} + F_{PPP}) * Frac_{GASM})] * EF_4$ Equin 11.9, p.11.21
Fraction of synthetic fertiliser N that volatilises as NH ₃ and NOx	Default	0.1 kg N volatilised/kg N applied	Table 11.3, p. 11.24
Fraction of applied organic N fertiliser materials (F _{ON}) and of urine and dung N deposited by grazing animals (F _{PPP}) that volatilises as NH ₃ and NOx	Default	0.2 kg N volatilised/kg of N applied or deposited	Table 11.3, p. 11.24
Emission factor for N ₂ O emissions from atmospheric deposition of N on soils and water surfaces	Default	0.01 volatilised kg N ₂ O-N/kg NH ₃ -N & NOx-N	Table 11.3, p. 11.24
(2) Annual N2O emissions from leaching and runoff			
fraction of all N added to/mineralised in managed soils in regions where leaching/runoff occurs that is lost through leaching and runoff	Default	0.3 kg N/kg N additions	Table 11.3, p. 11.24
Emission factor for N ₂ O emissions from N leaching and runoff	Default	0.0075 runoff kg N ₂ O-N/kg N leached and	Table 11.3, p. 11.24

Figure A1.4 Emission factors for indirect soil emission calculations window

5. Emissions from liming and urea applications

The agricultural practice of liming, the addition of lime in the form of calcic limestone or dolomite, is often carried out in order to reduce soil acidity. Emissions from liming are due to the release of bicarbonate of the carbonate limes which results in CO₂ emissions. These emissions are calculated using the following equation (De Klein et al.,2006):

$$CO_2 - C \text{ Emission} = (M_{Limestone} \cdot EF_{Limestone}) + (M_{Dolomite} \cdot EF_{Dolomite})$$

Where:

CO_2 -C Emission = annual C emissions from lime application, tonnes C yr⁻¹

$M_{Limestone}$ = annual amount of calcic limestone (CaCO₃), tonnes yr⁻¹

$EF_{Limestone}$ = emission factor, tonne of C⁻¹ [0.12]

$M_{Dolomite}$ = annual amount of dolomite (CaMg(CO₃)₂), tonnes yr⁻¹

$EF_{Dolomite}$ = emission factor, tonne of C⁻¹ [0.13]

Conversion of emissions into CO₂ = CO₂-C * 44/12

Urea, containing 46% Nitrogen, is commonly used as fertiliser in agriculture. During the industrial production process of urea, atmospheric CO₂ which is necessary to form ammonium carbamate, is fixed. However, through the application of urea as a soil fertiliser, this process is reversed which leads to a loss of CO₂. The CO₂ emissions from urea application are calculated as follows:

$$CO_2 - C \text{ Emission} = M \cdot EF$$

Where:

CO_2 -C Emission = annual C emissions from urea application, tonnes C yr⁻¹

M = annual amount of urea fertilisation, tonnes urea yr⁻¹

EF = emission factor, tonne of C (tonne of urea)⁻¹ [0.2]

Conversion of emissions into CO₂ = CO₂-C * 44/12

6. C storage

An important aspect which to date has been excluded from most carbon footprinting studies is the inclusion of C sequestered or stored within the farming system. So far little or no literature has been published on this issue although there have been calls to consider C stocks when calculating C footprints, especially within tree crop systems, to allow for a more objective view of C balance (Brenton et al., 2010; Chapter 4). Tree based systems have the possibility to store large amounts of above- and belowground carbon, offsetting some or all their GHG emissions associated with this particular stage within the supply chain.

To allow farmers a simple and cost effective assessment of their C stocks within the coffee systems, a sub-model that calculates C stocks of above-and belowground and soil C pools has been included in CAFCA. The assessment is based on a number of simple field measurements as outlined in the CDM baseline and monitoring methodology for small-scale agroforestry project (UNFCCC, 2011b).

6.1. Shade trees

6.1.1. Aboveground & belowground C

Aboveground biomass stocks are estimated by the use of allometric equations based on an extensive literature review. In addition, a number of species-specific equations have been developed through destructive sampling of shade tree species present in the two long standing experimental sites described previously. Belowground biomass for shade trees was calculated using a function developed by Cairns et al. (1997) and recommended by the IPCC (2003). Above-ground coffee biomass stocks are calculated using an allometric equation developed by Segura et al. (2006) for shaded and un-shaded coffee agroforestry systems in Nicaragua. A study by Dossa et al. (2008) that investigated the effects of open-grown and shaded coffee on below-ground biomass is being used to estimate coffee bush below-ground biomass. For conversion of total biomass into its C fraction default values of 0.47 and 0.37 was used for all woody and dead wood and litter biomass respectively (IPCC, 2003).

6.1.2. Destructive sampling shade trees

The shade trees for which specific allometric functions were developed within this study were chosen from the tree species present in the experiments in Costa Rica and Nicaragua: *Chloroleucon eurycyclum*, *Erythrina poeppigiana*, *Terminalia amazonia*, *Inga laurina*, *Tabebuia rosea*, *Samanea saman* and *Simarouba glauca*. Trees were chosen according to different diameter classes which ranged from 3 – 43 cm diameter at breast height (Dbh, 1.3m). In total 233 individual trees were sampled over a period of 9 months. Before felling, the Dbh and total height (h) of individual trees were recorded. The trees were then divided into four biomass components: foliage, small branches (< 2cm in diameter), large branches (> 2 cm in diameter) and stem. A record of the stump height and diameters was also taken to calculate stump volume using Smalian's equation (Loetsch et al., 1973). The different biomass components were then weighed individually and recorded before obtaining a sub-sample to determine dry matter content (dried at 80°C for 48 hours or until constant weight). To estimate specific gravity, two samples from the top and the bottom end of

each stem were taken and dried to constant weight at 80°C. To assess the mass of the sample the water displacement method was applied submerging the sample in a beaker filled with water on an electronic balance, and recording the mass of the displaced water (Williamson and Wiemann, 2010). The total aboveground biomass (B_T) was then calculated as a sum of all biomass components.

Table A1.1 Best-fit models for total aboveground biomass (B_T) of shade trees and coffee

Species	Model	Parameter			R^2	n	Diameter range (cm)
		a	b	c			
<i>Inga laurina</i>	$B_T = a + b \cdot \ln(dbh_1 + dbh_2 + \dots + dbh_x)$	6.562	1.31		0.74	42	3 - 36
<i>Simarouba glauca</i>	$B_T = a \cdot dbh^b$	8468.239	2.711		0.88	43	6 - 21
<i>Samanea saman</i>	$B_T = a \cdot dbh + b \cdot dbh^2 + c$	-1473.24	9962.6	74.9	0.91	21	8 - 18
<i>Tabebuia rosea</i>	$B_T = a \cdot dbh + b \cdot dbh^2 + c$	-534.83	7061.22	-2.52	0.9	41	8 - 23
<i>Chloroleucon eurycyclum</i>	$\ln(B_T) = a + b \cdot dbh$	1.432	15.556		0.83	22	8 - 26
<i>Erythrina poeppigiana</i> (pollarded)	$B_T = a \cdot dbh^3 + b \cdot dbh + c$	1374.61	19.686	9.122	0.73	36	14 - 31
<i>Erythrina poeppigiana</i> (regularly pruned)	$\ln(B_T) = a + b \cdot \ln(dbh) + c \cdot h$	5.993	1.799	0.105	0.78	18	25 - 43
<i>Terminalia amazonia</i>	$\ln(B_T) = a + b \cdot dbh$	1.229	16.955		0.91	10	8 - 26
<i>Coffea Arabica</i> *	$\text{Log}_{10}(B_T) = a + b \cdot \text{Log}_{10}(d15) + c \cdot \text{log}_{10}(h)$	-1.113	1.578	0.581	0.94		na

*Segura et al. (2006)

6.1.3. Statistical analysis

Models for biomass estimation for individual species were derived by correlation analysis between the dependent variable (B_T) and independent variables (Dbh and h), using linear and non-linear regression analysis to establish best fit models with the SPSS statistical package (vers.19). The selection of best-fit models was based on the adjusted determination coefficient (R^2), F test and graphical examination of the residuals.

6.2. Pruning models

Many shade trees within coffee agroforestry systems are managed due to competition and light requirements of coffee at certain stages of its development such as flowering. Shade trees are

therefore categorised within CAFCA into ‘managed’ and ‘unmanaged’ trees per species. ‘Managed’ trees are considered to be those which are pruned frequently for organic matter input to soil or to obtain firewood. ‘Unmanaged’ trees are categorised as those not regularly pruned for the aforementioned purposes, but might receive infrequent management of elevation or crown form. Based on the empirical data collected for the development of the allometric models for ABG biomass estimation, a number of sub models have been developed to allow the estimation of average pruned material inputs, for both shade trees and coffee bushes.

With the help of these models, CAFCA is able to calculate pruning residues when farmers do not know the amount of material pruned or firewood obtained from shade trees. At the same time, data collected from farmers can be verified against pruning model predictions. One shortcoming of the current version of CAFCA however is the limited number of available pruning models. The shade structure in CAFS can range from single species shade to multi-storey shade systems including a vast number of tree species. In order to allow an estimate of pruning inputs to be made for tree species where no empirical data is available, a number of assumptions have been made within CAFCA. Within the tree species available within CAFCA, once divided into ‘managed’ and ‘unmanaged’ trees, these are further categorised into timber trees, service trees and a mixture. According to the characteristics chosen for the individual trees surveyed, a pruning model is assigned. It is anticipated that in further versions of the tool more species-specific pruning models can be added to allow for a more accurate estimate of this emission source.

With the amount of pruning inputs estimated, CAFCA is able to calculate soil N₂O emissions from these. It draws the necessary % N values of leaf litter for the individual tree species from a publically available database based on a study by Wright et al. (2004) which collected data from over 2500 species. As volumes of firewood are often given in local volume measures, a number of publically available wood density databases for the individual tree species have been added. Where possible these values have been taken from the accompanying database to a study by Chave et al. (2006), otherwise values have been taken from the World Agroforestry Centre (ICRAF) tree wood density database (ICRAF, 2011).

In Costa Rica the only ‘managed’ shade tree species within the experiment is *E. poeppigiana*. There are two types of management present within the experiment: a) ‘drastic’ management in which the tree is pruned (pollarded) completely twice annually at a height of around 2 m to allow for maximum organic matter input and light exposure at times of flowering and fruit ripening and b) ‘regular’ management where trees are managed at a height of between 4 – 5 m in which a

total of three main branches are left as shade cover. However only a model for ‘drastic’ management has been established as linear correlation analysis did not result in an acceptable level of prediction for ‘regular’ pruning. The model is based on data collected for the two annual pruning events in 2009 on a total of 30 trees under ‘drastic’ management. For ‘regular’ management and situations where no data are available for average Dbh or h, an additional model for the estimation of average *E. poeppigiana* pruning residues has been added. The best fit model ($R^2 = 0.85$), which requires data on average age and tree density of the stand rather than Dbh and h, is based on 12 data sets (including the experiments) published by Beer (Beer, 1988).

