The effects of forest management on carbon dynamics of soil organic horizons

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DECLARATION

I confirm that this is my own work and the use of all material from other sources has been properly and fully acknowledged. Word count does not exceed the permitted maximum.

Mauro Lanfranchi

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Abstract

The carbon sink potential of temperate forests plays a central role in climate change mitigation strategies, and soil organic carbon sequestration can be achieved through afforestation and reforestation. Yet, the main factors responsible for influencing the dynamics of long-term forest carbon stabilization within the soil are poorly understood. This study investigates how different forest management practices affect the carbon sequestration potential within the soil organic surface horizon (Litter, Fragmented and Humic) under second rotation *Picea sitchensis* plantations in the UK. Fieldwork activities were carried out in two experimental sites of upland Britain to collect samples related to soil carbon quantity, carbon quality and the dynamics of fine root turnover.

Two separate experiments were carried out. The first was on a pre-existing experimental site (Forest of Ae) to assess differences between conventional stem-only harvest, whole-tree harvest and fertilization. The second experiment was designed on an existing trial (Clocaenog forest) to compare a stand with no interventions in the overstory or understory since the research area was established in 2002 (Control), and one stand in transformation to continuous cover forestry (irregular shelterwood).

At the Forest of Ae, results revealed that fertilization practices had a significant, positive effect on soil carbon storage within the L horizon (conventional harvest $p < 0.01$, whole-tree

harvest $p < 0.01$). Brash retained on site at the time of harvesting had a significant, positive effect on soil carbon storage within the F horizon (conventional harvesting $p = 0.03$ and fertilization $p = 0.01$). Results also suggest that soil nitrogen concentration can be used to predict the soil carbon storage of each organic horizon ($adjR^2 = 0.931$). Also, the fine root necromass within the 15 to 30 cm soil depth is significantly higher ($p = 0.02$) in the fertilized treatment when compared with whole-tree harvest, although this does not affect the carbon storage within the H horizon.

At Clocaenog forest, transformation to irregular shelterwood had a highly significant, positive effect on soil carbon storage within the soil H horizon ($p < 0.01$). Soil nitrogen concentration, C:N ratios and available nitrogen all consistently point towards a higher presence of nitrogen in the Control treatment which could be responsible for SOC and N mineralization in the H horizon.

Overall, the study shows that forest management decisions do affect C storage in the organic soil horizons of commercial forest plantations in upland Britain. These dynamics need to be taken into account in C and GHG balances and guidelines for soil protection.

Chapter 1

Introduction

There is substantial uncertainty over future evolutions in emissions and atmospheric concentrations of anthropogenic greenhouse gas (GHG). There is now evidence of plant and animal extinctions, losses in biodiversity and habitats as well as the endangerment of plants and animals in the world due to human activities and their effects on the climate and environment (Cavicchioli et al. 2019).

Physical and biological processes are responsible for the constant exchange of carbon (C) between the environment and the ecosystems (Keenan and Williams 2018). The burning of fossil fuels increases the amount of CO_2 in the atmosphere; this has become a serious environmental concern and raises the question of whether increasing atmospheric levels of in CO_2 represents a peril to humans by raising world temperatures (Keeling et al. 2020). Since the beginning of the industrial revolution, anthropogenic activities have brought the atmospheric concentrations of CO_2, CH_4 and N_2O to the highest levels in the last eight hundred thousand years. In May 2020, CO_2 concentration rose to 415 ppm; this compared to 280 ppm in the eighteenth century (Keeling et al. 2001), (see figure 1.1).

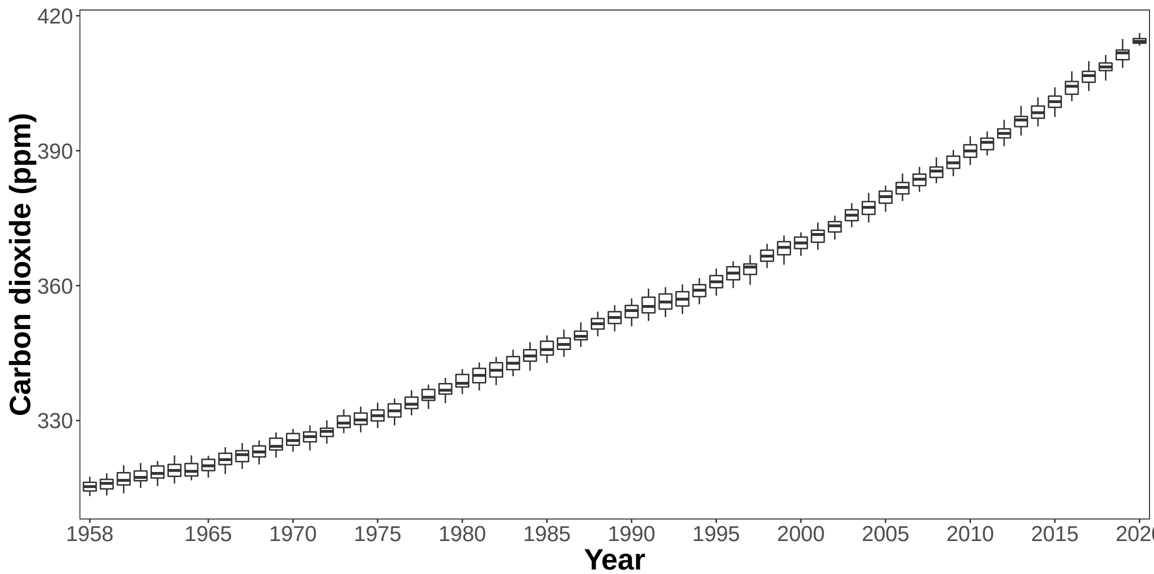

Figure 1.1: Mauna Loa Observatory, Hawaii. Yearly atmospheric CO_2 concentrations for the period 1958 - 2020, data Keeling et al. (2020).

In order to try to confine the rise of temperature within 2°C, measures have been put in place by the United Nations Framework Convention on Climate Change (UNFCCC) at the twenty-first Conference of the Parties in Paris (COP21), requiring major emitting countries to take immediate action. Since then, and up until the COP25 (Madrid, December 2019) the major focus of the UNFCCC has been to persuade all participating countries to commit to scientific evidence on how to achieve C neutrality by 2050 within a 1.5-degree temperature rise. In June 2019, Britain introduced an amendment to the Climate Change Act with a commitment to reach net zero C emissions by 2050 (Department for Business Energy and Industrial Strategy 2019).

The necessity to respond to the largely GHG-driven threat of climate change demands a rapid transition to low-carbon economies (Smith et al. 2010). Since 1995, the international community engages in formal meetings under the UNFCCC framework (Gosden 2015; UNFCCC) in an effort to reduce the GHG emissions and to slow global warming.

Recently, the Intergovernmental Panel on Climate Change (IPCC) brought in new guidelines accounting under the Kyoto Protocol which allow for the harvested wood products to be considered as C storage; this opens new opportunities for such products to be recognized in their importance for future mitigation strategies, particularly in light of the recent UN global targets (United Nations 2015).

1.1 Forest soil organic carbon and carbon fluxes

Globally, soils are the largest pool of actively cycling organic C, and soil C is a primary component of the global C cycle (Castellano et al. 2015; Hume et al. 2018); climate change mitigation strategies strongly rely on the ability to improve soil organic matter (SOM) stabilization. Soils store the equivalent of two times the amount of C stored in the atmosphere and vegetation (Godbold and Lukac 2011; Lehmann and Kleber 2015; Bradford et al. 2016), 240 times the amount of fuel emissions per year (10 Pg). Each year, soils release around 75 Pg C in the atmosphere as CO_2 and a similar amount enters the soil from the atmosphere via plant detrital C (Brady and Weil 2008; Marschner et al. 2008). Given the magnitude of such fluxes, relatively small variations could have major repercussions on the forest C budget (Paustian et al. 2016) and eventually atmospheric CO_2 and planetary warming (Crowther et al. 2016).

CO_2 emissions from soils account for 37% of emissions from the agricultural sector. CO_2 sequestration can be enhanced by using improved management practices whose mitigation potential is globally estimated in up to 8000 Tg CO_2eq yr^{-1}. These contribute to C storage resulting from the CO_2 captured by plants and the soil. Soil management strategies that contribute to a better storage of organic matter (OM) and optimize the N cycle can in turn provide improved productivity, biodiversity and fertility, attenuate the risk of erosion, water pollution and runoff.

Forests are a sink and a source of C (with temperate forest sink potential of 0.7 ± 0.2 Pg C y^{-1}), hence they have central role in climate change mitigation strategies (Lal 2005; Muller and Linhares-Juvenal 2016). 50 to 60% of the terrestrial C resides in woodland and forest ecosystems (Nave et al. 2010; Addo-Danso et al. 2015), over 60% of which is stored in the soil (Nave et al. 2010). With the exclusion of litter, globally about 2.3 to 2.4 Eg C are stored as SOM within the top one to two meters soil depth (Paustian et al. 2016; Jackson et al. 2017). The magnitude of this implies that a small percentage increase in net soil C storage results in a large C sink potential.

The potential of forest mitigation is huge. 2600 to 3500 x 10^6 ha of land could be replanted globally, about 25% of which has been estimated meeting the reforestation and afforestation eligibility criteria (Muller and Linhares-Juvenal (2016) and reference therein). This has a potential for C sequestration of 120 Pg C (440 Pg CO_2) of above-ground C by the end of this century in the case of natural regeneration of forests, decreasing to 80 Pg C (294 Pg CO_2) in the case of land use change. In the same way 725 to 940 x 10^6 ha of unused agricultural land (of which Europe will account for 13 to 17 x 10^6 ha by 2030) could sequester 116 to 146 Pg C (426 to 536 Pg CO_2). Furthermore, projections estimate 416 to 963 x 10^6 ha of woodland by 2100 with a sequestration potential of 39 to 102 Pg C (143 to 374 Pg CO_2) (Muller and Linhares-Juvenal 2016).

Forest C stocks are represented by the above- and below-ground biomass of plants and soil C storage. Photosynthesis is the key process through which CO_2 is absorbed by trees, allowing energy from sunlight to be fixed in organic molecules. CO_2 is later released as a result of litterfall decomposition, root turnover and exudation, C loss in the soil solution (much less than 10% of the trees net CO_2 uptake in British conditions), loss of soil particulate organic matter in erosion, fungal and bacterial metabolic activity and root respiration (see figure 1.2 and 1.3).

The remaining C is apportioned between seed, root, stem, branch biomass and stored in organic and mineral soil horizons (Brady and Weil 2008; Morison et al. 2012). Forest soil develops from a combination of parent material, relief and under different vegetation,

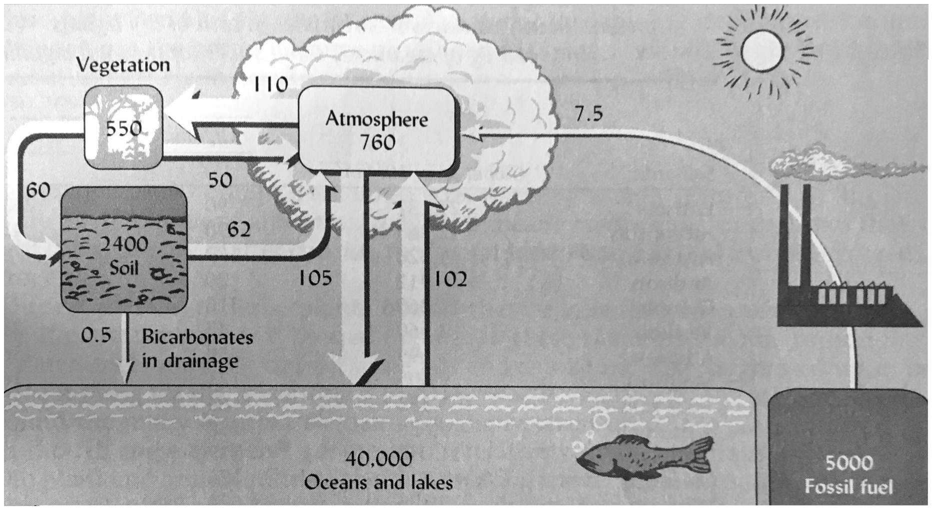

Figure 1.2: A simplified representation of the global C cycle showing the pools of C that interact with the atmosphere. Arrows show yearly flows of C between the pools. Numbers are Pg C. Anthropogenic activities cause more C to enter the atmosphere than being removed. From Brady and Weil (2008).

organisms and climate. These factors become largely responsible for the different soil chemical and physical properties, and for the clear stratification of the soil pedon (Jenny 1941; Godbold and Lukac 2011).

C storage in forest soils comprises 75% of total forest C in the UK (Vanguelova et al. 2013). The residence time of soil C is important for understanding the C change, cycling and balance of a forest ecosystem (Lundmark et al. 2016). The stock of soil C is affected by the above- and below-ground contribution of biomass to the soil type, litter and roots C:N ratio and lignin content, amount of disturbance, temperature and water regimes which affect SOM decomposition as well as soil erosion (Lal 2005).

Many factors contribute to the spatial variation of soil organic C (SOC) (Vanguelova et al. 2016). These are mainly attributable to management practices, climatic conditions (rainfall and moisture content), land use, slope, elevation, soil texture and type and parent material (Muller and Linhares-Juvenal 2016). The overall objective of the present research will be to understand the effect of forest management practices on the response variables described

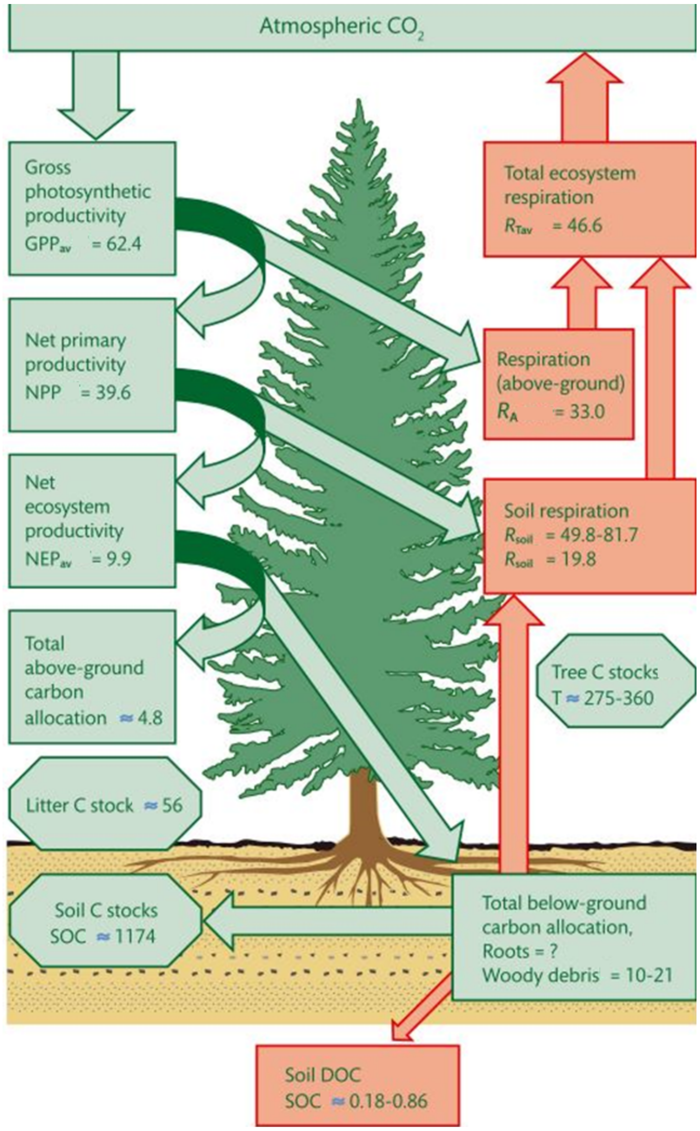

Figure 1.3: A summary of the C fluxes (Mg CO_2 ha^{-1} y^{-1}) and stocks (Mg CO_2 ha^{-1}). The example represents a 40 year old, second rotation Sitka spruce plantation (yield class 14 m^3 ha^{-1} y^{-1}) on peaty gley soils in northern England. Boxes identify average annual flux, octagons identify carbon stocks. From Morison et al. (2012).

in chapter chapter 1.4. As such, measures were put in place to maintain slope, elevation, land use, climate and tree species unvaried throughout the treatments. SOC concentrations, stoniness, soil thickness and bulk density (Bd) are also important variables for determining the soil C stock.

Harvesting operations can increase the variability in SOC due to uneven distribution of the residues and soil disturbances by machinery (Clarke et al. 2015).

C stocks are driven by C fluxes (Clarke et al. 2015). The difference between the input (Net Primary Productivity (NPP) = photosynthesis - autotrophic respiration) and the output (leaching and heterotrophic respiration) as well as the removal of C during the harvesting activities is the C balance of the ecosystem (Lundmark et al. 2016). This is dependent on the CO_2 emissions related to specific silvicultural operations as well as to the growth sustained by the forests after such operations have taken place. The total soil respiration in terrestrial ecosystems accounts for up to 90% of soil CO_2 fluxes to the atmosphere. This involves autotrophic and heterotrophic respiration with root and microbial decomposition of SOM respectively (Moinet et al. 2016). Input of below- and above-ground litter, thinning and harvesting operations and management of residues are responsible for transferring C between biomass stocks and soil C stocks, whereas mineralisation, decomposition and leaching of dissolved organic C (DOC) lowers the amount of soil C stock (Clarke et al. 2015).

The below ground C flux of the forest environment modifies the chemical, biological and physical qualities of soils. While the balance of C flux within the soil can be more easily estimated, research is still far from understanding the causes of such fluxes. Yet changes in C flux into and out of the soil can exacerbate or attenuate global warming (Keuskamp et al. 2013). One of the objectives of the present research will be to understand if soil quality affects soil C stock accumulation; this will be achieved by investigating the effects of response variables such as lignin, C:N ratio, available N and soil proximate C pools.

1.2 Forest Management

The advantages of good management practices are plentiful: increased yield, C storage, enhanced wood quality, biodiversity, as well as better protection against fire, wind and gusts, floods, pests and disease. Increased biodiversity of forest stands contributes to a greater C sequestration (Muller and Linhares-Juvenal 2016).

Sustainable forest management, forest restoration and decreased deforestation are effective practices for promoting climate change mitigation (Muller and Linhares-Juvenal 2016). Within the next few decades, forestry mitigation practices globally could potentially account for a reduction in CO_2 emissions of up to 0.2 to 13.8 Pg CO_2eq[1] per year; this is based on a C price of $100 per Mg. Harvested wood products (HWP) also play an important role within the climate change mitigation framework, although recent studies claim such products have a low persistence and soil C remains the best C sequestration pool on the long run (Butnor et al. 2017). The potential for biomass-derived energy from the forestry sector in reducing emissions is estimated in between 400 Tg and 4.4 Pg CO_2eq per year.

English woodlands cover 10% of land area, 780 Kha of which consists of hardwood woodland. Forests in England hold an estimated 105.4 Tg of C in living trees (Forestry Commission 2014; Ward 2020), 26.3% of which is conifer and 73.7% is broadleaves. In the UK, HWP account for 293 Mt CO_2,[2] increasing of 1.6 Mt CO_2 each year (Morison et al. 2012). This is a considerable quantity considering that the estimated stock in trees is around 595 Mt CO_2, although large majority of this is imported timber (Morison et al. 2012).

Research now widely recognises the loss of SOC and above-ground biomass as a result of

[1] The atomic weight of C and O atoms is 12.01 and 16 respectively. This means that, e.g. 1Mg C corresponds to (12.01 + (16 x 2))/ (12.01) / = 3.66 Mg CO_2).

[2] Equivalent to 80 Mt C. This value does not consider landfill which was estimated in 216 Mt C

the conversion of native ecosystems to cropland (for soil in particular this amounts to 0.5 - 2 Mg ha^{-1} y^{-1}, equivalent to 0.3 m depth or 30 to 50% of the topsoil (Paustian et al. 2016)). Yet changes between one forest type and another, as well as the effects of forest management practices, tree species, forest age, climate and soil type are less understood (Lewis et al. 2016; Paustian et al. 2016). Hence, the importance of investigating the effects of such response variables to clarify the potential of the forest to act as a C sink, by sequestering C from the atmosphere. The partial or total removal of the overstory canopy as a result of the harvesting activities can affect plant-soil interactions, microclimatic conditions and eventually the soil C and nutrient storage potential (Jandl et al. 2007; Hume et al. 2018). Hence, it is important to understand the effects of transitioning practices to more diverse silvicultural systems such as irregular shelterwood, where the stand structural objective is between the even-aged and uneven-aged structure, as well as the effects of clearfell silvicultural systems on soil C and nutrient dynamics. This highlights the key objective of the present research, whose questions are formulated around the role of forest management practices on the dynamics of C stock accumulation. Unmanaged and old forest stands store the highest amount of C, a large fraction of which resides below-ground (Powers et al. 2011; Christophel et al. 2013; Paustian et al. 2016; Ashwood et al. 2019). On the other hand, young stands have a large C sink potential, while forest plantations have a higher C turnover (Muller and Linhares-Juvenal 2016). However, because harvested products increase C storage and decrease emissions as a result of the substitution effects, increased harvest frequency could represent a better option when compared to increased rotation length. Findings suggest that the active management of forested areas over long timespans that result in a constant and abundant production of timber and soil C stock contribute to enhanced climate benefits (Lundmark et al. 2016). This is why the present study will investigate the effects of transitioning practices to irregular shelterwood, in which forest thinning operations take place at regular intervals, on the soil C storage potential.

The soil C response to different forest management practices depend on soil type, the quality and quantity of SOM, the climate and the tree species. The largest land use change in Britain over the last century has been the introduction of 315 Kha of conifer plantations on shallow peatlands (Swain et al. 2010). Soils with deep organic horizons are most affected and less studied; these are quantified in terms of changes in C stocks and pools due to forest harvesting practices (Vanguelova et al. 2010, 2018, 2019). Afforestation of wet, peaty soils has to undergo substantial changes to achieve the necessary conditions for tree establishment. These include lowering of the water table (drainage, ground preparation) by means of ploughing to improve aeration with consequential increase in the rate of OM oxidation. The disturbance introduced can increase C loss to groundwater and atmosphere (Morison et al. 2012), as opposed to it resulting in an improved C sink as above-ground biomass and soil during tree growth and enhanced C input to the soil (Vanguelova et al. 2019). Thus, the main aim of this thesis is to concentrate on the organic horizons of forest soils and how they are affected by different forest management practices. (see chapter 1.3 for an introduction on the organic surface horizons (OSH)).

1.2.1 Conventional Harvesting - Clearfelling

Conventional stem-only Harvesting (CH) is defined as 'Cutting down of an area of woodland (if it is within a larger area of woodland it is typically a felling greater than 0.25 ha).' (Forestry Commission 2017; UKWAS Certification Standard 2018). Harvesting activities for CH ideally coincide with the peak in mean annual increment (Clarke et al. 2015; Lundmark et al. 2016). CH activities imply a significant amount of biomass extraction from the forest stand by means of tree stems removal during the harvesting operations. At this stage twigs, branches, leaves, needles and dead roots are left on site and they serve as post harvest C input to the soil usually for up to two decades, or canopy closure of the new forest rotation.

Despite being a widely applied forest management option, CH remains a debated practice to attain the full C and greenhouse gas (GHG) benefits, especially when practiced on soils with high organic content and thick organic layers. This requires a deeper understanding of the dynamics associated with the quality, abundance and dynamics of dead organic matter at the time of harvesting and the C input and accumulation in the soil thereafter, which are addressed in this thesis.

1.2.2 Fertilization

Over the last century, softwood forest plantations in upland Britain relied upon the application of fertilization (particularly N, P and K). Among the UKWAS requirements, the use of inorganic and organic fertilizers should only be considered when dealing with nutrient deficiencies or to facilitate establishment, and following an environmental impact assessment. This has to be accompanied with the implementation of legal requirements and guidance for best practice during their application in forestry (UKWAS Certification Standard 2018). This poses questions on the nutrient sustainability and C benefits by fertilisation as a way to provide greater biomass production, while at the same time preserving the soil C and nutrient capital (Mason et al. 2012) which shall be addressed in this thesis.

1.2.3 Whole-Tree Harvesting

WTH is a forest practice which aims at maximizing biomass for bioenergy (Creutzburg et al. 2016). This is defined as 'The removal from a felled site of every part of the above-ground tree, except the stump' (Forestry Commission 2017). In Britain 10% of the clearfelling operations in 1997 were achieved through WTH. The mechanical removal of residues has been estimated eliminating 34 to 80% of dry residue mass left after CH (Nisbet et al. 1997; Mason et al. 2012; Kaarakka et al. 2014). Its popularity has been rapidly on the increase (Vanguelova et al. 2010) both in Britain, with foreseeable plans including upland conifer plantations, and Europe as bioenergy harvest is regarded as a good alternative practice to CH for climate change mitigation and energy security strategies (Kaarakka et al. 2014). Because of the removal of tree tops, needles, twigs, limbs and damaged trees from harvesting operations on site, WTH is a heavily impacting harvesting system. Current guidelines suggest 30% of the biomass should be left on site (Merilä et al. 2014). This practice could potentially expose the forest ecosystem to a series of threats such as soil erosion and physical damage, reduced fertility with potential long-term silvicultural repercussions, acidification, freshwater euthrophication, degraded habitat and landscape (Nisbet et al. 1997; Mason et al. 2012; Forestry Commission 2017). SOM resulting from the decomposition of the woody residues can alter the productivity of soils and sustain the growth of vegetation - forest productivity in particular (Vanguelova et al. 2010). SOM also supports C sequestration and cycling, affect the availability of water and N and increase biodiversity, CEC (Cation Exchange Capacity), aeration, soil aggregation and pH buffer capacity (Vanguelova et al. 2010; Jang et al. 2016). This poses new questions in the viability of whole-tree harvesting (WTH) as a way to provide energy and biomass production, while at the same time preserving the soil C and nutrient capital (Mason et al. 2012). Currently for the WTH forest management practice, research that focusses on organic and organo-mineral soil[3] is scarce, while mineral and organo-mineral soil are comparatively well researched and documented (Olsson et al. 1996; Wan et al. 2018). Hence, the present study will focus on the OSH.