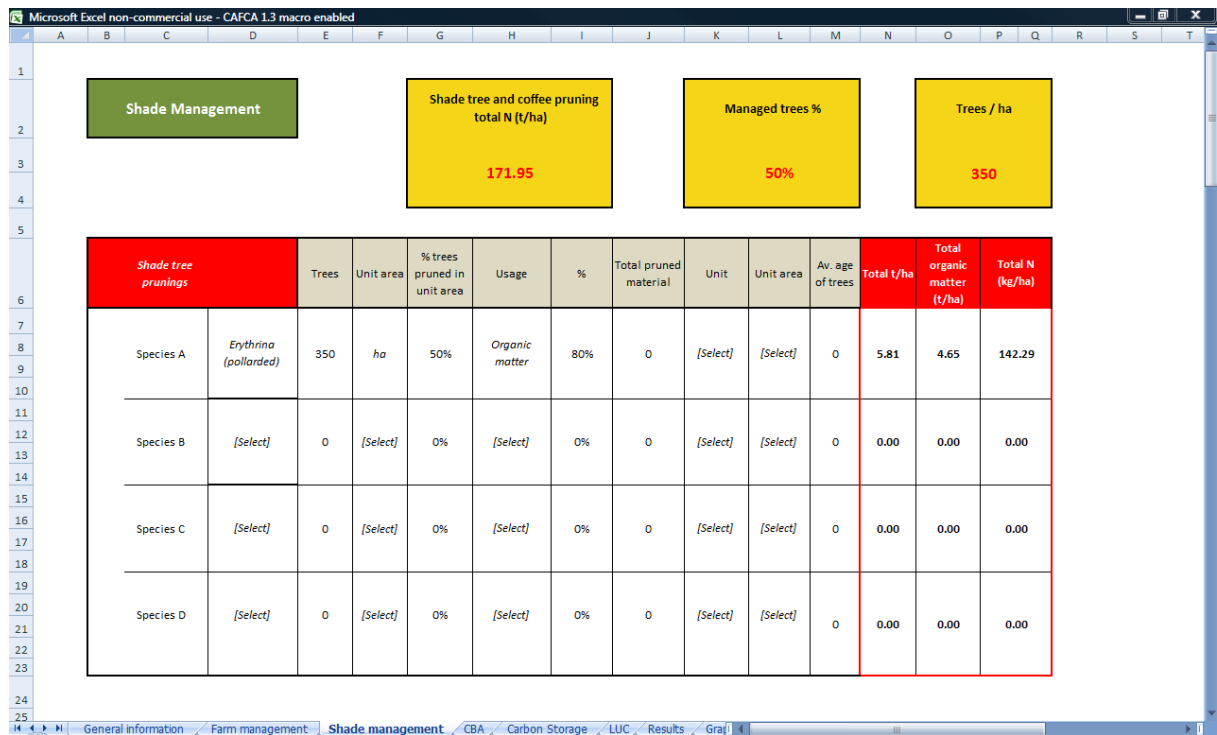


Figure A1.5 Shade management input window

In Nicaragua, pruning models have been developed for the tree species *I. laurina*, *T. rosea*, *S. saman* and *S. glauca*. These are based on pruning data that were collected in 2005 and 2009. *I. laurina* was managed to create a homogeneous canopy cover of approximately 40%, through annual pruning of branches at any height. In contrast, the timber tree species were managed for form and crown shape to maximise timber value but were not subjected to a systematic pruning regime.

6.2.1. Statistical analysis

Models for pruned biomass (PB_T) estimation for individual species were derived by correlation analysis between the dependent variable (PB_T) and independent variables (Dbh and h), using linear and non-linear regression analysis to establish best-fit models with the SPSS statistical package. The selection of best fit models was based on the adjusted determination coefficient (R^2), F test and graphical examination of the residuals.

Table A1.2 Pruning models for tree species found in the experiments in Costa Rica and Nicaragua.

Species	Model	Parameter			r^2
		a	b	c	
<i>I. laurina</i>	$LN(PB_T) = a + b*LN(Dbh) + c*h$	5.93	1.3	0.04	0.79
<i>S. glauca</i>	$LN(PB_T) = a + b*LN(Dbh) + c*h$	7.54	2.49	0.85	0.74
<i>S. saman</i>	$LN(PB_T) = a + b*LN(Dbh) + c*h$	8.51	2.56	0.03	0.76
<i>T. rosea</i>	$LN(PB_T) = a + b*LN(Dbh) + c*h$	9.04	2.89	0.05	0.84
<i>E. poeppigiana</i> ('drastic')	$PB_T = a + b*\log_{10}(Dbh)$	86.76	97.74		0.42
<i>E. poeppigiana</i> ('regular')	$PB_T = a + b*(tree\ density) + c*(age)$	70.3	-0.106	0.594	0.85

6.3. Coffee

Similar to the pruning estimation of shade trees, for coffee, emission calculations are based on relative percentages of N contribution and are derived from field measurements from the experiments in Costa Rica and Nicaragua (Montenegro, 2005; Romero, 2006). Pruning estimations of coffee are based on individual coffee plants and can be estimated within CAFCA by specifying the percentage of plants being pruned every year. This is achieved through a default setting in which field measurements of a sufficient number of plants are required, detailing the type of pruning/life stage the plants are in. Depending on the details provided, CAFCA calculates the percentage of plants which have been pruned within the last three years and assigns an annual value for the calculation of emissions from coffee pruning inputs. Pruned material such as leaves, branches and stems have been analysed for N content and averaged with other peer reviewed data (van Oijen et al., 2010). Due to differences in the management of coffee plants between countries, one is able to choose between a number of options within CAFCA that allow to distinguish between the amount of pruned material obtained and left in the

field. As such, either a manual input of the percentage of pruned plants per year within the sampling area or an amount of pruned material from the coffee plants that is used for firewood can be inputted. The latter case enables CAFCA to calculate the pruning inputs with the help of the relative percentages of plant parts and their N contributions according to the overall pruned coffee material used for firewood.

6.4. Cost-benefit analysis (CBA)

Carbon footprinting or the quantification of GHGs alone is not considered to be a good indicator of sustainable development. In order to help identify the most optimal farming system when considering environmental and financial aspects together, suggestions have been made that a possible category in helping to assess rural development could be obtained by calculating a carbon footprint per income or profit (Brenton et al., 2010). This will allow assessing and comparing the cost-effectiveness of farm inputs and management. To enable the farmer to assess the financial effects of changes in the overall carbon footprint through changing e.g. amounts of fertiliser usage, a financial sub model that carries out a simple cost-benefit analysis (CBA) has been added to CAFCA. Costs of all material inputs are automatically calculated according to the entries made in the 'Farm management' sub model which is used to describe in detail all inputs used in the management and cultivation of coffee within the farm boundaries. Base prices and costs of individual input items have to be added into a database which CAFCA uses as a reference list for all cost calculations. As a default option, average prices for a wide range of input materials such as fertilisers, pesticides and sundries have been added. These have been collected and calculated from over 60 farm surveys and compared to the prices of materials for the two experimental sites for the years 2007 -2009. Labour inputs and costs are entered separately according to their associated activity within the farm. Due to the biennial yield pattern of coffee productivity (Maestri and Santos-Barros, 1977), yield data based on the harvest of the past three years is required.

As the functional unit of all calculations 1kg of fresh (unprocessed) coffee cherries has been chosen, coffee prices must be related to this unit. However, farmers do not always sell their coffee in this un-processed form (and therefore don't know the actual amounts as fresh cherries) and larger farms especially may sell their coffee in a processed form termed 'oro', also known as 'green' coffee in the UK. The price difference between un-processed cherries and processed 'oro' can be quite substantial especially in the case of speciality or certified coffees. Therefore

conversion factors have been built into CAFCA so that yield data can be inputted in various ways, and translated back to the same functional unit (Table A1.3).

Table A1.3 Coffee cherry conversion from *'fresh'* to *'oro'* (green) in Costa Rica and Nicaragua

	1 fanega fresh cherries (kg)	1 quintal 'oro' (kg)	Conversion factor fanega fresh to quintal 'oro'
Costa Rica	258	46	1
Nicaragua	141	46	2.5

The country difference in conversions is due to the difference in coffee pulp to grain ratio between regions. Coffee from higher zones has a lower ratio than from lower zones as the grains are larger and denser at higher altitudes.

Other economic benefits such as income from firewood, timber and fruit if harvested from within the coffee system have been accounted for by using the quantities and prices reported by individual farms. As PAS 2050 states that co-products from the main system must be allocated a portion of the carbon footprint according to their economic value (BSI, 2011), a relative percentage of the economic value of co-products has been deducted from the overall coffee footprint and assigned to the co-products.

7. Calculation of land-use change emissions (LUC)

Land-use change emissions and removals of CO₂ are consequences of changes in ecosystem carbon stocks. These emissions and removals are calculated using the IPCC guidelines for national greenhouse gas inventories for agriculture, forestry and other land use (IPCC, 2006) (Supplementary Information, Section B). Changes in carbon stocks for a given land-use category are calculated based on fluxes for the carbon pools of aboveground and belowground biomass, litter, dead wood and soil organic matter including inputs and outputs and transfers between pools. Non-CO₂ emissions derived from sources such as manure, dead wood and litter and emissions from soils have also been included. To estimate non-CO₂ emissions, gas- and source-specific emission factors are used. All changes in C stocks are reported in CO₂ equivalents; units of C are converted by multiplication of 44/12 (ratio of molecular weights) for reporting purposes. Although changes in C stocks for example through land-use change often result in

immediate carbon balance alteration, IPCC guidelines specify a period of 20 years in which the land remains in the conversion category before a new C stock equilibrium is expected (IPCC, 2006). For this purpose, C stock changes are annualised for a period of 20 years. Management and shade type for additional LUC area has been assumed equal to that of the tested case in the experimental plot.

8. Further Developments

The current CAFCA model represents an transparent estimation of GHG emissions for coffee farming systems. However, substantial uncertainties may be associated with some calculations especially when calculating soil N₂O emissions. This is due to the limited number of region-specific emission factors for soil N₂O emissions which are necessary for IPCC tier 2 methods (Section A). In contrast, IPCC tier 1 methods are designed to estimate emissions on a regional or global basis, omitting detailed farm characteristics that could impact the overall outcome significantly. As a function of this, variations in climate, soil properties and farming practices have the greatest effect on overall GHG emissions stemming from the cultivation of coffee. The accuracy of the CF at the farm level will greatly depend on the choice of emission factors and therefore plays a crucial role for further investigation.