An interest in WTH comes with increased demand for biofuels and bioenergy. It is important to understand the impact of such intensive harvesting technique on the productivity of the forest, as well as its conformity to guidelines for the sustainable management of forests (Jang et al. 2016). It is also most important to understand the impact or benefit of WTH on soil C and nutrient capacity which this thesis addresses so to realize at the same time the full GHG benefits of such harvesting practices but also the likely risks associated with it.

1.2.4 Continuous Cover Forestry

To maintain and enhance climate mitigation by forests, it is essential that forests adapt to current and future levels of climate change. This entails the evaluation of the hazards and risk analysis, as well as scenario modelling to predict forest management outcomes in a systematic way (Stokes and Kerr 2009). Forests that adapt will continue to sequester and store C and provide substitution from harvested wood. Consequently, diversifying forest structure and tree species composition are essential components of climate smart forestry although it is likely that they will initially reduce productivity. One adaptation measure in forest management is transformation to CCF (Continuous-Cover Forestry) (Stokes and Kerr 2009). CCF is defined as ‘a silvicultural system whereby the forest canopy is maintained at one or more levels without clearfelling’ (Forestry Commission 2017). Most of the forested area in the UK is clearfelled, which means that conversion to CCF forestry has to undergo

[3]Organic: the forest floor (L,F,H horizons); organo-mineral: A horizon (Zanella et al. 2011)

a transitory (or transformation) period in order to gain structural diversity. The recent paper from Kerr et al. (2017) explains such transformation process through a successful example with the Bradford-Hutt system on mixed species experiment started in the late fifties within the Tavistock Woodlands (Plymouth, Devon). The Bradford-Hutt system utilizes the main elements of clearfelling (planting, thinning and felling) organized on a grid pattern to achieve both continuous canopy cover and good access for forest operations. The system was designed with Units (18x18 m) and internal Plots (6x6 m), with each Unit capable of producing a mature, 54 year old Douglas fir every six years in perpetuity. Currently in the UK there are a series of forests undergoing transformation. These are largely planted on contrasting site types with species commonly grown in the UK to demonstrate multiple beneficial effects in terms of ecosystem services, economy and management (Ireland 2006; Poetzelsberger and Hasenauer 2015).

Clearfell-based silvicultural systems can exacerbate the mineralization and decomposition of SOC, negatively affecting the total C stock (Lundmark et al. 2016). On the other hand, thinning or CCF silvicultural systems might be able to mitigate soil C losses, although research is still far from a definite answer on the long-term effects of forest management on soil dynamics (Thiffault et al. 2011). The present research will investigate the effects of forest management practices for clearfell-based silvicultural systems and the effects of transitioning practices to irregular shelterwood on the soil OSH C storage potential. This represents the ability of such practices to mitigate the effect of climate change by sequestering atmospheric CO_2. In UK forests, the C stocks of the organic soils are twice as much that of mineral soils (Vanguelova et al. 2019). Hence, the present study specifically focuses on the soil organic surface horizons.

1.3 Soil organic surface horizons identification

The OSH, also referred to as ectorganic horizons or forest floor (Van Breemen and Buurman 2002) have C concentrations $\geq$ 20% ($\sim$ 35–40% OM) on a dry-weight basis and are defined as follows (Klinka et al. 1981; Zanella et al. 2011; SSSA):

- L (OL, Oi) litter horizon: a terrestrial (upland) master organic horizon with stratified organic material prevalently composed of relatively fresh fallen leaves, stems, bark, needles and twigs with no or little signs of decomposition (fibric material).
- F (OF, Oe; O1) fragmented / fermented horizon: a terrestrial (upland) master organic horizon made of decomposed litter with macroscopically discernible vegetative structures (hemic material) lying below the L layer.
- H (OH, Oa; O2) horizon: a terrestrial (upland) master organic horizon typical of the 'mor' humus - this being recognizable from thick litter layers with stratified F horizon and slow decomposition (Van Breemen and Buurman 2002) made of well-decomposed organic matter whose plant structures are not recognizable (sapric material). Lying below the F layer.
- O (H) horizon: a semi-terrestrial (wetland ecosystems) master organic horizon affected by water table or occurring in upland regions when drainage is affected by edaphic properties.

The present study will concentrate on the L, F and H horizons. For the sake of comparing treatments, all of the humic horizons were labelled H horizons even if in a few cases these more closely reflected the characteristics of the O horizons; when this is the case it will be highlighted in the text.

To a lesser extent, the organo-mineral A horizon will be included in this study to understand if the underlying organo-mineral horizon shows trends that suggest contrasting C dynamics with respect to the OSH. This is mainly to compare C and N concentration, but not C mass as the depth of the A horizon was not collected:

- Aa (A, anmoor): a histic organo-mineral horizon mostly built by microorganisms; with plastic, massive structure. Dark coloured and C content from 7 to 20 %.

1.4 Aims and Objectives of this Thesis

This thesis focusses on evaluating forest management practice impacts on soil organic horizon C stocks, pools and cycling. The forest management practices covered in this research are conventional clearfell systems, whole-tree harvesting systems, fertilisation and continuous cover forestry systems.

The research objectives of the thesis are formulated as follows:

- **Carbon quantity (stocks)**
  - To compare the effects of clearfell systems - brash removal (WTH), conventional stem-only harvesting (CH, Control) and fertilization (CHF) on soil C quantity in the litter, fragmented and humified organic surface horizons (OSH).
  - To compare the effects of thinning to transform to irregular shelterwood (CCF) with unthinned (UN, Control) on soil C quantity in the OSH.

  The hypotheses for this research chapter are:

  - The WTH treatment reduces the soil OSH C stock and C %, whereas the CHF treatment increases the soil OSH C stock and C % compared with the CH treatment.
  - The CCF treatment increases the soil OSH C stock and C % compared with the UN treatment.
  - Other hypotheses tested are differences in bulk density, soil moisture content and thickness of the soil OSH between the treatments.

- **Carbon quality (proximate pools and N dynamics)**
  - To compare the effects of clearfell systems - WTH, CH and CHF on soil C quality in the OSH.
  - To compare the effects transitioning practices to CCF silvicultural system - CCF and UN, on soil C quality in the OSH.

  The hypotheses for this research chapter are:

  - The WTH treatment contributes towards a decrease in N % and available N and an increase in C:N ratio when compared with the CH treatment. The CHF treatment contributes towards an increase in N % and available N and a decrease in C:N ratio when compared with the CH treatment.
  - The CCF treatment contributes towards a decrease in N % and available N and an increase in C:N ratio when compared with the UN treatment.
  - Other hypotheses tested are differences in proximate C pools and LCI.

- **Fine root biomass and dynamics**
  - To compare the effects of clearfell systems - WTH, CH and CHF on tree fine roots (< 2mm diameter) dynamics.

  The hypothesis for this research chapter is:

  - The WTH treatment contributes towards a decrease in fine root standing biomass and production in the 0 to 15 cm and 15 to 30 cm soil depth when compared with the CH treatment. The CHF treatment contributes towards an increase in fine root standing biomass and production in the 0 to 15 cm and 15 to 30 cm soil depth when compared with the CH treatment.

– Other hypotheses tested are differences in fine root turnover.

1.5 Thesis structure

Chapter 1 covers the drivers for this research. These are climate change mitigation and the opportunities for the forestry sector, in compliance with the requirements related to the elements of sustainable forest management (Forestry Commission 2017), to perform a vital role as C stocks and sinks, by removing CO_2 from the atmosphere. This chapter also includes the aims and objectives of the present research.

The 'Sites and methodology' chapter introduces and describes the experimental set up and methodologies utilized in the present research.

The three experimental chapters addressing the research objectives will be submitted for publishing as scientific papers. These are grouped according to the effects of all management practices investigated (results were kept separated between experimental sites) on three specific soil C characterizations:

1. carbon quantity (stocks).
2. carbon quality (proximate pools and N dynamics).
3. tree fine roots biomass and dynamics.

C stock represents a direct measure of soil C storage, hence the ability of treatment to store C by sequestrating it from the atmosphere. The C quality chapter provides insights on why such changes on C stock occurred - e.g. the presence of different soil proximate C pools and N can be linked to the rate of C and N mineralization, which may result in loss of soil C stock (Vanguelova et al. 2010). The chapter on fine root dynamics is necessary to understand the contribution of fine roots to the soil C stock. This is because fine root turnover represents a major contribution to the nutrient and carbon input to the soil (Kätterer et al. 1995).

The general 'Discussion' section at the end of the thesis includes a synthesis of main findings from all three experimental chapters and how they relate to the main aims, objectives and hypothesis of the research, highlighting also future research gaps, needs and opportunities.

A list of acronyms utilised throughout the thesis can be found in the Appendix (table 6.5).

Chapter 2

Experimental sites and Methodology

2.1 Description of the experimental sites

The present study focusses on the dynamics of organic and organo-mineral soil horizons under Sitka spruce plantations. The choice of studying the OSH was driven by the scarce understanding of how tree litterfall is converted and stored as SOM and in what quantity and form (Pries et al. 2017). Currently the UK forest cover is one of the lowest in Europe (13%, Forestry Commission (2017)) and while afforestation and reforestation practices are encouraged (Lefèvre et al. 2017), there is limited understanding of the effects of such practices on C stocks (Vanguelova et al. 2019). In this instance, the present study will also be useful to improve current uncertainties related to finding suitable locations with a high potential for climate change mitigation in the future. From a research perspective, monospecificity can be seen as an opportunity to better concentrate on the dynamics of soil in response to forest management practices as the variability introduced by tree species is removed.

2.1.1 Clearfell experiment: Forest of Ae, South West of Scotland

The experimental site under study is located in the Forest of Ae (Dumfries and Galloway, Scotland)[1]. This was identified from mature, first rotation *Picea sitchensis (Bong.) Carr.* (Sitka spruce) stands in an earlier, more extended experiment (Proe et al. (2001), see figure 2.1).

With a temperate oceanic climate, the upland experimental site at the Forest of Ae was thought to represent a standard UK harvesting site. Soils were originally classified as moderately fertile, but later corrected to upper poor (refer to table 2.1 for more characteristics of the site) (Mason et al. 2012). The site is laid out in a randomized block-replicated design, with three blocks and three treatments (see figure 2.2): whole-tree harvest (WTH), conventional stem-only harvest (CH) and conventional harvest with fertilization (CHF).

Fertilization was N as NH_4NO_3 at 160 kg N ha^{-1}, P as unground rock PO_4 at 60 kg P ha^{-1}, and K as KCl at 100 kg K ha^{-1}. Plots were fertilised by hand the autumn after planting and every 3 years until canopy closure (around 12 years), see figure 2.3 (Proe et al. 2001). Residues from CH and CHF treatments were retained within the plot of origin.

Treatment plots have an area of 400 m^2 and an internal assessment area of 100 m^2, equivalent to 25 trees. The second rotation of Sitka spruce was planted (1996) with one-year-old

[1] The original experiment started with three sites including Kielder Forest (western Northumberland, England) and Teindland Wood (Moray, Scotland). Data was collected and preliminary laboratory activities were carried out in the same way as for the Forest of Ae, but they were later stored for future activities. A total of 324 observations were collected with soil corer and quadrats during the whole experiment at Ae, Teindland and Kielder. Other 99 observations were added in the summer of 2018 at the Forest of Ae (Bd cylinders and quadrats).

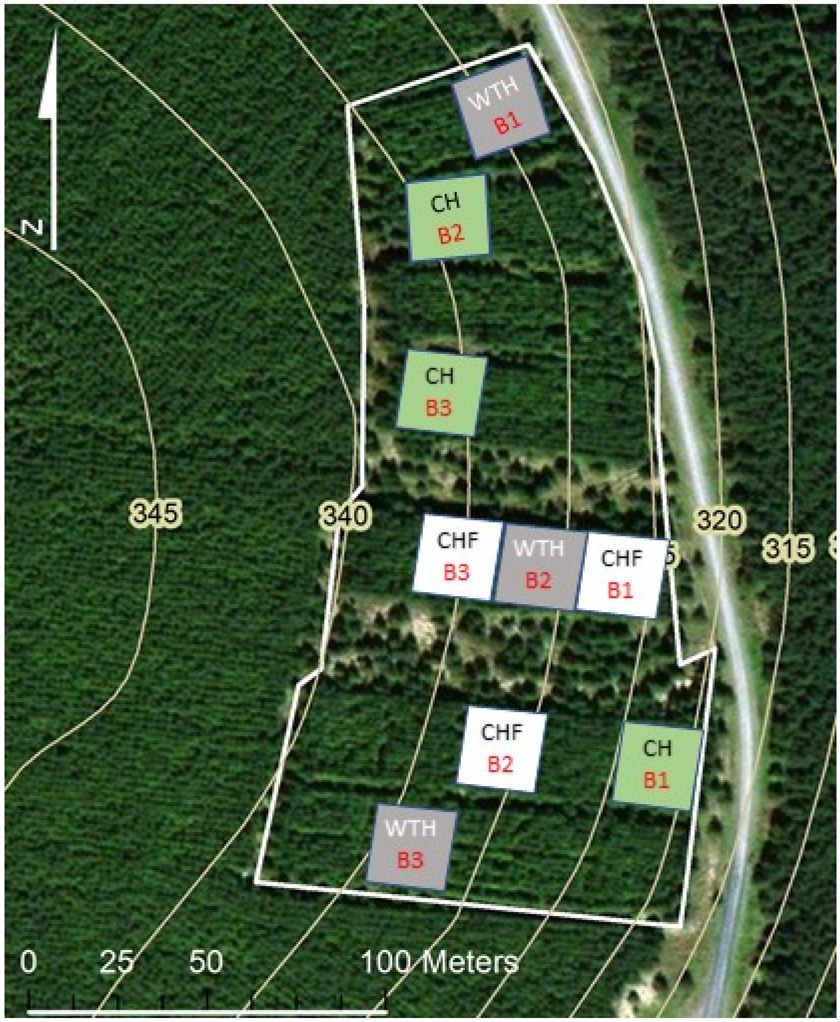

Figure 2.1: Map of the experimental site at the Forest of Ae. Treatments are WTH, CH and CHF. B_i = block-replication number.

Table 2.1: Characteristics of the Clearfell experiment at the Forest of Ae (from Proe et al. (2001) modified).

Attribute	Ae
Coordinates	NY 00281 91396
First rotation	Sitka spruce
Age (years)	22
Elevation (m)	320
Slope/aspect	12°; E
Soil classification	Histo-placic podzol
Mean temperature range (°C)	2 to 13
Precipitation (mm)	1510
Yield class ($m^3 ha^{-1} y^{-1}$)	20
Setup of second rotation seedlings	1996-97

Figure 2.2: Forest of Ae: the experimental setting consists of a randomized block-replicated design with three blocks and three treatments: WTH: whole-tree harvest, CH: conventional, stem-only harvest and CHF: conventional harvest and fertilization.

containerized seedlings at 1 m spacing within the assessment plots; this was to account for annual destructive sampling over the following half a decade. Density around the assessment plots was at 2 m spacing. In order to alleviate damage by *Hylobius abietis* (Pine weevil) permethrin treatments were applied during the first two growing seasons. Following 30 % seedling mortality in the first year caused by warm dry weather, dead trees were replaced by two-year-old bare-root seedlings the following year (Proe et al. 2001; Mason et al. 2012).

Figure 2.3: Panoramic views of the three treatments (example replicates) in the Forest of Ae. Top: WTH; centre: CH; bottom: CHF.

Table 2.2: Characteristics of the CCF experiment at Clocaenog Forest (Forestry Commission 2007; Arcangeli 2016, 2018).

Attribute	Clocaenog
Grid Reference	SJ 04263 54032
First rotation	Sitka spruce
Elevation (m)	390 - 405
Slope/aspect	<= 8°, S - SW
Soil classification	Iron pan, podzol, surface water, peaty gleys, deep peat
Accumulated growing season temperature (>5.6°C)	1000
Precipitation (mm)	> 1300
Exposure (DAMS)*	16
Setup of second rotation seedlings	1951
Moisture regime	Moisture deficit: 60mm
Latest thinning	UN: before 2002; CCF: 2015
basal area (m^2ha^{-1})†	UN: 58.1; CCF: 25.6
Yield class ($m^3ha^{-1}y^{-1}$)	UN: 22; CCF: 20
Percentage species composition (2016)‡§	UN: SS 90.22, WH: 9.78; CCF: SS 93.00, LP 5.25, ROW 1.75

* wind risk estimates may have been overly pessimistic.
† UN: Dec 2017; CCF: Mar 2016.
‡ SS: Sitka spruce, WH: *Tsuga heterophylla* (Western Hemlock).
§ LP: *Pinus contorta* (Lodgepole pine), ROW: *Sorbus aucuparia* (Rowan).

2.1.2 Continuous-Cover-Forestry trial: Clocaenog, North of Wales

Clocaenog Forest lies on the southern side of the Denbigh Moors (Denbighshire, Wales), extending over an area of more than 4000 ha, with an elevation range between 300 and 500 m and 40 % of the forest undergoing transformation to CCF management (Ireland 2006). The underlying geology of the bedrock is Silurian made up of slates, shales and grits (Forestry Commission 2007). Soils are fine textured on sloping sites, where brown earths predominate. These are about 50 cm deep and generally stony (Pitman et al. 2011). On less steep slopes sudden change in drainage causes the soil to vary from iron pan and podzol to surface water and peaty gleys, or even deep peat as soil drainage becomes insufficient (Forestry Commission 2007). According to the Ecological Site Classification (Forest Research 2020), the brown earths are slightly dry with poor soil nutrient regime (refer to table 2.2 for more characteristics of the site).

A number of species are to be found in Clocaenog - *Picea abies* (Norway spruce) being the second most abundant. This is followed by clusters of pine, larch and mixed broadleaf species (Pitman et al. 2011), but the forest cover is dominated by Sitka spruce. Natural regeneration often occurs under the main canopy, particularly in areas affected by previous windthrow events. The majority of stands are now second rotation crops. The stand used in this study was planted in 1951 with the idea of maximising production under a clearfelling system, but it fell into neglect after an early thinning. A number of late thinnings followed which consolidated the stand stability and regeneration. In 2002, a number of permanent sample plots were established to investigate the growth of stands managed under different CCF systems.

The experimental area is setup with two plots within 200 m distance from each other, representing the treatments:

1. Control (unthinned - UN: no interventions in the overstory or understory have occurred since the research area was established in 2002, although the plot has a history of thinning prior to being taken on as an experimental plot (Arcangeli 2018)).

2. in transformation to irregular shelterwood[2] (CCF). The CCF treatment had a history of thinning prior to being taken on as an experimental plot and has been thinned further as part of its experimental treatment (2004, 2009, 2012 and 2015 (Arcangeli 2016)). CCF is an open plot with extensive regeneration, some of which is at the stage of being recruited into the canopy (i.e. dbh $\geq$ 7 cm).

The treatments look very different from the inside; with respect to the UN treatment the competition lead to a much darker understory where regeneration was mainly composed of

[2]While a shelterwood system usually consists of an even-aged new stand in the shelter of an old stand, the irregular shelterwood is different because it is determined by timing of regeneration rather than spatial arrangement. The forest cover is extended for a long period of time to achieve special management objectives (Raymond et al. 2009). Hence, the new stand is really not even-aged. In this instance the irregular shelterwood may be more closely represented by a group- or single-tree selection systems, rather than other shelterwood variants.

dead and dying trees and tree height often in excess of 20 m. The CCF treatment was much lighter; a large area was populated with trees below 2 m height as well as a good presence of trees within the range 10 to 20 m and over (figure 2.4).

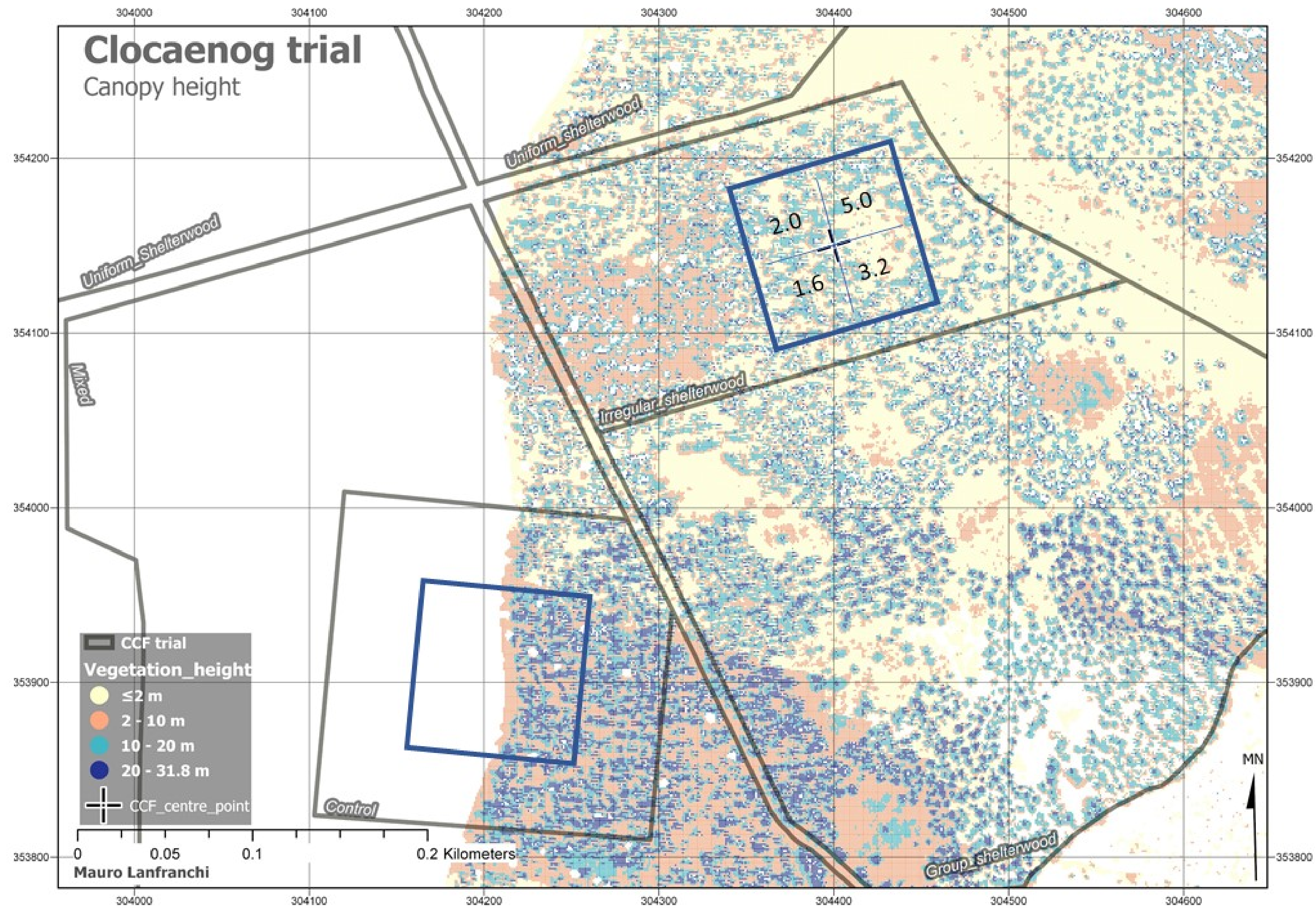

Figure 2.4: Canopy structure at the Clocaenog trial. The experiment involved the areas "Control" (UN, unthinned) and "Irregular shelterwood" (CCF, in transformation to irregular shelterwood). Lidar data is limited to about 50% of the UN plot. Quadrats represent the internal assessment plots. CCF: Cross on the map is centre of the respacing treatments (numbers (m) are the distance between regeneration trees after respacing). Raw data: (EDINA Digimap Ordnance Survey Service 2016b, 2016a).

The CCF treatment was also subject to a respacing experiment (2006) with the area divided in four sub-plots with a 1.6 to 5 m distance between regeneration trees after respacing (Forestry Commission 2007; Owen 2013). While the respacing experiment is not relevant to this study, the experimental design will take into account the potential influence of an such experiment by collecting more observations in this treatment as opposed to the control treatment. One assumption in this experiment is that within the respacing subplot the characteristics of the soil are unvaried. In order to limit the variability of soil type, the plots have been selected based on aspect (S - SW) and slope ($\leq$ 8 degrees) which represented the entirety of the Control plot. More specifically, soil samples were collected within the inner 10000 m^2 quadrat of the control plot. The CCF samples were collected from four 2500 m2 quadrants (the respacing treatments) created by a cross departing from grid reference X304400 - Y354150 that ran parallel to the straight sides of the plot. The experiment took place within the elevation range 390 - 405 m (figure 2.5). Treatment plots have an area of 10000 m^2. Buffer around plots was $\geq$ 15 m.