Further, although PAS 2050 states that carbon storage should be taken into account in the assessment of a product, it specifies that only non-living stores of carbon may be included (BSI, 2011). While it has been acknowledged in the specification that *“forest management activities may result in additional carbon storage in managed forests through the retention of forest biomass”* this has so far been omitted from the methodology. Similarly, soils are recognized as playing an important part in the carbon cycle, both as a source and sink for carbon. However due to ‘considerable uncertainty’ regarding the impact of differing farm management techniques on emissions and sequestration of soil C, soils are omitted from the calculations. Although included within CAFCA, aboveground and soil C pools merit further investigation. For aboveground C estimations the importance lays with the development of more species- and management-specific allometric functions for additional shade trees species commonly used in coffee systems in various regions. For soils, the limitations of our understanding are much greater and complex and warrant more site-specific research if this pool is to be considered in C balance calculations of coffee agroforestry systems at all.

9. Supplementary Information

A. Tier 1 and 2 emission factors for calculations in CAFCA

Table A1.4 Tier 1 (default) and tier 2 emission factors for direct N₂O emissions estimates from managed soils

Emission factor	Tier 1 (default) EF	Tier 2 EF
EF ₁ for N additions from mineral fertilisers, organic amendments and crop residues, and N mineralised from mineral soil as a result of loss of soil carbon [kg N ₂ O–N (kgN) ⁻¹]	0.01†	0.01 -0.012‡, 0.003* for crop residues
EF _{2 CG, Temp} for temperate organic crop and grassland soils (kg N ₂ O–N ha ⁻¹)	8†	na
EF _{2 CG, Trop} for tropical organic crop and grassland soils (kgN ₂ O–N ha ⁻¹)	16†	na
EF _{2F, Temp, Org, R} for temperate and boreal organic nutrient rich forest soils (kg N ₂ O–N ha ⁻¹)	0.6†	na
EF _{2F, Temp, Org, P} for temperate and boreal organic nutrient poor forest soils (kg N ₂ O–N ha ⁻¹)	0.1†	na
EF _{2F, Trop} for tropical organic forest soils (kg N ₂ O–N ha ⁻¹)	8†	Na

† (De Klein, *et al.*, 2006); ‡(0.01 = Full sun & timber shade systems; 0.012 = Legumes shade systems; (Hergoualc’h *et al.*, 2008)); *Hergoualc’h pers. comm. 2010;

Table A1.5 Tier 1 (default) emission factors for indirect N₂O emissions (volatilisation and leaching) estimates from managed soils (De Klein *et al.*, 2006).

Emission factor (EF)	Tier 1 (default) value
EF ₄ [N volatilisation and re-deposition], kg N ₂ O–N (kg NH ₃ –N + NO _x –N volatilised) ⁻¹ [22]	0.01
EF ₅ [leaching/runoff], kg N ₂ O–N (kg N leaching/runoff) ⁻¹ [23]	0.0075
Frac _{GASF} [Volatilisation from synthetic fertiliser], (kg NH ₃ –N + NO _x –N) (kg N applied) ⁻¹	0.1
Frac _{GASM} [Volatilisation from all organic N fertilisers applied, and dung and urine deposited by grazing animals], (kg NH ₃ –N + NO _x –N) (kg N applied or deposited) ⁻¹	0.2
Frac _{LEACH-(H)} [N losses by leaching/runoff for regions where Σ(rain in rainy season) - Σ (PE† in same period) > soil water holding capacity, OR where irrigation (except drip irrigation) is employed], kg N (kg N additions or deposition by grazing animals) ⁻¹	0.3

†In the definition of Frac_{LEACH-(H)} above, PE is potential evaporation, and the rainy season(s) can be taken as the period(s) when rainfall > 0.5 * Pan Evaporation. For other regions the default Frac_{LEACH} is taken as zero.

B. LUC emissions calculations according to the IPCC guidelines for national GHG inventory

- i. Annual carbon stock changes for a stratum of a land-use category as a sum of changes in all pools

$$\Delta C_{LUI} = \Delta C_{AB} + \Delta C_{BB} + \Delta C_{DW} + \Delta C_{LI} + \Delta C_{SO}$$

ΔC_{LUI} = carbon stock changes for a stratum of a land-use category

Subscripts denote the following carbon pools:

AB = above-ground biomass

BB = below-ground biomass

DW = deadwood

LI = litter

SO = soils

- ii. Annual change in biomass carbon stocks on land converted to other land-use category (Tier 2)

$$\Delta C_B = \Delta C_G + \Delta C_{CONVERSION} - \Delta C_L$$

ΔC_B = annual change in carbon stocks in biomass on land converted to other land-use category, in tonnes C yr⁻¹

ΔC_G = annual increase in carbon stocks in biomass due to growth on land converted to another land-use category, in tonnes C yr⁻¹

$\Delta C_{CONVERSION}$ = initial change in carbon stocks in biomass on land converted to other land-use category, in tonnes C yr⁻¹

ΔC_L = annual decrease in biomass carbon stocks due to losses from harvesting, fuel wood gathering and disturbances on land converted to other land-use category, in tonnes C yr⁻¹

iii. Initial change in biomass carbon stocks on land converted to another land category

$$\Delta C_{CONVERSION} = \sum_i \{ (B_{AFTER_i} - B_{BEFORE_i}) * \Delta A_{TO_OTHERS_i} \} * CF$$

$\Delta C_{CONVERSION}$ = initial change in biomass carbon stocks on land converted to another land category, tonnes C yr⁻¹

B_{AFTER_i} = biomass stocks on land type i immediately after the conversion, tonnes d.m. ha⁻¹

B_{BEFORE_i} = biomass stocks on land type i before the conversion, tonnes d.m. ha⁻¹

$\Delta A_{TO_OTHERS_i}$ = area of land use i converted to another land-use category in a certain year, ha yr⁻¹

CF = carbon fraction of dry matter, tonne C (tonnes d.m.)⁻¹

i = type of land use converted to another land-use category

iv. Annual change in organic carbon stocks in mineral soils

$$\Delta C_{Mineral} = \frac{(SOC_0 - SOC_{(0-T)})}{D}$$

$$SOC = \sum_{c,s,i} (SOC_{REF_{c,s,i}} * F_{LU_{c,s,i}} * F_{MG_{c,s,i}} * F_{I_{c,s,i}} * A_{c,s,i})$$

$\Delta C_{Mineral}$ = annual change in carbon stocks in mineral soils, tonnes C yr⁻¹

SOC_0 = soil organic carbon stock in the last year of an inventory time period, tonnes C

$SOC_{(0-T)}$ = soil organic carbon stock at the beginning of the inventory time period, tonnes C

SOC_0 and $SOC_{(0-T)}$ are calculated using the reference carbon stocks and stock change factors assigned according to the land-use and management activities and corresponding areas at each of the points in time (time = 0 and time = 0-T)

T = number of years over a single inventory time period, yr

D = Time dependence of stock change factors which is the default time period for transition between equilibrium SOC values, yr. Commonly 20 years, but depends on assumptions made in computing the factors F_{LU} , F_{MG} and F_I . If T exceeds D , use the value for T to obtain an annual rate of change over the inventory time period (0 - T years).

c = represents the climate zones, s the soil types, and i the set of management systems that are present in a country.

SOC_{REF} = the reference carbon stock, tonnes C ha⁻¹

F_{LU} = stock change factor for land-use systems or sub-system for a particular land-use, dimensionless

F_{MG} = stock change factor for management regime, dimensionless

F_I = stock change factor for input of organic matter, dimensionless

A = land area of the stratum being estimated, ha. All land in the stratum should have common biophysical conditions (i.e., climate and soil type) and management history over the inventory time period to be treated together for analytical purposes.

Appendix 2 Farmer questionnaire



Formulario No.:

El almacenamiento de carbono y las emisiones de gases invernadero en la finca

CATIE – BANGOR - CAFNET

PRESENTACIÓN

CONFIDENCIALIDAD
El informante es libre de responder o no este formulario, y en cualquier caso la Información será tratada con toda reserva.

Mi nombre es Martín Noponen, soy estudiante del Centro Agronómico Tropical de Investigación y Enseñanza (CATIE), localizado en Managua, Nicaragua. Estoy realizando un estudio sobre almacenamiento de carbono que hacen los árboles en los cafetales. El propósito del estudio es:

- 1.) Evaluar el carbono que se almacena en su cafetal
- 2.) Evaluar la cantidad de gases de efecto invernadero (emisión de gases por la agroindustria y los productos derivados de ella, como los fertilizantes y plaguicidas) que son emitidos a través de la aplicación de fertilizantes y pesticidas. Esto nos permitirá calcular un balance de carbono de su finca. Más carbono almacenado en los árboles ayuda a reducir los gases de efecto invernadero que contribuyen al calentamiento global.

Aunque no hay beneficios inmediatos para el agricultor, en el largo plazo (5 – 10 años), esperamos poder influir en la toma de decisiones de políticas en Nicaragua, del que se beneficiarán los productores de café.

Para realizar este trabajo, necesitamos información de un grupo de productores (aproximadamente 25 personas de la zona, usted es uno de ellos). Seleccionamos su finca porque tiene elementos claves de manejo incluyendo diferentes tipos de sombra.

Al final del estudio, nos gustaría ofrecerle un breve informe con los resultados obtenidos. Esto le dirá cuánto carbono está almacenado en la finca.

Me gustaría pedirle permiso para entrevistarle y aclararle algunos aspectos importantes:

- Su participación en esta entrevista es totalmente voluntaria (Si no desea participar o si existe alguna pregunta que no desea contestar puede decímelos sin ningún problema).
- Si en algún momento se incomoda y no quiere continuar, por favor me lo hace saber.
- Otra cosa que me gustaría aclarar es que su respuesta es anónima, es decir, aunque sus respuestas y las de las otras personas son importantísimas para entender las condiciones productivas cafetaleras particulares de esta región, serán estudiadas en conjunto y por eso no se va a saber cuáles fueron sus respuestas en particular.
- Si mi pregunta no es clara o si desea alguna explicación adicional por favor no dude en preguntarme.
- Estaremos tomando notas (o fotos) de nuestra entrevista para no perder la información y poderla analizar. Esperamos que esto no le incomode, si le incomoda, por favor me lo hace saber.

Muchas gracias por su colaboración.