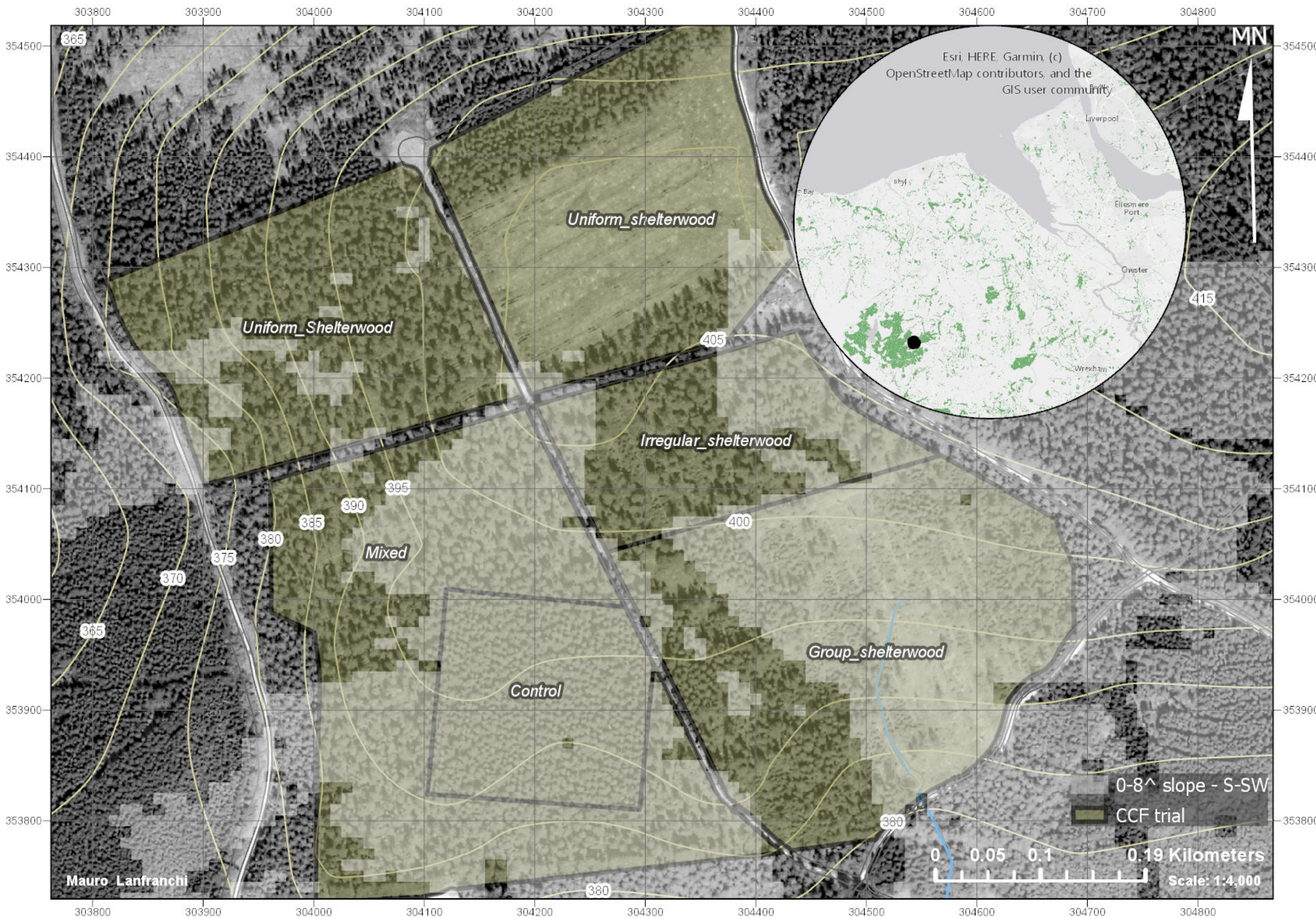

Figure 2.5: Map of the Clocaenog trial. Area transparent white is less or equal to 8° slope and S to SW directed. Area in yellow is the entire trial at Clocaenog Forest. The experiment involved the areas “Control” (UN, unthinned) and “Irregular shelterwood” (CCF, in transformation to irregular shelterwood). Raw data: (EDINA Digimap Ordnance Survey Service 2017b, 2017a).

2.2 Methodology

2.2.1 Clearfell experiment: Forest of Ae - Carbon quantity

The fieldwork took place from 7th to 9th of November 2016. (figure 2.6).

Figure 2.6: Fieldwork activities at the Forest of Ae, November 2016.

Six soil cores were randomly collected in each plot at two depths (0 to 15, 15 to 30 cm) with the aid of a metal cylindric corer (h 15 cm Ø[3] 6 cm). Another sampling point was utilized when stoniness was excessive to the point of making sample collection problematic (this being as close as possible to the original sampling point). A total of 108 cores (2 depths, 6 cores per plot, 9 plots) were collected during the whole experiment.

In August 2018 a second fieldwork took place to accurately assess the soil C stock of the OSH. For each plot, six quadrats with an inner size of 25 cm were used to collect the litter layer. A total of 54 quadrats (6 observations, 9 plots) were collected for litter mass estimation. Five bulk density rings (h 4.7 cm Ø 4.7 cm) were also randomly collected from

[3]Diameter.

the H horizon in each of the nine plots within the Forest of Ae (forty-five in total) to estimate the density (g cm^{-3}) and C stock (Mg ha^{-1}) of the H horizon. Rings were collected from pits formed as a result of harvesting root meshes (figure 2.7); these were part of the study on fine root dynamics (discussed in chapter 5). The depth of the F and H horizons was also measured from each auger observation.

Refer to chapter 2.1 for an introduction on the experimental sites).

Figure 2.7: Forest of Ae. Left: bulk density ring (h 4.7 cm Ø 4.7 cm) collected to assess the density and C stock in the H horizon; centre: quadrat (25 cm) collected to assess the C stock in the L horizon; right: the (approximate) 90 pits dug to extract the root meshes were utilised to extract the Bd rings from the H horizon.

2.2.1.1 Laboratory processing

Soil cores were laid on pre-weighed aluminium trays and the weigh was recorded. Observations were manually processed to extract fine (<2mm) Sitka spruce roots (figure 2.8) for the fine roots dynamics experiment (chapter 5).

Figure 2.8: Forest of Ae. Roots were extracted from soil cores before soil was oven-dried at 105°C.

The root-free 0-15 and 15-30 cm depth density cores, Bd ring observations and litter quadrats were oven-dried at 105°C overnight, then weighed to calculate water content as the difference between field and oven-dry weight. Observations were corrected for the presence of stones[4] and core depth when less than a depth of 15cm.

Bulk density (Bd) was calculated as follows (g cm^{-3}):

$$Bd = w_{105C}/V_c \tag{2.1}$$

where 'w_{105C}' is the mass of the oven-dry soil and 'V_c' is the volume of the core.

2.2.1.2 Carbon stocks calculations

C stock with respect to F and H horizons results from a combination of data from Dutch auger and soil corers or Bd rings. For the purpose of C stock calculations the F horizon Bd was taken from the 0-15 cm corer; the soil ring was utilized for the H horizon[5]. C stock was calculated as follows (Mg ha^{-1}):

$$C_{stock} = (Bd_i * C\%_i * d_i) \tag{2.2}$$

where '$_i$' represents the observation within a specific horizon (F or H), '$C\%$' the C concentration on a dry-mass basis from elemental analysis and 'd' the depth of the horizons. The C stock (Mg ha^{-1}) of the L horizon was instead calculated by area (the

[4]Observations were subtracted the mass from stones. The resulting core volume reflected the volume occupied by the stones.

[5]0-15 cm soil cores were not separated between the F and H horizon. The average Bd for C stock calculations was taken from the 0-15cm core of the CHF treatment for all treatments; this is because CHF has the deepest F horizon on average among the three treatments (13,5cm), hence it is less biased by the presence of the H horizon.

quadrat) on a dry-mass basis *'m'*, then by C concentration (C%):[6]

$$C_{stock-lit} = (m_i * C\%_i) \tag{2.3}$$

2.2.1.3 Statistical analysis

Data visualization and statistical analysis on C quantity (see chapter 3.2) were carried out with R (RStudio Team 2016; R Core Team 2018).

Data visualization was carried out with box-and-whisker plots. This was preferred to standard barplots for their ability to convey more information. Boxplots are effective in visually representing skewness, main percentiles, random effects as well as the effect of secondary variables within the experiment (Crawley 2013) (e.g. the effect of 'batch' during forage fibre analysis) in one plot. Data visualization utilized R library `ggplot2` (Wickham 2016).

For the purpose of statistical analysis, data were averaged by block replication. Data can be found in the Appendix (tables 6.6, 6.7 6.8, 6.9). Statistical analysis on continuous variables utilized mixed-effects model (library `lme4`) fitted to data by restricted maximum likelihood. The model is summarized as:

$$Y_{ijk} = \mu + \tau_i + B_j + \epsilon_{ijk} \tag{2.4}$$

where Y_{ijk} is the response variable observed for horizon k, in block j with forest management

[6] values from the litter quadrat (g /0.0625 m^2) were scaled to Mg ha^{-1}:

$$\frac{((g\ of\ litter)\ \cdot\ (4 \cdot 4\ \cdot 10000))}{10^6}$$

.

i, μ is the overall mean, τ_i is the fixed effect of forest management $_i$, B_j is the random effect of block $_j$, and ϵ_{ijk} is the residual error.

Data was transformed if necessary to meet the model assumptions of linearity, homoscedasticity and normality distribution of residuals. Alternatively a generalized linear mixed-effects model (`glmer`) was fitted to data by maximum likelihood (Bates et al. 2015). The Mixed-effects model was utilized to define block replication as a random variable as part of the nested design. Backward elimination of random-effect terms in linear mixed models was performed with the `step` function (Kuznetsova et al. 2017). Function `gls` for a linear model using generalized least squares was fitted to data by restricted maximum likelihood when random-effects were non-significant (Pinheiro et al. 2018). Estimated marginal means (EMM) was utilised to adjust marginal means for unbalanced design (Lenth 2018).

2.2.2 Clearfell experiment: Forest of Ae - Carbon quality

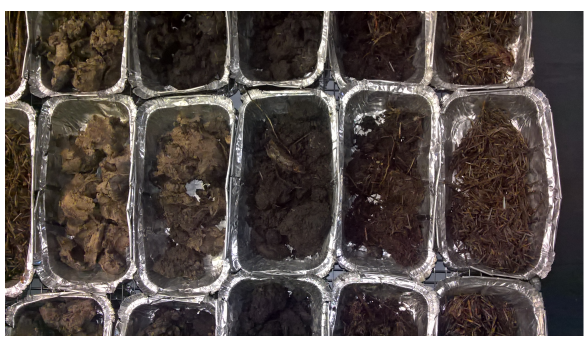

Figure 2.9: A total of 54 series of soil were collected from the Forest of Ae. One soil series (from left to right: 40-60 cm; 20-40 cm; 0-20 cm (H); F; L).

Six random[7] observations were taken per plot from the litter (L), fragmented (F), 0-20cm (H), 20-40cm, 40-60cm horizons (five horizons, thirty observations per plot)[8] with the aid

[7]When stoniness was excessive, the sampling point was found as described in chapter 2.2.1.

[8]While samples were collected from five depths, only the organic surface horizons (L, F and H) will be

of a Dutch auger (figure 2.9).

2.2.2.1 Soil available nitrogen

Within 10 hours of sampling, observations from the 0-20 cm soil depth (H horizon) were extracted with 1M KCl to determine soil available nitrate and ammonium (10 g soil in 50 ml KCl) using field-moist soil subsamples (figures 2.10 and 2.11). The available nitrate and ammonium in the KCl extracts were measured by Continuous Flow Analyser (Rothamsted Research, Harpenden, Hertfordshire).

Figure 2.10: Field activities to determine available N. At collection stage 50ml, 1M KCl was added to 10g soil from H horizon.

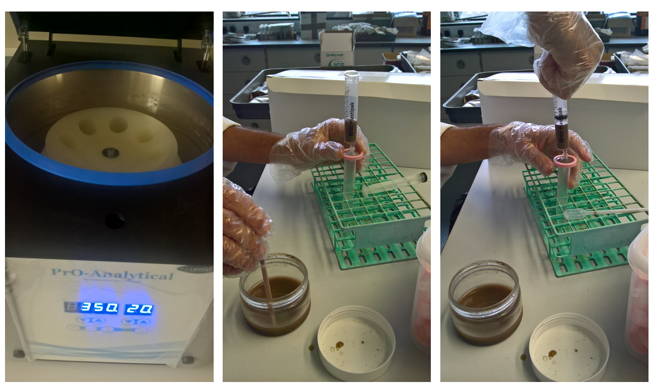

Figure 2.11: Left: solution containing soil from the H horizon was centrifuged at 3500 rpm for 20 minutes, then filtered (25mm Ø nylon, 0.45 μm filter) before laboratory analysis (centre and right).

analysed, while the remaining 20-40 cm and 40-60cm were dried, crushed and sieved, then stored for future activities.

2.2.2.2 Soil carbon and nitrogen concentration

Observations were kept cool during transport and then stored at 4°C until processing. Observations from the Forest of Ae were processed within ten days (20th - 30th of November 2016).

Observations were laid in 20x10cm aluminium trays, coded and dried in oven (Hedinair) at 35°C for 48 hours (figure 2.12). They were then sieved (2mm mesh) and stored in pre-coded, sealable plastic bags. Most of the organic and mineral layers from the forests of Ae were processed in a jaw rock crusher before sieving due to the formation of hard to crumble clods.

The soil was stored at room temperature until analysis.

Figure 2.12: Forest of Ae. Soil samples were oven-dried at 35°C for 48 hours.

The following activities were carried out at the 'Instituto Vasco de Investigación y Desarrollo Tecnológico' Neiker Tecnalia - Bilbao, Spain (Neiker) as part of the 'European Cooperation in Science and Technology', Short Term Scientific Mission (STSM) Action FP 1305 Biolink: 'Linking below-ground biodiversity and ecosystem function in European forests'.

Elemental analysis for the L, F and H horizons was carried out at Neiker Tecnalia with a

Leco TruSpec Micro CHN (LECO Corporation, Michigan, USA)[9]. The same analysis for the lower H horizon (A, collected in the 20 to 40 cm H depth) took place at Forest Research, Surrey (Thermo Electron Corporation Flash EA 112 CN - Thermo Fisher Scientific).

Bulked observations were placed in aluminium foil cups (Leco tin foil cups) and weighed (0.1g for the L and F horizon, 0.15g for the H horizon). Observations were prepared in triplicates (243 in total, horizons L,F, and H) and duplicates (54 in total; A horizon, averaged for total C and N. Values were adjusted to account for the residual humidity using results from the thermogravimetric analyser (LECO TGA-601, horizons L,F and H horizons) and from oven-dry at 105°C until constant mass (A horizon).

2.2.2.3 Soil organic matter and ash content

Organic matter calculations were carried out on a Leco TGA-601 thermogravimetric analyser (LECO Corporation, Michigan, USA) (figure 2.13).

Soil samples from the L, F, and H horizons from the Forest of Ae were bulked into couples from six to three groups of 10g each per forest plot as follows: observations '1 and 2', '3 and 4', '5 and 6'. The total number of observations for the organic layers were therefore reduced from 162 to 81 in order to process the entire forest within the timeframe of the STSM.

Cruicibles were oven dried for 24 h previous to analysis. Together with organic matter, the analyser provided data for the residual water content, which was then utilised to adjust for the proximate C pools (equation (2.9)) as well as a second measurement for ash content, the first being the ash calculated after the ADL extraction.

[9]This is a system based on the Dumas method of combustion. The machine is a whole gas analyser which utilises a combination of a flow-through carrier gas system used in conjunction with infrared and thermal conductivity detection systems.

Figure 2.13: Leco TGA-601 thermogravimetric analyser was utilised to measure organic matter and residual water content on bulked samples from the Forest of Ae. Left: Leco TGA-601 thermogravimetric analyser; right: Particular of the TGA-601 carousel.

2.2.2.4 Forage fibre analysis - NDF procedure

Observations for soil fractions were taken from the same observations used for soil C and N (see chapter 2.2.2.7). These were transported to Neiker for analysis and processed from 13th January - 10th February 2017. Observations were bagged, coded and labelled for reference.

Litter observations were milled for 80 s at 15,200 rpm (IKA Tube Mill control) then processed through a 1mm sieve (figure 2.14).

Neutral-detergent fibre, Acid-detergent fibre (ADF) and acid-detergent Lignin (ADL) were determined with a digestion apparatus Ankom200 fiber analyzer (Van Soest et al. 1991b; ANKOM).

Figure 2.14: Coding and milling of observations before forage fibre analysis.

Neutral Detergent Fibre is the remaining residue after digesting in a detergent solution. The proximate C residues are identified in hemicellulose, cellulose and lignin. This procedure is therefore thought to remove the cell soluble component from the soil.

For each observation, the weight of the empty filter bag was recorded. After this, 0.5 ± 0.05 g of previously dried soil was recorded and moved into the filter bag, which was then heat sealed within 5mm of the edge. The fibre analyser allows for 24 bags (max) for each cycle[10]; this includes 22 observations, one of which (the 23rd) was replicated and utilized to help identify anomalies, and one blank (empty) filter bag.

2L FND20C premixed chemical solution was used in each of the NDF cycles; this was poured into the vessel of the Ankom fibre analyser. The bag suspender was then placed in the vessel, the temperature set to 100°C and 'Agitate' switched on. The lid of vessel was then sealed and left to operate for 75 minutes.

At the end of the cycle agitate and heat were turned off, the drain valve opened to drain the hot solution, then closed again. 2L water (90 to 100°C) was poured in the vessel to rinse the soil observations and 'Agitate' turned on for 5 minutes. The rinse was repeated three times.

After rinsing, the observations were removed from the suspender and excess water removed from the filter bags which were then soaked in acetone for 3 minutes. Excess acetone was removed from the filter bags.

Acetone rinse was followed by the drying process. Observations were initially laid on a filter paper under the fume hood until acetone was completely evaporated; this took approximately 2 hours. Observations and filter paper were then dried in the oven at 105°C overnight. Bags were finally placed in a desiccator for 15 minutes before weighing.

[10]For clarity, 'cycle' refers to one unique extraction procedure either with Ankom (NDF, or ADF) or in beakers (ADL), whereas 'series (or batch)' refers to all NDF, ADF and ADL procedures within the same observations.

2.2.2.5 Forage fibre analysis - ADF procedure

Acid Detergent Fibre is the residue remaining after digesting with 1 N H_2SO_4 and CTAB. The proximate C residues are identified in cellulose and lignin. This procedure is therefore thought to remove the hemicellulose component from the soil.

List of reagents for 1L (2 L are needed for 24 observations - containing 1 blank and 1 duplicate):

- 20g cetyl trimethylammonium bromide (CTAB).
- 1 L 1.00 N H_2SO_4 previously standardized.

Each cycle (2 L solution) consisted of 40g CTAB in distilled water to which 55ml H_2SO_4 (97% concentration) was added. The ADF solution was placed on a magnetic stirrer set to 400 rpm for 30 m at room temperature, then left in a tank overnight until the experiment took place. The extraction procedure took place after performing NDF determinations; this was very similar to the NDF procedure, with the exception of the length of the extraction procedure (for ADF it was 60 minutes instead of 75). C pools calculations are highlighted on chapter 4.1.1.1 and chapter 2.2.2.7.

2.2.2.6 Forage fibre analysis - ADL procedure

Acid Detergent Lignin follows ADF and it is the residue that remains after digesting with 24 N H_2SO_4. The proximate C residues are identified with lignin. ADL removes the cellulose component from the soil; therefore two pools of C can be calculated with this last extraction procedure.

72% by weight H_2SO_4 was prepared by standardising reagent grade H_2SO_4 to specific gravity 1634 g/L at 20°C or 24.00 N. 1213g H_2SO_4 was added to 421g H2O in 1 L MCA (class A volumetric flask). The amount of H_2SO_4 needed was calculated as follows:

$$H_2SO_4(L) = (N \ * L \ * A_m)/(C \ * S_g) \tag{2.5}$$

where N is the normality to attain, L are the litres of solution needed, A_m is the atomic mass, C is concentration (%), S_g is the specific gravity at concentration.

$$H_2SO_4(g) = H_2SO_4(L) * S_g * L \tag{2.6}$$

Cooling was setup to counteract the exothermic reaction by keeping the flask under running water for the whole preparation, which took 1 hour (approximately). H_2SO_4 was standardised to 1634 g/L at 20°C the morning after preparation by removing solution and adding distilled water or H_2SO_4 as follows to account for the thermal expansion of the MCA (as advised by laboratory staff at Neiker Tecnalia):

- H_2SO_4 level below the 1 L notch in the MCA:
  - extract 1.5 ml solution.
  - Add 2.5 ml distilled water.
- H_2SO_4 level above the 1 L notch in the volumetric flask:
  - Extract 5 ml solution.
  - Add 4.5 ml concentrated H_2SO_4.

After ADF, observations were placed in 8 x 100ml jars with ADL solution, then sealed. Jars were then placed on a perforated tray, then onto a platform shaker for 3 hours (Heidolph promax 2020; speed 140 - 150).

After 3 hours, observations were retrieved and rinsed in the fibre analyser (agitation ON, heat OFF) with hot water (90-100°C) to remove all acid. Rinses were repeated until pH neutral (5 or 6 times, test with pH indicator). Acetone soak and oven-dry were identical to NDF and ADF.

2.2.2.7 Soil proximate C pools calculations and ash content calculations

As mentioned in chapter 2.2.2.4, each sample cycle contained a blank filter bag for correction (multiplication factor). The within-cycle multiplication factor (M_f) was calculated as:

$$M_f = bl_t/b_w \tag{2.7}$$

where bl_t is the blank bag tare and b_w is the blank weight after fibre analysis.

The raw weight of the pool - w_R(%) not corrected for moisture) after fibre analysis was calculated as:

$$w_R = (((w_{bs} - w_a) - (b_t * M_f))/w_b) * 100 \tag{2.8}$$

where w_{bs} is bag and soil weight after fibre analysis, w_a is ash weight, b_t is filter bag tare and w_b is soil weight before fibre analysis.

The above formula adjusts for ash content (which was determined after 4 h at 550°C; this was done after the ADL procedure) and fibre particle losses during extractions.

In order to calculate the % mass remaining after each extraction procedure (w_P - NDF,ADF,ADL), observations needed to account for the residual water content within the soil; results from the above formula were corrected as follows based on water content values from the thermogravimetric analyser:

$$w_P = 100 * w_R/dm_{105C} \tag{2.9}$$

where dm_{105C} is the percentage wass after sample was oven dried at 105°C.

The proximate C pool - C_p, was calculated as:

$$Cp = Ob_l - w_P \tag{2.10}$$

where Ob_l is the percentage C pool(s) left after the previous extraction (NDF = 100, ADF = NDF and ADL = ADF. More detailed information in chapter 4.1.1.1).

After ADL, observations were placed in pre-weighed crucibles (these previously left in the oven at 105°C for 24h, followed by desiccator for 30 minutes) and in a muffle furnace at 525°C for 3 hours. Samples were cooled in a desiccator for 45 minutes, then weighed. Ashes were corrected with the blank, similarly to the extraction procedures.

2.2.2.8 Statistical analysis

Data visualization and statistical analysis on C quality (see chapter 4.2) was carried out in a similar way as for the C quantity chapter (see chapter 2.2.1.3 and model (2.4)).

2.2.3 Clearfell experiment: Forest of Ae - Fine roots standing biomass, production and turnover

2.2.3.1 Standing biomass of fine roots

Root samples were taken from the 0 to 15 and 15 to 30 cm soil depths by cylindrical cores (depth 15 cm, Ø 6 cm) from the Forest of Ae (see chapter 2.2.1.1). Root samples were washed out from the soil, then separated into live (fine root standing biomass) and dead (necromass) subsamples on the basis of colour, brittleness, structure of the cortex or bark and colour of stale and xylem (Vanguelova et al. (2007), and reference therein). These were then stored in 20% ethanol solution until analysis took place. The remaining soil was used for bulk density and C stock estimations. Roots were oven-dried at 80°C for at least 16 h to determine the dry weight of the samples (fine root standing biomass) (Vanguelova et al. 2007). The mass of fine roots from the soil cores was scaled[11] to Mg ha^{-1}.

2.2.3.2 Production of fine roots

During November 2016, 10 x 30 cm meshes (knitted 1 x 1 mm meshes to facilitate the growth of the roots) were inserted (on a grid system the size ∼ 1 m x 3 m in two rows of five meshes) into the soil in each of the plots with the aid of a spade and a metal sheet with front blade. This was designed in order to speed up the process of insertion and at the same time to introduce as little disturbance to the soil as possible (Lukac and Godbold 2010; Wang et al. 2014). A total of 90 meshes were used in the whole experiment (10 meshes, 9 plots). Enough mesh replicates were used to allow for redundancy, such as damage during

[11] Values from the soil core (g 0.0028 m^{-2}, representing the area of the circle in the soil core) were scaled as follows:

$$\frac{((g\ ovendry\ soil\ core\ fine\ roots)\ \cdot\ (10000/0.0028))}{10^6}$$

the permanence into the soil as well as at the time of harvesting. In each plot, six meshes were used for analysis.

Figure 2.15: Forest of Ae - Extraction of the fine root meshes. From left: Individual observation marked in the soil; cube of soil containing mesh; mesh visible at lower-end of the soil block; soil-free mesh with visible fine roots ‘unusually’ extending to the visible H horizon and ready for storage.

The entire mesh was inserted into the soil, with the uppermost side (10cm) parallel to the ground. When stoniness prevented this, the mesh was inserted until the reach of a rocky substrate.