Fecha de Encuesta: o que cubre la encuesta:

Nombre del encuestador:

Desde → Hasta

MÓDULO A. Información básica

<p>SECCIÓN A. Identificación</p> <p>1. Localización de la finca (Dirección):</p> <p>a. Departamento _____</p> <p>b. Municipio _____</p> <p>c. Comunidad _____</p> <p>d. Nombre de la Finca _____</p> <p>e. Teléfono (si tiene) _____</p> <p>2. En la finca usted es (marque solo una opción):</p> <p>1. Propietario <input type="checkbox"/> <input type="text" value="1"/> <input type="text"/></p> <p>2. Administrador <input type="checkbox"/> <input type="text" value="2"/> <input type="text"/></p> <p>3. Otro ¿Cuál? <input type="checkbox"/> <input type="text" value="3"/> <input type="text"/></p> <p>3. Nombre del Informante:</p> <p>_____</p> <p>4. Nombre(s) y Apellido(s) de la persona que toma las decisiones en la finca: (si es diferente del nombre anterior)</p> <p>_____</p> <p>5. Sexo de quien toma las decisiones (no pregunte, observe)</p> <p>Hombre: <input type="checkbox"/> <input type="text" value="1"/> <input type="text"/> <input type="checkbox"/> <input type="text" value="2"/> <input type="text"/></p>	<p>6. Número de hogares que hay en la finca:</p> <p><input type="text"/> <input type="text"/></p> <p>7. Cuántos miembros tiene el hogar del productor:</p> <p><input type="text"/> <input type="text"/></p> <p>8. Tenencia de la tierra</p> <p>1. Propietario residente en la finca <input type="checkbox"/></p> <p>2. Propietario no vive en la finca <input type="checkbox"/></p> <p>3. Arrendatario <input type="checkbox"/></p> <p>4. Otro ¿Cuál? _____ <input type="checkbox"/></p> <p>9. Altitud sobre nivel del mar:</p> <p><input type="text"/> <input type="text"/> <input type="text"/> <input type="text"/> <input type="text"/> m</p> <p>10. ¿Esta finca está certificada como productora de algún sello de café?</p> <p>SI <input type="checkbox"/> NO <input type="checkbox"/></p>
--	---

11. ¿Qué tipo de Sello tiene? (Puede marcar varias opciones) y anote el mes o año en que empezó a certificarse con cada sello.

	Mes												Año											
a. Organic																								
b. Utz certified																								
c. FLO																								
d. Rainforest Alliance																								
e. Nespresso AAA																								
f. 4C																								
g. Café Practices (Starbucks)																								
h. Other (specify)																								
j. Conventional																								

12. ¿A quién le vende su café?

1. Comprador particular			
2. Cooperativa			
3. Asociación			
4. Trillador Privado			
5. Exportador			
6. Tostador			
7. Otro, ¿Cuál?			

13. En qué forma vende la mayoría de su café:

1. Uva o cereza		%
2. Uva o cereza seca		%
3. Pergamino Húmedo		%
4. Pergamino seco		%
5. Oro		%
6. Otro, ¿Cuál?		%

14. Lista de evidencia de apoyo:

	No	Yes			N/A
	Estimación del productor	Parte de la información tiene soporte	Toda la información tiene soporte	Algunas veces le ha usado para tomar decisiones	
Cantidades, costos de insumos y aplicación de fertilizantes					
Cantidades, costos de insumos y aplicación de plaguicidas y herbicidas					
Costos pagados de mano de obra					
Costos anuales de recolección y procesamiento subcontratado fuera de la finca					

MÓDULO B. Información de finca. Por favor, rellene en la unidad, que cada vez se siente más cómodo.

15. Áreas y densidad de siembra

	Mz	Ha
a. Área total de la finca		
b. Área en solo bosque		
c. Área en café de pleno sol		
d. Área sembrada en café		
e. Área en otros cultivos		

Por favor, rellene las siguientes preguntas para cada parcela que el agricultor atiende - "Parcela" es lo que será definido por los agricultores de acuerdo a cómo se definen sus áreas agrícolas en la producción de café. El propósito para el uso de la distribución no es para obtener detalles complicados, sino para hacer más fácil a los agricultores proporcionar información exacta. Use hojas separadas para cada parcela.

Parcela No.

Tipo de parcela: _____

16. Información de café

	Mz	Ha
a. Área total de café		
b. # total de plantas de café		
c. # total de plantas reemplazadas/resiembra		
d. # total de plantas productivas		
e. Ø distancia entre calle de café (m)		
f. Ø distancia entre plantas de café en fila la misma (m)		

17. ¿Cuál es la variedad predominante en esta finca?

1. Caturra		%
2. Catimor		%
3. Catuai		%
4. Borbon		%
5. Maragojipe		%
6. Maracaturra		%
7. Pacamara		%
8. Otro, ¿Cuál?		%

<p>18. ¿Cómo se utiliza el material podado de café principalmente?</p> <p>a. Leña ----- <table border="1" style="display: inline-table; border-collapse: collapse; width: 40px; height: 20px; vertical-align: middle;"></table></p> <p>b. Cerca/valla ----- <table border="1" style="display: inline-table; border-collapse: collapse; width: 40px; height: 20px; vertical-align: middle;"></table></p> <p>c. Fertilización de suelo ----- <table border="1" style="display: inline-table; border-collapse: collapse; width: 40px; height: 20px; vertical-align: middle;"></table></p> <p>d. Otro, ¿Cuál? ----- <table border="1" style="display: inline-table; border-collapse: collapse; width: 40px; height: 20px; vertical-align: middle;"></table></p>	<p>20. ¿Cuántos años ha producido café en esta parcela?</p> <p style="text-align: right;">Años <table border="1" style="display: inline-table; border-collapse: collapse; width: 60px; height: 20px; vertical-align: middle;"></table></p> <p>Si es menos de 20 años,</p> <p>a. ¿en qué año fue la tierra convertida en cafetal? <table border="1" style="display: inline-table; border-collapse: collapse; width: 60px; height: 20px; vertical-align: middle;"></table></p> <p>b. ¿Cuál fue el uso anterior de la parcela? <table border="1" style="display: inline-table; border-collapse: collapse; width: 60px; height: 20px; vertical-align: middle;"></table></p>																																																																																		
<p>19. ¿Cuánto material de poda de café que utiliza para leña?</p> <table style="width: 100%; border-collapse: collapse;"> <tr> <td style="text-align: center; width: 25%;">Mz</td> <td style="width: 25%;"></td> <td style="text-align: center; width: 25%;">Parcela</td> <td style="width: 25%;"></td> </tr> <tr> <td style="border: 1px solid black; width: 40px; height: 20px;"></td> <td style="text-align: center; font-size: small;">Marca</td> <td style="border: 1px solid black; width: 40px; height: 20px;"></td> <td style="text-align: center; font-size: small;">Marca</td> </tr> </table>		Mz		Parcela			Marca		Marca																																																																										
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<p>21. Información de árboles para sombra</p>																																																																																			
<p>a. Cuantos años tienen los arboles en este parcela? <table border="1" style="display: inline-table; border-collapse: collapse; width: 300px; height: 20px; vertical-align: middle;"></table></p> <p><i>Por favor, especifique el nombre común / nombre científico en la parcela</i></p> <p>1. _____ 2. _____ 3. _____</p> <p>4. _____ 5. _____ 6. _____</p> <p>7. _____ 8. _____ 7. _____</p> <p>a. Usted tiene arboles de resiembra en la parcela? Si <input type="checkbox"/></p> <p style="margin-left: 300px;">No <input type="checkbox"/></p> <p>En caso afirmativo, ¿cuántos años los arboles de resiembra tienen? _____</p> <p>Cual especies? _____</p>																																																																																			
<p>22. Por favor, indique el tipo de manejo de los árboles (%)</p> <table border="1" style="width: 100%; border-collapse: collapse; text-align: center;"> <thead> <tr> <th rowspan="2"></th> <th rowspan="2">Nombre</th> <th colspan="2">Tipo de manejo</th> <th rowspan="2">Qué tipo de poda</th> </tr> <tr> <th>No poda</th> <th>No poda</th> </tr> </thead> <tbody> <tr> <td>a. Árbol de leguminosa</td> <td></td> <td></td> <td></td> <td></td> </tr> <tr> <td>b. Árbol de madera</td> <td></td> <td></td> <td></td> <td></td> </tr> <tr> <td>c. Otro, ¿Cuál?</td> <td></td> <td></td> <td></td> <td></td> </tr> </tbody> </table>			Nombre	Tipo de manejo		Qué tipo de poda	No poda	No poda	a. Árbol de leguminosa					b. Árbol de madera					c. Otro, ¿Cuál?																																																																
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Nombre de árbol	Leña		Madera																																																																																
	Mz	parcela	Mz	parcela																																																																															

24. ¿Usted corta / cosecha los árboles de sombra a propósito por madera?

Si No

En caso afirmativo, ¿por qué razón fueron los árboles cortados? Por favor, nombre de 2 o de 3 los recientes acontecimientos para los que corto los árboles.

a. ¿Con qué frecuencia cortar/cosecha los árboles por madera? Una vez/año Cada 2-5 años > 5 años

b. ¿Usted replanta árboles o deja que se la regeneren naturalmente? Regeneración natural -----

Replantar -----

MÓDULO C. Dimensión económica / LCA

25. Qué actividades económicas realiza el hogar agrícola para obtener sus ingresos? (Marque con "X"). ¿Qué porcentaje o parte representan aproximadamente las otras actividades económicas para los ingresos del hogar? (solo por área de café)

Actividades económicas para la generación de ingresos del hogar	"X"	Porcentaje (%) del ingreso familiar que representa la actividad económica
Cultivo del café		
Otros cultivos (especificar):		
Maderables		
Tenencia de animales (ganadería)		
Ecoturismo		
Asalariado o jornalero en otra finca		
Trabajador en actividades no agropecuarias		
Ingresos por remesas o giros del exterior		
Otra (Especifique):		

26. Cuenta con mano de obra familiar sin remuneración fija? (solo por área de café)

Si

Cuántas personas

No

Por favor, rellene las siguientes preguntas para cada parcela que el agricultor atiende - "Parcela" es lo que será definido por los agricultores de acuerdo a cómo se definen sus áreas agrícolas en la producción de café. El propósito para el uso de la distribución no es para obtener detalles complicados, sino para hacer más fácil a los agricultores proporcionar información exacta. **Use hojas separadas para cada parcela.**

Parcela No. _____

27. Costos de fertilización (sólo por el área de café) - por 2009, 2007, 2008

a. Cantidades y costos de insumos

Fertilizante (componentes-N/P/K Mg(S) o Nombre Comercial	Año	Org = orgánico Ch = químico/ sintético	Unidad qq = quintal l = Litros kg = kilogramo	Cantidad Total Aplicada	Mixta con agua (cantidad)	Dosis (Mz Parcela Ha)	No. Veces (año)	Costo unitario (C\$)	Costo Total (C\$)
1.									
2.									
3.									
4.									
5.									
6.									