Fine root production in Scandinavian countries peaks in late spring. This is typical of the boreal ecosystems (Lukac and Godbold 2010). During their root inclusion net experiment on a *Larix principis-rupprechtii* plantation (Northern China) Wang et al. (2014) identified August and September as months of peak in fine root production. Wang et al. (2014) experimental site is based in the Saihanba National Forest. The annual mean temperature is -1.4°C; 68% of the annual rainfall is between June and August. This may be responsible for the increased biological activity in the late summer months. The present study harvested root meshes after 20 months of permanence into the soil (August 2018). Similarly to the procedure in Lukac and Godbold (2010) the nets were extracted by sawing a parallelepiped[12] with a 5 cm buffer around the mesh. These were cleaned free of soil, counted and stored in plastic bags in a cool environment (see figure 2.15). Once in the laboratory the meshes were sprayed with ethanol, then stored at 4°C until analysis took place. Root meshes were processed by creating a virtual parallelepiped (2 x 10 x 30 cm) of fine roots around the mesh (July 2019). Extracted roots were oven-dried at 80°C for at least 16 h to determine the dry mass (the fine root production).

The mass of fine roots from the virtual volume around the meshes was scaled[13] to Mg ha^{-1}, this representing the fine root production.

2.2.3.3 Fine root turnover

Turnover of fine roots was calculated by matching results from the randomized soil core collection (fine root standing biomass) and the grid system of the root inclusion net (RIN) technique. Fine root turnover was calculated with median values of the plots as (Lukac and Godbold 2010):

$$Fine\ root\ production/Fine\ root\ standing\ biomass \tag{2.11}$$

[12]A six-face prism, all parallelograms.

[13]Values from the virtual volume around the mesh (g / 0.002 m^2, this representing the area around the short side of the mesh) were scaled as follows:

$$\frac{((g\ ovendry\ fine\ root\ mesh\ inclusions)\ \cdot\ (10000/0.002))}{10^6}$$

2.2.3.4 Statistical analysis

Data visualization and statistical analysis on fine root C dynamics (see chapter 5.2) was carried out in a similar way as for the C quantity chapter (see chapter 2.2.1.3 and model (2.4)).

2.2.4 Continuous-Cover-Forestry trial: Clocaenog - Carbon quantity

Fifteen random[14] observations were taken at the 0 to 15 cm depth with a soil corer in the UN (Control) plot (h 15 cm, Ø 6 cm) (6^{th}, 7^{th} June 2018). To account for the variability of the respacing experiment within the CCF treatment, twenty random observations were taken from the 0 to 15 cm (refer to chapter 2.1 for an introduction on the experimental sites). An equivalent number of observations were collected with 25 x 25 cm quadrats to quantify the mass of the litter horizon. Fifteen soil Bd rings (h 4.7 cm Ø 4.7 cm) were collected from three soil pits (five observations per pit) in each horizon (H and A) in the CCF treatment and from the A horizon of the Control treatment[15]. The depth of the F and H horizons was also measured from each auger observation.

2.2.4.1 Laboratory processing

Contrary to the procedure utilised for the Forest of Ae, fine roots were not extracted from the soil cores[16]. Hence, fine roots were included in the soil C estimations for the experiment at Clocaenog forest. Nevertheless, research found that the effect of fine root mass on volume

[14]When stoniness was excessive, the sampling point was found as described in chapter 2.2.1.

[15]This is because the H horizon in the Control plot (UN) was consistently thinner than 5 cm (figure 2.16).

[16]This decision was solely based on resources and time availability. Clocaenog experiment started at a later stage in the PhD studies. The root inclusion net technique (fine root production) would have taken at least an extra year; hence it was not worth the extra labour of extracting roots from the soil cores if these were not going to be utilized.

Figure 2.16: Top left: detail of the H horizon in the Control (UN, unthinned) treatment. This was consistently $\leq$ 5 cm deep; bottom left: soil pit no.1 at the UN treatment; top right: detail of the H horizon in the CCF (transformation to irregular shelterwood) treatment; bottom right: one of the three soil pits in the CCF treatment.

and Bd is minimal in forest soils, with fine root mass introducing a variation in mean Bd (soil core method) from 1.142 $\pm$ 0.206 to 1.148 $\pm$ 0.206 g cm^{-3} (Vanguelova et al. (2016), and reference therein). Apart from this, soil water content and Bd were calculated the same way (see formula (2.1)).

2.2.4.2 Carbon stocks calculations

The C stock of the L, F and H horizons was calculated in the same way as for the Forest of Ae (see formulas (2.2) and (2.3)). For the F horizon, Bd was taken from the 0-15 cm corer[17], whereas for the H horizon the Bd from the soil ring was utilized[18].

2.2.4.3 Statistical analysis

Statistical analysis on continuous variables was carried out in a similar way as for the Forest of Ae (see chapter 2.2.1.3 and model (2.4)).

For the CCF trial in Clocaenog the random effect was identified in the respacing experiment within the irregular shelterwood treatment only. Data (averaged by respacing to limit the size of the table) can be found in the Appendix (tables 6.12, 6.13, 6.14, 6.15).

2.2.5 Continuous-Cover-Forestry trial: Clocaenog - Carbon quality

Fifteen random observations were taken (6th, 7th June 2018) from the L, F, H and A soil horizons in the UN plot with the aid of a Dutch auger[19], attempting to avoid stony areas. To account for the variability of the respacing experiment within the CCF treatment, twenty random observations were taken from the same horizons. A total of 140 observations were collected with Dutch auger.

2.2.5.1 Soil available nitrogen

On day of collection, jars containing 50ml 1M KCl were added to 10g soil from the H and A horizons for a total of 70 observations. Jars were stored in a cool place until processing took place at the Forest Research laboratories (Alice Holt, Surrey). The procedure was identical to the one utilised for the Forest of Ae (see chapter 2.2.2).

[17]Humic material was removed when present.

[18]For the H horizon the average Bd utilised for C stock calculations was taken from the CCF treatment.

[19]For the H horizon in the UN treatment, observations were collected with a trowel due to the shallowness of the soil horizon.

2.2.5.2 Soil carbon and nitrogen concentration

Observations were kept in a cool place until reaching the University of Cumbria laboratories (Ambleside, Cumbria) where they were stored at 4°C until processing. Soil samples were oven-dried (LabQuip) at 35°C (13th June 2018 onwards), L and F horizons (5 days); H and A horizons (12 days). These were initially sieved in a 4 mm mesh. After this, observations were milled and sieved within the range 1mm - 108μm (figure 2.17) then stored.

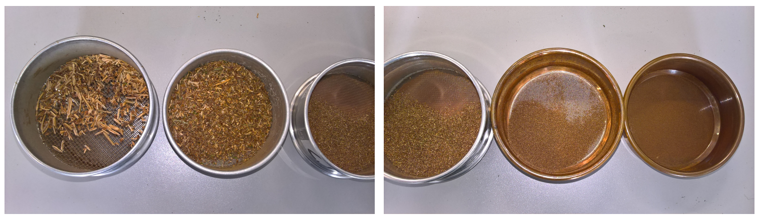

Figure 2.17: Clocaenog trial. Milling process: Observations were milled, then sieved to create a range of fragments between 1mm and 108μm. The finer fragment size was assumed to be appropriate given the porosity of the filter bags utilised for forage fibre analysis (25μm).

Figure 2.18: Clocaenog trial: Single observation prepared for elemental analysis. From left: ball-milling; after ball milling; weighing sample for elemental analysis; observation ready for analysis.

Elemental analysis for the L, F, H and A horizons was carried out at Forest Research (Thermo Electron Corporation Flash EA 112 CN - Thermo Fisher Scientific). Observations were initially ball-milled then weighed[20] in aluminium foil cups (figure 2.18). Observation were prepared in duplicates (280 in total, horizons L,F, H and A), then averaged for total C

[20]The amount was mostly based on the horizons or, occasionally, the appearance and colour of the observation.

and N. Values were adjusted to account for the residual humidity using results from oven-dry at 105°C until constant mass.

2.2.5.3 Forage fibre analysis

Observations for soil fractions were taken from the same observations used for soil C and N.

The successful replication (carried out July 2018) of the forage fibre analysis procedure at the University of Cumbria fulfilled the aim of the COST action FP1305 Biolink (figure 2.19 and 2.20).

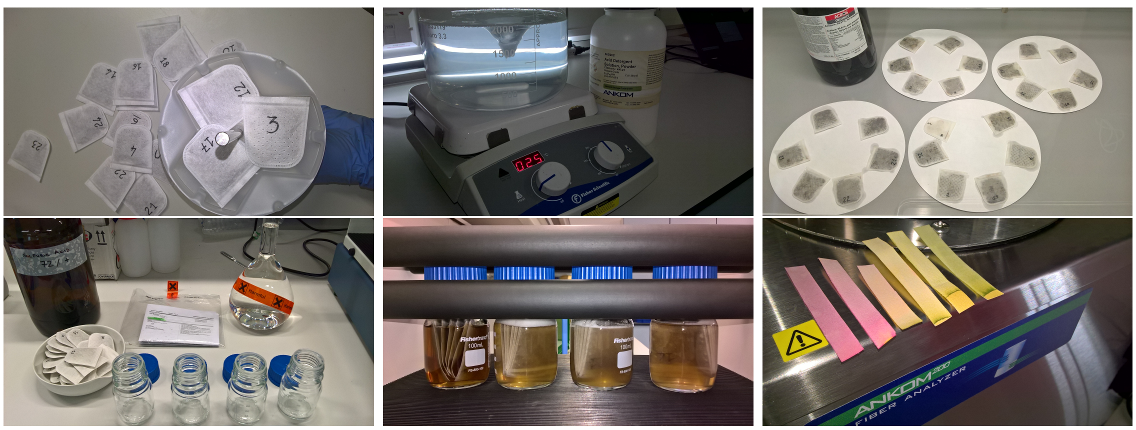

Figure 2.19: Clocaenog forest. Forage fibre analysis, from top left: observations ready for a cycle; preparation of ADF solution; sample-drying after acetone rinse; observations ready for ADL cycle; ADL cycle in beaker, on platform shaker; rinse and pH check after ADL.

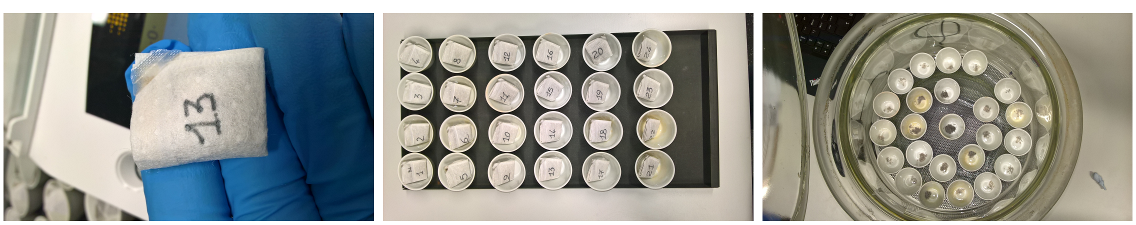

Figure 2.20: Clocaenog forest. Ash calculation after forage fibre analysis, from left: observation is folded and sealed before ashing; observations ready for ashing; observations ready for weighing after ashing: from batch n. 2 of the Ankom procedure. Outer circle crucibles contain observations from the L horizon of UN treatment. Inner circle crucibles contain observations from soil F horizon of CCF treatment. Note that ash is visibly more abundant in the F (CCF) horizon.

Methods for determining NDF, ADF, ADL and ash are described in chapter 2.2.2.4. Proximate C pools calculations were identical to the ones used for the Forest of Ae (see chapter 2.2.2.7).

2.2.5.4 Statistical analysis

Statistical analysis on continuous variables was carried out in a similar way as for the C quantity chapter (see chapter 2.2.1.3 and model (2.4)).

Chapter 3

Forest management impacts on soil C quantity

3.1 Introduction

3.1.1 Soil C stocks

Soil is formed from a combination of mineral weathering and organic matter decomposition, thus all soils contain C. Soil stores a large quantity of C as a result of long-term inputs derived from forest photosynthetic activity (Clarke et al. 2015; Paul 2016). Besides storing almost 75% of the UK total forest C stock (Forestry Commission 2018) soils also affect biodiversity, ecosystem dynamics, biofuels, fresh water quality, water infiltration and erosion (Paul 2016). Hence, the storage of soil C is a fundamental ecosystem service and it plays a pivotal role in climate change regulation and soil fertility. Despite this, there are strong unknowns with regards to the factors that control the storage of soil C at regional and national scale (Manning et al. 2015). Hence, an in-depth understanding of the dynamics of forest soil C

Table 3.1: Soil C stock contribution of the litter and fragmented organic surface horizons in Scotland, England and Wales (Vanguelova et al. 2013).