b. Costos por labor o actividad en la finca (pagados)

ACTIVIDAD	No dh	Unidad (Mz, parcela, ha)	Costo unitario (C\$)		Costo total (C\$)
			Familia	Mano de obra contratada	
1. Preparación de productos					
2. Aplicación de productos					
3. Transporte de productos					

Comentarios:

Costo total fertilización

a. Costos de insumos C\$

b. Costos por labor C\$

C\$

28. Costos de Insecticida, Herbicidas, Fungicidas (sólo por el área de café) – por 2009, 2008, 2007

a. Cantidades y costos de insumos

Insecticidas, Herbicidas, Fungicidas (componentes) o Nombre Comercial	Año	Org = orgánico Ch = químico/ sintético	Unidad qq = quintal l = Litros kg = kilogramo	Cantidad Total Aplicada	Mixta con agua (cantidad)	Dosis (Mz Parcela Ha)	No. Vaces (año)	Costo unitario (C\$)	Costo Total (C\$)
1.									
2.									
3.									
4.									
5.									
6.									

b. Costos por labor o actividad en la finca (pagados)

ACTIVIDAD	No dh	Unidad (Mz, parcela, ha)	Costo unitario (C\$)		Costo total (C\$)
			Familia	Mano de obra contratada	
1. Preparación y aplicación de productos					
2. Transporte de productos					
3. Malezas (arvenses, limpias)					
4. Otros-(EJ: control de broca)					

Comentarios:

Costo total plaguicidas

a. Costos de insumos C\$

b. Costos por labor C\$

C\$

29. Costo de manejo (sólo por el área de café)

a. Cosecha y pos cosecha

ACTIVIDAD	Cantidad	Costo unitario (C\$)	Costo total (C\$)
1. Costos de recolección de café (se refieren sólo al jornal)			
2. Costos de recolección por sacos			

b. Manejo de finca (solo por área de café)

ACTIVIDAD	Cantidad	Costo unitario (C\$)	Costo total (C\$)
1. Costos de renovación de café (costo por planta)			
2. Siembra de nuevas plantas de café			
3. Manejo de Cafetal (poda, deshije, recpo)			
4. Prácticas de conservación de suelos (Siembra de barreras vivas, trazos de curvas de nivel)			
5. Siembra de árboles (sombra y cortinas rompe vientos)			
6. Manejo de la sombra			
7. Administración y supervisión			
8. Otro, ¿Cuál?			

Comentarios:

Costo total a. & b.

a. Cosecha/pos cosecha

b. Manejo de finca

c. Material y otros insumos (solo por área de café)

ACTIVIDAD	Cantidad	Costo unitario (C\$)	Costo total (C\$)
1. Canastos recolector			
2. Sacos para empaçar café			
3. Herramientas agrícolas (ej. Machetes, Lima)			
4. Agua			
5. Electricidad			
6. Otro, ¿Cuál?			

d. Costos de combustible

ACTIVIDAD (que utiliza energía)	Tipo de combustible (anote el número de la opción de combustible que utiliza) - (1) Madera, (2) Gasolina, (3) Diesel, (4) Lubrificantes, (5) Otro	Cantidad	Costo unitario (C\$)	Costo total (C\$)
1. Aplicación de fertilizantes				
2. Preparación de abonos orgánicos o transporte de insumos				
3. Transporte de fertilizantes orgánico				
4. Moto bomba, moto sierras y aspersores				
5. Transporte de café				
6. Despujado del café				
7. Secado del café				
8. Otro, ¿Cuál?				

* Indique la fuente de la madera o leña a) plantación forestal b) bosque c) podas (café o árbol) d) compra

Comentarios:

Costo total c. & d.

C\$

c. Material y otros insumos

C\$

d. Costos de combustible

C\$

31. Ingresos totales por venta de café y sobreprios (certificados y no certificados)

		*Certificación	Volumen qq = quintales fg = fanegas	Área en producción de café	Precio promedio por quintal (C\$)	Ingreso total (C\$)	Sobreprio por quintal (C\$)
2009	a. Café certificado	Vendido como certificado					
	b. Café no certificado	Vendido como no certificado					
2008	a. Café certificado	Vendido como certificado					
	b. Café no certificado	Vendido como no certificado					
2007	a. Café certificado	Vendido como certificado					
	b. Café no certificado	Vendido como no certificado					

*(Ponga un número de acuerdo con la certificación que el productor uso para vender su café) 1.Café Practices, 2.FLO, 3. Nespresso AAA, 4.Orgánico, 5.Rainforest, 6. Utz certified

32. Total ingresos y volumen de productos distintos de café, cosecha de la zona de cultivo de café

	Nombre de producto (e.g. banana, plátano, etc.)	Área en producción	Volumen cosecha qq = quintales kg = kilogramo	Volumen ventas	Precio promedio (C\$)	Ingreso total (C\$)	Volumen consumido por los hogares	Uso (e.g. consumo humano, alimentación animal, etc.)
2009								
2008								
2007								

Appendix 3 Supporting information Chapter 3

Table A3.1 Mean greenhouse gas emission contributions expressed on a per land area per time basis (Mg CO₂e ha⁻¹ yr⁻¹, ±SE for emissions from pruning) of each emission category to the total product carbon footprint, for the four sub-plot treatments (Conventional intensive (CI); Conventional moderate (CM); Organic intensive (OI); Organic moderate (OM)) for a) Costa Rica and b) Nicaragua.

Country	Sub-plot management treatments	Fertiliser production	Pesticide production	Fuels (used for non-transport purposes)	Materials and sundries	Transport	Direct/indirect soil N ₂ O emissions from fertiliser application	Direct/indirect soil N ₂ O emissions from pruning inputs	Total
a) Costa Rica									
	CI	2.89	0.29	¹	0.01	²	1.87	0.36 (±0.14)	5.42
	CM	1.51	0.09	0.13	0.01	²	1.02	0.33 (±0.09)	3.09
	OI	0.05	²	0.13	0.01	0.02	1.56	0.45 (±0.12)	2.21
	OM	0.03	0.04	0.14	0.01	0.01	0.20	0.59 (±0.22)	1.00
b) Nicaragua									
	CI	1.05	0.08	³	0.01	²	0.95	0.16 (±0.01)	2.25
	CM	0.54	0.07	³	0.01	²	0.49	0.18 (±0.01)	1.29
	OI	0.11	²	³	0.01	0.03	1.83	0.19 (±0.01)	2.16
	OM	0.00	²	³	0.01	0.02	0.37	0.19 (±0.01)	0.58

¹In Costa Rica CI weed control was managed with chemical herbicides applied manually. ²Emissions are considered here to be negligible if < 5 kg of total CF. ³ In Nicaragua no fuels were used in the management of the systems. Sub-plot treatments in a) Costa Rica (CI, n = 9; CM, n = 15; OI, n = 12; OM, n = 6) and b) Nicaragua (CI, n = 9; CM, n = 15; OI, n = 12; OM, n = 6). All values except direct/indirect soil N₂O emissions from pruning inputs are expressed without SE, as these are the same throughout the main-plot treatments.

Table A3.2 Mean N₂O emissions from pruning residues per area per time and per unit of coffee production (Mg CO₂e ha⁻¹yr⁻¹ and kg CO₂e t⁻¹ fresh cherries respectively) (±SE) for each of the shade types (main-plot treatments) for a) Costa Rica and b) Nicaragua.

Country	Main-plot treatment (shade-tree)	Emissions per area per time (tCO ₂ e·ha ⁻¹ ·yr ⁻¹)	Emissions per unit of coffee production (kgCO ₂ e·t ⁻¹)
a) Costa Rica	FS ³	0.09 ¹	11 (±1.9)
	E	1.01 (±0.025)	136 (±11.3)
	T	0.09 ^{1,2}	22 (±7.6)
	C	0.09 ^{1,2}	14 (±0.3)
	ET	0.47 (±0.013)	79 (±7.7)
b) Nicaragua	FS	0.12 ¹	17 (±2.0)
	SGTR	0.16 (±0.003)	31 (±5.9)
	SSTR	0.15 (±0.002)	24 (±3.0)
	ILSG	0.24 (±0.002)	51 (±3.1)
	ILSS	0.22 (±0.005)	41 (±2.8)

¹No standard errors are shown for these treatments as the emissions from pruning residues are based on inputs only from coffee plants which are assumed equal throughout the experiment; ²for these treatments some data on leaf and small branch material left as residues after thinning is missing, but it is considered negligible as a component of the total N₂O emissions from pruning residues shown. ³Full species names to which these abbreviations refer are given in Table A3.1 of the main text.

Appendix 4 Supporting information Chapter 4

Table A4.1 Above- and below-ground C pools

Treatment ¹	Subplot ¹	C stock shade trees (Mg C ha ⁻¹)	C stock coffee bushes (Mg C ha ⁻¹)	C stock litter (Mg C ha ⁻¹)	C stock deadwood (Mg C ha ⁻¹)	C stock roots (Mg C ha ⁻¹)	C stock total (Mg C ha ⁻¹)
C	CM	87.57 (±9.88)	4.05 (±0.35)	3.29 (±0.86)	2.24 (±0.55)	18.80 (±1.86)	115.95 (±11.66)
C	OI	87.62 (±9.66)	4.35 (±0.75)	3.30 (±0.84)	1.79 (±1.44)	18.86 (±1.82)	115.92 (±11.11)
E	CI	9.69 (±1.51)	5.16 (±0.21)	3.70 (±0.96)	0.50 (±0.10)	3.55 (±0.39)	22.61 (±1.81)
E	CM	18.79 (±0.35)	4.54 (±0.62)	3.95 (±1.17)	2.19 (±0.92)	5.50 (±0.09)	34.97 (±0.52)
E	OI	16.96 (±0.57)	5.55 (±0.52)	4.67 (±1.41)	0.57 (±0.21)	5.28 (±5.28)	33.03 (±1.33)
E	OM	16.64 (±1.67)	5.58 (±0.60)	1.94 (±0.49)	0.86 (±0.09)	5.22 (±0.26)	30.25 (±1.79)
ET	CM	41.82 (±2.01)	4.50 (±0.20)	3.93 (±0.98)	1.15 (±0.36)	10.25 (±0.36)	61.65 (±1.75)
ET	OI	23.98 (±0.35)	3.82 (±0.32)	2.82 (±0.90)	2.10 (±1.05)	6.47 (±0.13)	39.19 (±0.82)
FS	CI		4.98 (±0.18)	3.21 (±0.86)	0.31 (±0.08)	2.39 (±0.09)	10.88 (±1.11)
FS	CM		3.41 (±0.76)	2.12 (±0.57)	0.27 (±0.15)	1.64 (±0.37)	7.44 (±0.85)
T	CI	81.82 (±11.17)	5.41 (±0.33)	4.35 (±1.10)	1.46 (±0.26)	18.00 (±2.03)	111.04 (±12.86)
T	CM	41.21 (±6.14)	4.19 (±0.39)	6.19 (±1.55)	0.79 (±0.52)	10.05 (±1.15)	62.42 (±8.52)
T	OI	38.65 (±10.79)	4.36 (±0.76)	2.66 (±0.67)	0.64 (±0.28)	9.53 (±2.15)	55.83 (±13.48)
T	OM	36.39 (±10.72)	1.51 (±0.66)	0.37 (±0.19)	0.44 (±0.38)	8.51 (±2.31)	47.22 (±14.08)

¹Abbreviations are defined in full in Table 3.1 and 3.3 in Chapter 3.

Table A4.2 Models for estimating total shade tree and coffee above- and belowground biomass

Species	Model	Parameter			r^2	n	Diameter range
		a	b	c			
<i>Chloroleucon eurycyclum</i>	$\ln(B_T) = a + b \cdot dbh$	1.432	15.556		0.83	22	8 - 26
<i>Erythrina poeppigiana</i> (pollarded)	$B_T = a \cdot dbh^3 + b \cdot dbh + c$	1374.61	19.686	9.122	0.73	36	14 - 31
<i>Erythrina poeppigiana</i> (regularly pruned)	$\ln(B_T) = a + b \cdot \ln(dbh) + c \cdot h$	5.993	1.799	0.105	0.78	18	25 - 43
<i>Terminalia amazonia</i>	$\ln(B_T) = a + b \cdot dbh$	1.229	16.955		0.91	10	8 - 26
Shade tree belowground*	$B_T = \exp [a + b \cdot \ln(ABD)]$	-1.0587	0.8836				
<i>Coffea arabica</i> aboveground†	$\text{LOG}_{10}(B_T) = a + b \cdot \text{LOG}_{10}(d15) + c \cdot \text{LOG}_{10}(h)$	-1.113	1.578	0.581	0.94		
<i>Coffea arabica</i> aboveground (full sun)‡	$B_T = 0.48 \cdot \text{ABG}(\text{coffee})$						
<i>Coffea arabica</i> aboveground (shaded)‡	$B_T = 0.19 \cdot \text{ABG}(\text{coffee})$						

B_T = dry weight of total biomass (kg), dbh = Diameter (m) at breast height (1.3m), h = height (m), $d15$ = diameter at 15 cm aboveground; *Cairns et al (1997), †Segura et al. (2006), ‡Dossa et al. (2008).

Table A4.3 Mean annual system net CO₂e balance (±SE) for the LUC scenario (sum of sequestration into above-ground and below-ground biomass and litter (C sequestered) minus the carbon footprint (CF) on the existing farmed area (CF), minus the land-use change emissions and the carbon footprint of the additionally farmed land area converted from forest to offset the opportunity cost assuming the same management and shade type (LUC+CF), Mg CO₂e ha⁻¹ yr⁻¹) for the five shade types (defined in Figure A4.1) under the four different management treatments (defined in Figure 1). Break-even prices (±SE) for avoiding the land conversion from shaded to full sun coffee systems based on the opportunity cost (shortfall of annual NPV) using a C-market scenario (break-even price based on annual net CO₂e balance rate or net annual CO₂e sequestration rate).

Shade treatment	Net annual NPV (US\$·ha ⁻¹ ·yr ⁻¹)	Opportunity cost (US\$·ha ⁻¹ ·yr ⁻¹)	Opportunity cost (US\$·ha ⁻¹ ·yr ⁻¹)	Agricultural input costs (US\$·ha ⁻¹ ·yr ⁻¹)	CF ₂ (tCO ₂ e·ha ⁻¹ ·yr ⁻¹)	C sequestered in biomass and litter (Mg CO ₂ e·ha ⁻¹ ·yr ⁻¹)	Annual net CO ₂ e balance (Mg CO ₂ e·ha ⁻¹ ·yr ⁻¹)	Avoided LUC emissions (intensification) (Mg CO ₂ e·ha ⁻¹ ·yr ⁻¹)	GHG emissions from intensification (Mg CO ₂ e·ha ⁻¹ ·yr ⁻¹)	CO ₂ e balance after intensification (Mg CO ₂ e·ha ⁻¹ ·yr ⁻¹)	Break-even C market price based on CO ₂ e sequestration (US\$·Mg CO ₂ e ⁻¹)	Break-even C market price based on CO ₂ e balance (US\$·Mg CO ₂ e ⁻¹)	Cost of intensification (US\$·ha ⁻¹ ·yr ⁻¹)
	[V _k]	[O _k = V _{KCI} - V _{KV}]	[OALUC _k]	[A _k]	[CF _k]	[C _k]	[C _k - CF _k]	[ALUC _k]	[EX _k]	[C _k - CF _k - EX _k]	[OALUC _k /C _k - CF _k]	[C _k - CF _k - EX _k]	[C _k - CF _k - EX _k]
E	CI	2210 (±102)	0	2461 (±54)	6.13	9.21 (±1.3)	3.08 (±0.7)	5.08 (±0.3)	0	3.08 (±1.3)	9.3 (±54.1)	28.6 (±151.2)	0
	CM	756 (±192)	1454 (±250)	2003 (±82)	3.77	14.25 (±0.4)	10.48 (±0.2)	7.34 (±0.1)	30.31 (±10.8)	-19.84 (±10.5)	109.7 (±26.4)	149.5 (±36.2)	485.5 (29.6)
	OI	538 (±215)	1671 (±316)	2519 (±133)	2.92	13.46 (±1.0)	10.54 (±0.5)	7.00 (±0.2)	100.32 (±78.5)	-89.78 (±78.5)	135.3 (±48.7)	173.9 (±63.4)	-57.4 (79.2)
	OM	971 (±314)	1239 (±372)	2026 (±168)	1.50	12.32 (±1.3)	10.82 (±0.7)	6.47 (±0.3)	19.42 (±8.9)	-8.60 (±8.2)	111.3 (±28.3)	119.9 (±40.1)	434.5 (173.4)
T	CI	1499 (±308)	0	2055 (±139)	5.14	45.24 (±9.1)	40.10 (±5.2)	22.27 (±2.4)	0	40.10 (±5.2)	17.3 (±12.2)	19.7 (±13.9)	0
	CM	879 (±251)	620 (±481)	1772 (±125)	2.81	25.43 (±6.0)	22.63 (±3.5)	13.37 (±1.5)	13.82 (±10.5)	8.80 (±7.1)	59.7 (±16.0)	67.9 (±18.6)	282.3 (264.0)
	OI	901 (±305)	598 (±97)	2603 (±56)	1.72	22.74 (±9.5)	21.02 (±5.5)	12.16 (±2.5)	11.07 (±6.1)	9.96 (±10.5)	81.0 (±40.1)	89.8 (±44.6)	-548.7 (98.3)
	OM	-209 (±446)	1710 (±154)	2522 (±609)	0.50	19.24 (±9.9)	18.74 (±5.7)	10.58 (±2.6)	³	³	196.3 (±117.4)	206.5 (±125.9)	434.0 (31.8)
C	CM	852 (±35)	0	2035 (±93)	2.95	47.24 (±8.2)	44.29 (±4.7)	25.36 (±2.1)	0	44.29 (±4.7)	31.7 (±12.7)	33.7 (±13.9)	0
	OI	179 (±94)	673 (±124)	2600 (±104)	1.92	47.23 (±7.8)	45.31 (±4.5)	25.34 (±2.1)	147.63 (±121.5)	-102.33 (±122.1)	44.7 (±10.5)	46.1 (±10.9)	-565.7 (40.7)
ET	CM	1247 (±126)	0	1065 (±633)	3.20	25.12 (±1.2)	21.92 (±0.7)	15.16 (±0.3)	0	21.92 (±0.7)	42.3 (±25.2)	48.6 (±28.8)	0
	OI	208 (±43)	1040 (±986)	2136 (±78)	2.29	15.97 (±0.6)	13.68 (±0.3)	11.04 (±0.1)	62.12 (±13.0)	-48.44 (±13.1)	133.0 (±35.7)	155.9 (±41.9)	-230.5 (76.6)
FS	CI	2313 (±526)	0	2304 (±265)	5.00	4.43 (±0.5)	-0.57 (±0.5)	0	0	-0.57 (±0.5)	0	0	0
	CM	1641 (±637)	671 (±115)	1979 (±249)	2.71	3.03 (±0.4)	0.32 (±0.4)	<i>na</i>	5.32 (±4.1)	-12.04 (±9.8)	<i>na</i>	<i>na</i>	325.0 (60.2)

¹Abbreviations are defined in full in Table 3.1 and 3.3 in Chapter 3. ²Management inputs are considered the same across the 3 replicates and within the same sub-treatment and therefore show no SE. ³No data shown as the mean NPV was negative and therefore LUC emissions due to additional land requirements could not be calculated.

Table A4.4 Sensitivity analysis for the opportunity costs (US\$ ha⁻¹ yr⁻¹) of the intensification and extensification scenarios using the lower and upper 95% confidence interval boundaries of the mean coffee price (102.09 ± 22.08 US\$ per 254 kg of fresh coffee cherries) from 2003 to 2009. All main-plot and subplot treatments are defined in Figure 2 and Figure 1 respectively.

Main-plot treatment	Subplot treatment	Mean NPV	NPV lower CI	NPV upper CI	Mean Opportunity cost of intensification on		Opportunity cost of intensification on at lower NPV CI		Opportunity cost of intensification on at upper CI		Opportunity cost of extensification on at lower NPV CI		Opportunity cost of extensification on at upper NPV CI	
					intensification on	intensification on	intensification on at lower NPV CI	intensification on at upper CI	intensification on at lower NPV CI	intensification on at upper CI	extensification on at lower NPV CI	extensification on at upper NPV CI		
E	CI	2210.00	1518.31	3714.82	103.00	147.72	142.49	0	0	0	0	0	0	
E	CM	756.00	392.83	1715.09	1557.00	1273.19	2142.22	1454.00	1125.47	1999.73	1125.47	1999.73	1999.73	
E	OI	538.00	-15.26	1366.49	1774.00	1681.28	2490.82	1671.00	1533.56	2348.33	1533.56	2348.33	2348.33	
E	OM	971.00	403.13	1744.33	1342.00	1262.90	2112.99	1239.00	1115.18	1970.50	1115.18	1970.50	1970.50	
T	CI	1499.00	1094.82	2828.94	814.00	571.21	1028.37	0	0	0	0	0	0	
T	CM	879.00	529.55	1797.92	1434.00	1136.47	2059.39	620.00	565.27	1031.02	565.27	1031.02	1031.02	
T	OI	901.00	289.00	1883.12	1412.00	1377.02	1974.20	598.00	805.81	945.82	805.81	945.82	945.82	
T	OM	-209.00	-430.30	224.25	1522.00	2096.32	3633.06	1710.00	1525.11	2604.69	1525.11	2604.69	2604.69	
C	CM	852.00	421.57	1774.89	1461.00	1244.45	2082.42	0	0	0	0	0	0	
C	OI	179.00	-345.73	896.33	2133.00	2011.75	2960.99	673.00	767.30	878.56	767.30	878.56	878.56	
ET	CM	1247.00	831.41	2340.72	1065.00	834.61	1516.59	0	0	0	0	0	0	
ET	OI	208.00	-220.73	834.97	2105.00	1886.75	3022.34	1040.00	1052.14	1505.75	1052.14	1505.75	1505.75	
FS	CI	2313.00	1666.02	3857.31	0	0	0	0	0	0	0	0	0	
FS	CM	1641.00	1118.59	2828.37	671.00	547.43	1028.94	671.00	547.43	1028.94	547.43	1028.94	1028.94	

Equation 1 – Net present Value (NPV)

$$NPV = PV_B - PV_C = \sum_{y=0}^n \left[\frac{B_y}{(1+r)^{-y}} - \frac{C_y}{(1+r)^{-y}} \right]$$

B_y : Project benefits (revenues) in a given year y

C_y : Project costs in a given year y

r : Discount rate in a given year y

n : Experiment lifespan (in years)

The annual discount rates varied between 8.10 and 12.22 per cent, based on historical values of the interest rate for agriculture from the Banco Central de Costa Rica (Banco Central de Costa Rica 2010). A sensitivity analysis of ± 5 per cent of the discount rate used had no significant effect on the overall results ($p > 0.05$). Cost estimations of material and labor inputs for individual treatments were based on daily data recording per sub-plot across the three replicates. The material inputs used in the sub-plots' management correspond to the requirements for CF calculation and were divided into the following categories: (a) organic and inorganic fertilisers, (b) pesticides, (c) fuels and (d) materials and sundries including seedlings for replacement or restoration. Labor and management were divided into tasks commonly associated with coffee farming. The price of coffee was recorded for each production year at the site. All coffee harvests were sold as a single entity and no premium prices were obtained for the organic treatments.

Equation 2 – Mass estimates of deadwood

$$V_x = \pi * (D_1^2 + D_2^2 + \dots + D_n^2) / (8 * L)$$

$$Bm_x = V_x * wd_x$$

Where:

V_x : volume ($m^3 ha^{-1}$)

D_1, D_2, \dots, D_n : diameter of each of n pieces intersecting the line (cm)

L : length of the line (m)

Bm_x : biomass of dead wood according to density class ($kg \cdot ha^{-1}$)

wd_x: wood density of density class (kg·m⁻³)

Land-use change C stock change calculations according to IPCC

Equation 3 - Annual carbon stock changes for a stratum of a land-use category as a sum of changes in all pools

$$\Delta C_{LUi} = \Delta C_{AB} + \Delta C_{BB} + \Delta C_{DW} + \Delta C_{LI} + \Delta C_{SO}$$

ΔC_{LUi} : carbon stock changes for a stratum of a land-use category

Subscripts denote the following carbon pools:

AB: above-ground biomass

BB: below-ground biomass

DW: deadwood

LI: litter

SO: soils

Equation 4 - Annual change in biomass carbon stocks on land converted to other land-use category (Tier 2)

$$\Delta C_B = \Delta C_G + \Delta C_{CONVERSION} - \Delta C_L$$

ΔC_B = annual change in carbon stocks in biomass on land converted to other land-use category, in tonnes C yr⁻¹

ΔC_G = annual increase in carbon stocks in biomass due to growth on land converted to another land-use category, in tonnes C yr⁻¹

$\Delta C_{CONVERSION}$ = initial change in carbon stocks in biomass on land converted to other land-use category, in tonnes C yr⁻¹

ΔC_L = annual decrease in biomass carbon stocks due to losses from harvesting, fuel wood gathering and disturbances on land converted to other land-use category, in tonnes C yr⁻¹

Equation 5 - Initial change in biomass carbon stocks on land converted to another land category

$$\Delta C_{CONVERSION} = \sum_i \{ (B_{AFTER_i} - B_{BEFORE_i}) * \Delta A_{TO_OTHERS_i} \} * CFr$$

$\Delta C_{CONVERSION}$ = initial change in biomass carbon stocks on land converted to another land category, tonnes C yr⁻¹

B_{AFTER_i} = biomass stocks on land type i immediately after the conversion, tonnes d.m. ha⁻¹ [here 0]

B_{BEFORE_i} = biomass stocks on land type i before the conversion, tonnes d.m. ha⁻¹ [here 110 Mg C ha⁻¹]

$\Delta A_{TO_OTHERS_i}$ = area of land use i converted to another land-use category in a certain year, ha yr⁻¹

CFr = carbon fraction of dry matter, tonne C (tonnes d.m.)⁻¹ [here 0.47]

i = type of land use converted to another land-use category

Equation 6 - Annual change in organic carbon stocks in mineral soils

$$\Delta C_{Mineral} = \frac{(SOC_0 - SOC_{(0-T)})}{D}$$

$$SOC = \sum_{c,s,k} (SOC_{REF_{c,s,k}} * F_{LU_{c,s,k}} * F_{MG_{c,s,k}} * F_{I_{c,s,k}} * A_{c,s,k})$$

$\Delta C_{Mineral}$ = annual change in carbon stocks in mineral soils, tonnes C yr⁻¹

SOC_0 = soil organic carbon stock in the last year of an inventory time period, tonnes C

$SOC_{(0-T)}$ = soil organic carbon stock at the beginning of the inventory time period, tonnes C;

SOC_0 and $SOC_{(0-T)}$ are calculated using the reference carbon stocks and stock change factors assigned according to the land-use and management activities and corresponding areas at each of the points in time (time = 0 and time = 0-T)

T = number of years over a single inventory time period, yr

D = Time dependence of stock change factors which is the default time period for transition between equilibrium SOC values, yr. Commonly 20 years, but depends on assumptions made in

computing the factors F_{LU} , F_{MG} and F_I . If T exceeds D , use the value for T to obtain an annual rate of change over the inventory time period (0- T years).

c = represents the climate zones, s the soil types, and k the set of management systems that are present in a country.

SOC_{REF} = the reference carbon stock, tonnes C ha⁻¹ [here 77 Mg C ha⁻¹]

F_{LU} = stock change factor for land-use systems or sub-system for a particular land-use [here 1]

F_{MG} = stock change factor for management regime [here 1.22]

F_I = stock change factor for input of organic matter [here 1.44]

A = land area of the stratum being estimated, ha. All land in the stratum should have common biophysical conditions (i.e., climate and soil type) and management history over the inventory time period to be treated together for analytical purposes.

Appendix 5 Supporting information Chapter 5

Tree management

At both sites timber tree shade was primarily managed through periodic thinning of tree to reduce tree density (Table A5.2). Across all four management treatments trunks and major branches of thinned and pruned timber trees were removed from the plots whereas leaf and small branch material were left. Coffee bushes were pruned according to standard coffee agronomic practice, to the same level across all treatments, and all the pruned material was also left in the plots.

In Costa Rica, in the conventional intensive (CI) sub-plot treatments with *E. poeppigiana*, the trees were pruned at a height of 1.8-2.0 m with the removal of all branches above this height (pollarding). This practice is frequently found in conventional high-intensity coffee agroforestry systems in Costa Rica. In the other three sub-plot treatments, however, *E. poeppigiana* trees were managed according to the recommendations of Muschler (2001) with pruning at a height of around 4 m and a minimum of three branches left for partial shade cover.

Soil sampling and analyses

The soil sampling design was systematic with samples taken at three different positions relative to shade trees within two different coffee rows: (a) within 1 m of the shade tree stem, (b) half way between two shade trees within the same coffee row, and (c) half way between sampling points (a) and (b). For each of these positions three samples were taken at different distances from the coffee row: (i) within the coffee row, (ii) between adjacent coffee rows, and (iii) half way between position (i) and (ii). Separately for each of the three depths, all 18 of the samples collected in each sub-plot were thoroughly mixed and then a single composite sample was taken for analysis of C content. The composite samples for each depth for each sub-plot in 2001 and 2010 were air dried on the same day as collection from the field. They were then ground and sieved through a 2-mm sieve to remove larger pieces of root material and the stone fraction.

For assessing bulk density the soil cores were sieved through a 2-mm sieve to determine the fine fraction and the stone fraction which were weighed. Bulk density of the finer soil fraction was then calculated using the following equations:

$$V_{\text{stone}} = W_{\text{stone}} / D_{\text{stone}}$$

$$V_{\text{soil}} = V_{\text{cylinder}} - V_{\text{stone}}$$

$$BD = DWS/V_{\text{soil}}$$

Where:

V_{stone} = volume of the stone fraction (> 2 mm particle size) (cm^3)

D_{stone} = density of the stone fraction (2.65 g cm^{-3} (Maynard & Curran 2006))

V_{soil} = volume of the soil fraction (< 2 mm particle size) (cm^3)

V_{cylinder} = volume of the coring cylinder

BD = Bulk density of the fine soil fraction ($\leq 2 \text{ mm}$ particle size) (g cm^{-3})

DWS = oven-dry weight of the fine soil fraction (g)

Table A5.1 Bulk densities (\pm SEM) for a) Costa Rica and b) Nicaragua for all main-plot x subplot treatment combinations

a)

Subplot\Treatment	C	E	ET	T	FS
CI		0.85 (± 0.10)		0.92 (± 0.06)	0.83 (± 0.04)
CM	0.91 (± 0.04)	0.73 (± 0.08)	0.76 (± 0.04)	0.82 (± 0.08)	0.85 (± 0.08)
OI	0.87 (± 0.02)	0.81 (± 0.07)	0.78 (± 0.08)	0.94 (± 0.08)	
OM		0.91 (± 0.04)		0.76 (± 0.13)	

b)

Subplot\Treatment	ILSG	ILSS	SGTR	SSTR	FS
CI		0.61 (± 0.02)	0.59 (± 0.04)		0.60 (± 0.03)
CM	0.60 (± 0.03)	0.62 (± 0.02)	0.57 (± 0.02)	0.63 (± 0.02)	0.65 (± 0.05)
OI	0.65 (± 0.04)	0.62 (± 0.02)	0.62 (± 0.03)	0.66 (± 0.02)	
OM		0.60 (± 0.03)	0.57 (± 0.02)		

The soil samples from the two countries were analysed for bulk density at the Universidad Nacional Agraria (UNA) in Managua, Nicaragua and at the Soil Laboratories of the Centro Agronómico Tropical de Investigación y Enseñanza (CATIE) in Turrialba, Costa Rica. At the latter, soil samples were analysed for C content using a Thermo Finnegan combustion analyser.

Table A5.2 Mean total change of SOC stock (\pm SE) (Mg C ha^{-1}) for three soils depths (cm) of a) five shade treatments b) four management treatments in a coffee agroforestry experiment in Costa Rica over the period from 2001 to 2010. Shade and management treatment abbreviations are given in Tables 3.1 and 3.3

a)

Depth (cm)	Shade treatment				
	FS	E	ET	C	T
0 - 10	0.85 (\pm 0.82)	2.76 (\pm 0.71)	4.17 (\pm 1.09)	1.52 (\pm 1.11)	1.45 (\pm 0.76)
10 - 20	-1.55 (\pm 0.74)	-3.93 (\pm 0.41)	-2.06 (\pm 0.74)	-2.44 (\pm 0.99)	-1.72 (\pm 0.68)
20 - 40	-8.53 (\pm 2.66)	-12.69 (\pm 1.71)	-8.00 (\pm 2.20)	-11.62 (\pm 3.31)	-6.99 (\pm 2.32)
Total 0 - 40	-9.23 (\pm2.52)	-13.86 (\pm1.93)	-5.89 (\pm1.85)	-12.54 (\pm4.05)	-7.26 (\pm2.92)

b)

Depth (cm)	Management treatment			
	CI	CM	OI	OM
0 - 10	-0.10 (\pm 0.76)	1.79 (\pm 0.60)	3.53 (\pm 0.70)	3.60 (\pm 0.73)
10 - 20	-3.20 (\pm 0.68)	-1.69 (\pm 0.72)	-2.72 (\pm 0.34)	-2.88 (\pm 0.57)
20 - 40	-8.10 (\pm 2.42)	-11.04 (\pm 2.04)	-8.30 (\pm 1.28)	-11.16 (\pm 3.76)
Total 0 - 40	-11.40 (\pm1.06)	-10.94 (\pm1.10)	-7.49 (\pm0.95)	-10.44 (\pm1.90)

Table A5.3 Mean total change of SOC stock (\pm SE) (Mg C ha^{-1}) for three soils depths (cm) of a) five shade treatments and b) four management treatments in a coffee agroforestry experiment in Nicaragua over the period from 2001 to 2010. Shade and management treatment abbreviations are given in Tables 3.1 and 3.3

a)

Depth (cm)	Shade treatment				
	FS	ILSG	ILSS	SGTR	SSTR
0 - 10	0.16 (\pm 2.05)	2.36 (\pm 2.09)	0.20 (\pm 1.56)	1.14 (\pm 1.52)	3.67 (\pm 1.36)
10 - 20	1.09 (\pm 2.12)	2.48 (\pm 1.68)	1.15 (\pm 1.23)	0.21 (\pm 1.14)	3.44 (\pm 1.68)
20 - 40	-4.16 (\pm 4.91)	-4.82 (\pm 7.04)	-5.31 (\pm 5.81)	-3.72 (\pm 3.02)	7.10 (\pm 4.19)
Total 0 - 40	-2.97 (\pm8.28)	0.00 (\pm9.54)	-3.97 (\pm7.21)	-2.37 (\pm5.11)	14.20 (\pm6.64)

b)

Depth (cm)	Management treatment			
	CI	CM	OI	OM
0 - 10	-0.20 (\pm 1.35)	0.86 (\pm 1.23)	2.69 (\pm 1.29)	1.62 (\pm 3.08)
10 - 20	-0.92 (\pm 1.69)	1.26 (\pm 1.13)	1.68 (\pm 0.91)	4.60 (\pm 0.99)
20 - 40	-4.96 (\pm 3.46)	-1.05 (\pm 2.86)	-2.25 (\pm 4.26)	-5.40 (\pm 11.54)
Total 0 - 40	-6.08 (\pm1.37)	1.07 (\pm1.10)	2.12 (\pm1.51)	0.82 (\pm3.89)

Table A5.4 Assessment of test variables in Costa Rica and Nicaragua for normality and homogeneity of variance.

a) Costa Rica

	K-S test		Levene statistic			
	df	Sig.	F	df1	df2	Sig.
AGC	42	0.001	6.84	4	37	< 0.001
SOC (0-10)	42	0.2	0.53	4	37	0.711
Pruning inputs	42	< 0.001	3.23	4	37	0.091
Organic fertiliser	42	< 0.001	1.78	4	37	0.171
Litter inputs	42	0.2	2.16	4	37	0.094

b) Nicaragua

	K-S test		Levene statistic			
	df	Sig.	F	df1	df2	Sig.
AGC	42	0.035	3.15	4	37	0.026
SOC (0-10)	42	0.2	0.50	4	37	0.735
Pruning inputs	42	0.2	2.00	4	37	0.136
Organic fertiliser	42	< 0.001	1.48	4	37	0.242

Table A5.5 Mean soil nutrient levels (\pm SEM) for the experimental treatments in a) Costa Rica and b) Nicaragua in 2010.

a)

Treat ment	pH	Acidez	Ca	Mg	K	P	Cu	Zn	Mn	Fe	N
	cmol (+) / l					mg/l					%
C	5.41 (\pm 0.08)	0.75 (\pm 0.14)	5.21 (\pm 0.46)	1.57 (\pm 0.09)	0.34 (\pm 0.05)	29.25 (\pm 8.21)	18.69 (\pm 1.46)	5.68 (\pm 1.11)	16.43 (\pm 1.87)	168.94 (\pm 21.96)	0.20 (\pm 0.02)
E	5.21 (\pm 0.07)	1.05 (\pm 0.15)	4.97 (\pm 0.35)	1.39 (\pm 0.06)	0.35 (\pm 0.03)	15.98 (\pm 2.74)	16.68 (\pm 1.20)	4.68 (\pm 0.66)	23.31 (\pm 2.20)	147.72 (\pm 10.54)	0.19 (\pm 0.01)
ET	5.31 (\pm 0.08)	0.75 (\pm 0.13)	5.60 (\pm 0.43)	1.55 (\pm 0.09)	0.32 (\pm 0.04)	22.87 (\pm 6.73)	14.20 (\pm 0.87)	5.96 (\pm 1.10)	21.42 (\pm 2.54)	133.61 (\pm 17.12)	0.21 (\pm 0.02)
T	5.44 (\pm 0.07)	0.70 (\pm 0.11)	5.68 (\pm 0.33)	1.56 (\pm 0.06)	0.42 (\pm 0.02)	15.78 (\pm 3.10)	14.25 (\pm 0.45)	4.59 (\pm 0.66)	18.07 (\pm 1.52)	124.05 (\pm 9.36)	0.20 (\pm 0.02)
FS	5.08 (\pm 0.06)	1.22 (\pm 0.18)	4.53 (\pm 0.24)	1.10 (\pm 0.05)	0.28 (\pm 0.03)	8.33 (\pm 1.29)	12.20 (\pm 0.86)	4.71 (\pm 1.00)	26.54 (\pm 3.54)	123.56 (\pm 14.42)	0.22 (\pm 0.02)

b)

Treat ment	pH	Acidez	Ca	Mg	K	P	Cu	Zn	Mn	Fe	N
			cmol (+) / l			mg/l					%
ILSG	5.99 (±0.07)	0.18 (±0.03)	14.11 (±0.93)	4.22 (±0.31)	0.99 (±0.12)	14.08 (±3.28)	20.49 (±1.29)	2.87 (±0.45)	18.95 (±1.19)	111.50 (±10.12)	0.52 (±0.03)
ILSS	6.02 (±0.05)	0.21 (±0.03)	12.01 (±0.59)	3.98 (±0.21)	0.89 (±0.07)	10.00 (±1.49)	19.71 (±0.79)	1.75 (±0.20)	18.46 (±1.65)	110.44 (±7.37)	0.46 (±0.02)
SGTR	6.09 (±0.04)	0.16 (±0.02)	12.15 (±0.58)	3.89 (±0.21)	0.91 (±0.08)	8.15 (±1.38)	19.13 (±0.63)	1.82 (±0.20)	16.79 (±0.91)	100.17 (±5.28)	0.50 (±0.02)
SSTR	6.03 (±0.03)	0.18 (±0.04)	12.53 (±0.88)	3.68 (±0.24)	0.83 (±0.10)	11.38 (±2.70)	19.83 (±0.90)	2.22 (±0.32)	14.21 (±1.04)	99.56 (±8.18)	0.50 (±0.02)
FS	5.96 (±0.10)	0.22 (±0.03)	14.22 (±2.76)	3.84 (±0.46)	0.63 (±0.08)	10.14 (±2.23)	18.89 (±0.84)	1.77 (±0.33)	17.87 (±1.66)	106.94 (±8.96)	0.41 (±0.03)

Appendix 6 Supporting information Chapter 6

Table A6.1 Assessment of test variables in a) Costa Rica and b) Nicaragua for normality and homogeneity of variance.

a)

	K-S test		Levene statistic			
	df	Sig.	F	df1	df2	Sig.
CF_{kg}	20	0.182	0.005	1	18	0.947
CF_{ha}	20	0.140	0.357	1	18	0.558
AGC	20	0.008	1.429	1	18	0.248
SOC	20	0.190	3.264	1	18	0.088
TC	20	0.100	3.796	1	18	0.067
Yield	20	0.108	0.186	1	18	0.672
NB	20	0.001	0.169	1	18	0.686
TD	20	0.200	0.192	1	18	0.666
BA	20	0.03	0.061	1	18	0.808

b)

	K-S test		Levene statistic			
	df	Sig.	F	df1	df2	Sig.
CF_{kg}	26	0.001	3.136	1	24	0.090
CF_{ha}	26	0.479	6.731	1	24	0.017
AGC	26	0.365	3.246	1	24	0.085
SOC	26	0.297	1.349	1	24	0.258
TC	26	0.149	2.004	1	24	0.171
Yield	26	0.059	2.950	1	24	0.100
NB	26	< 0.001	3.402	1	24	0.079
TD	26	0.080	0.020	1	24	0.890
BA	26	0.459	0.817	1	24	0.376