	Tg C			%
	forest soil C stock	Conifer soil C stock		Overall soil C contribution
Country	Combined L and F	L	F	Combined L and F
Scotland	21	7.8	9.5	9.4
England	17	2.8	3.4	8.0
Wales	4	1.2	1.5	5.9

storage is becoming more and more essential for predicting variations in ecosystem goods and services such as water resources, forest products and greenhouse gas mitigation (Nave et al. 2010).

Within Britain the BioSoil survey evaluated the forest soil C stock down to 80 cm depth in between 108 and 448 Mg ha^{-1} on average, with soil type and depth, tree species and stand being the main source of variability (Vanguelova et al. 2013). Some soils contain more C than others, so research to determine how management can increase soil C storage is necessary to provide managers with guidance on how to use soils to combat climate breakdown. Deep peats store the most soil C, followed by peaty gleys, ironpans and podzols, brown earths, rankers and rendzinas (Kennedy 2002); conifer forests store more soil C on average compared to broadleaf forests. On average, peaty gley soils are the greatest contributors to soil C stock in Scotland in conifer forests (58.7%), while in England these are brown earths and peaty-gleys/podzol (27 and 24% respectively) (Vanguelova et al. 2013). In Wales, podzols and brown earths predominate in soil C stock contribution in coniferous forests (34 and 23% respectively). Within the OSH, the L and F horizons hold 7.3 and 8.8 Mg ha^{-1} on average respectively, and these contribute towards 21, 17 and 4 Tg C stock accumulation in Scotland, England and Wales respectively (Vanguelova et al. 2013), (see table 3.1).

Overall, the total forest soil C stock (including the OSH) in Great Britain is estimated in

664 Tg within the first meter of soil depth (Vanguelova et al. 2013).

Forest managers are often faced with the dilemma of having to preserve SOM or to use it; the greenhouse effect is mitigated through soil C stabilization, but the productivity of soil is enhanced by OM decomposition resulting from microbial metabolism. Thus, the ultimate goal is to strike a balance in between achieving soil C storage and providing high quality timber materials and products. Forest productivity may significantly affect the climate change mitigation potential of the soil C pool. Harvesting causes the removal of biomass by disturbing the soil and altering the microclimate, affecting plant and microbial processes (Nave et al. 2010; Muller and Linhares-Juvenal 2016).

Following replanting, SOC balance can easily become negative depending on the amount of above ground biomass removed during the harvesting operation, but also on the harvesting method adopted. For example, clearfell operations can potentially exacerbate soil C mineralization and decomposition, thus affecting the soil C stock (Jandl et al. 2007). Management practices could modify the C balance of a forest over long periods of time by affecting the standing biomass and the way SOC is released into the atmosphere (Lundmark et al. 2016).

C fluxes and SOC stocks are affected by a series of factors that occur as a consequence of harvesting activities (Clarke et al. 2015). For example, practices which remove additional forest biomass reduce the input of C to the soil. In forest harvesting operations this could also result in increasing heterotrophic respiration due to fine and coarse roots mortality (Covington 1981; Clarke et al. 2015). More intensive management practices can lead to reduced forest productivity; this could also apply to thinning operations, particularly in the case of high nutrients removal resulting from the harvested biomass (Mason et al. 2012; Clarke et al. 2015; Wilkinson et al. 2016). Biomass decomposition and DOC leaching could be exacerbated by the intensity of the harvesting operations as a consequence of the intensity of ground disturbance and depending on temperature, rainfall and soil moisture. Soil water table might be affected by the harvesting activities and could potentially modify the amount of leaching and either decrease or increase decomposition. SOM could be affected by forest ground preparation resulting in soil mixing or compaction, increasing or decreasing the speed of decomposition respectively.

Research found that managed forest stands hold a lower total ecosystem C stock when compared to unmanaged forests. For some forests, management practices do not affect the ecosystem C stock at all, whereas when such differences are evident, often there is a greater biomass (live tree) contribution to the total C pool (Powers et al. 2011; Puhlick et al. 2016). According to results from a meta-study on temperate forests (Nave et al. 2010) harvesting activities significantly lower soil C by 8 % on average, with more pronounced losses from the OSH when compared to mineral soils. These in particular affect C pools in terms of size and C concentration. Losses of 30 % on average in C stock are reported from the OSH, these being higher for broadleaves than coniferous or mixed forests (-36%, -20% and -20% respectively).

While time since harvesting is an important variable to take into account when measuring the soil C stock change, the effect of residue management on soil C is less clear. CH usually leads to higher soil C stock within the short term (up to ten years, +6.3%) when compared with WTH ($p < 0.01$) (Wan et al. 2018) although this may be explained by the residue left on site at the time of harvesting. Long-term dynamics may be more related to soil biogeochemistry variables such as microbial quantity and diversity, C concentration, pH and biomass development.

In light of the mentioned research gaps and uncertainties, the objective of the present study is to understand the effects of forest management practices (conventional clearfell, whole-tree harvesting, fertilization and in transition to continuous-cover forestry, see chapter 1.2 for an introduction on the treatments) on the soil C storage potential, the soil water and C concentration and soil bulk density of forest soil OSH and organo-mineral horizons in upland Britain.

3.2 Results

Please refer to chapter 2.2.1.3 for a description of the statistical methods utlised in this chapter.

3.2.1 Clearfell experiment: Forest of Ae

Estimated marginal means for mixed effect model show that the CHF treatment holds significantly more C stock than WTH and CH ($p < 0.01$) in the L horizon (see table 3.2). Both the CHF and CH treatments hold significantly more C stock than WTH in the F horizons ($p = 0.03$ and $p = 0.01$ respectively).

The only significant differences in C concentration (%) are found in the L horizon, where the WTH treatment is significantly higher than both CHF ($p < 0.01$) and CH ($p = 0.01$). C% in the CH treatment for the L horizon is significantly higher than CHF ($p = 0.01$).

CHF and CH both have a significantly thicker F horizon when compared to WTH ($p = 0.01$ and $p = 0.02$ respectively).

Contrasts between EEM of the treatments are shown in figures 3.6. Refer to figures 3.1 to 3.5 for visual data interpretation.

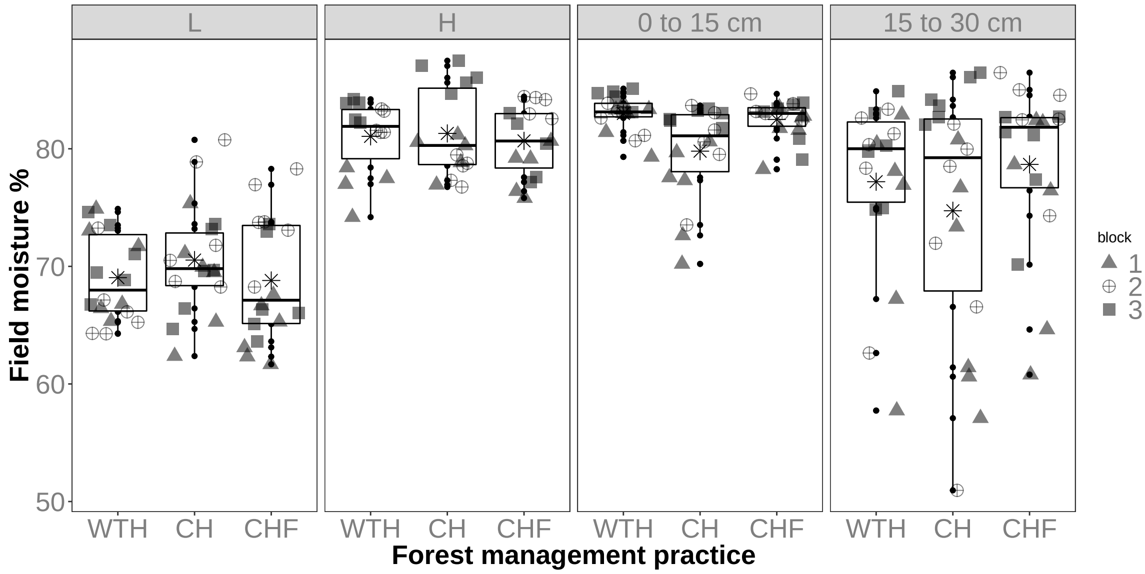

Figure 3.1: Forest of Ae - boxplot of soil field moisture content (%) by management practice. L, H, 0 to 15 cm and 15 to 30 cm are soil horizons (L,H) and layers. H horizon was extracted from pits used in the fine roots experiment, five per plot. Black dots refer to observations that may be outliers according to the rule ± 1.5 * interquartile range (Kabacoff 2015). Shape refers to block replication. Dots are randomly located on the x axis within the boxplot to improve visibility. Asterisk symbols are mean values.

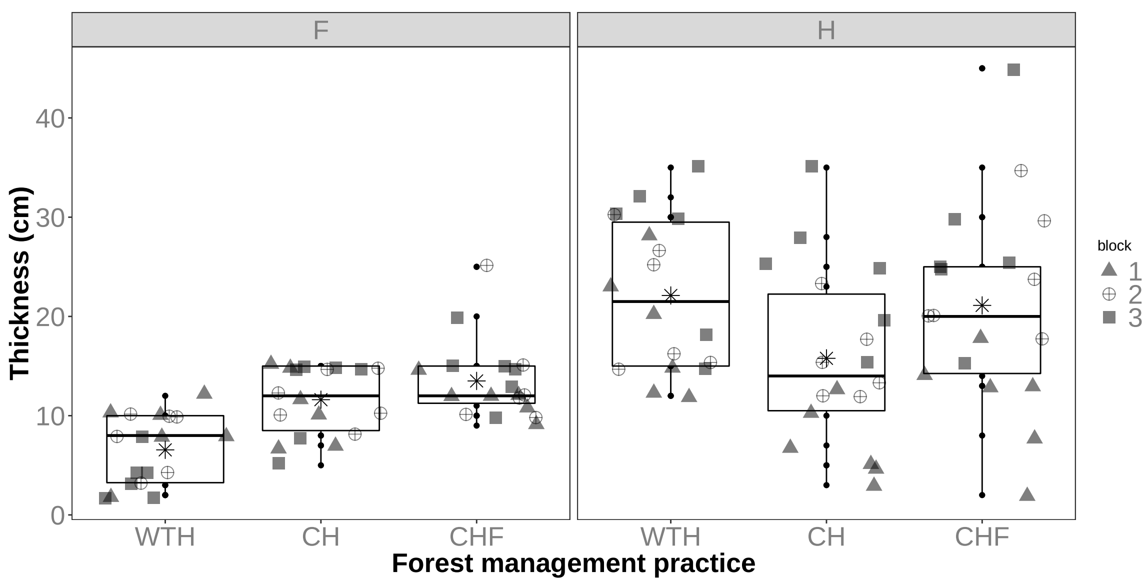

Figure 3.2: Forest of Ae - boxplot of soil horizon thickness (cm) by management practice. F and H are soil horizons. Shape refers to block replication. Asterisk symbols are mean values.

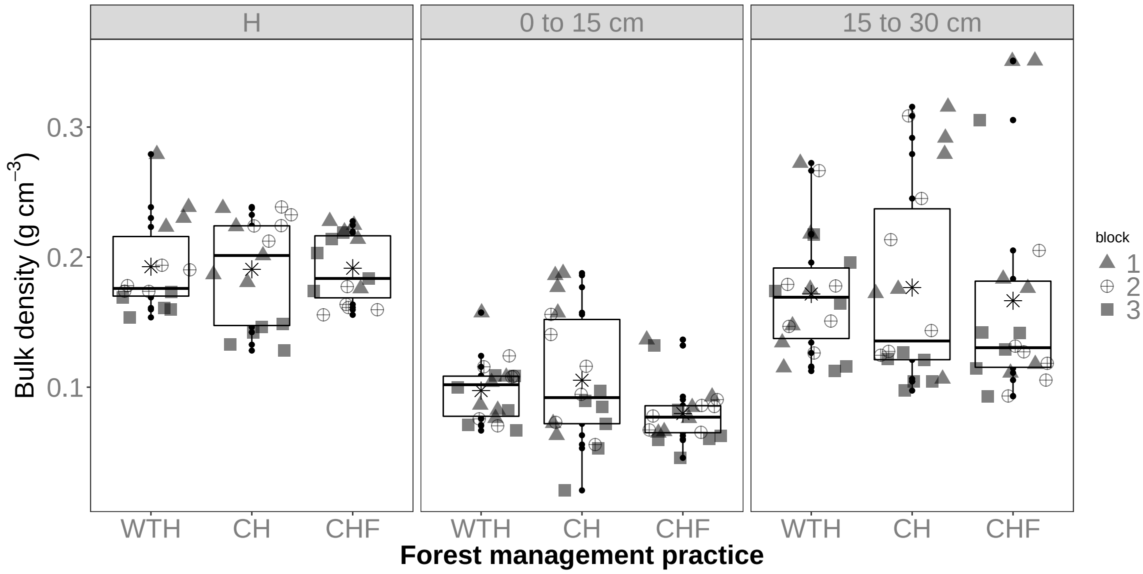

Figure 3.3: Forest of Ae - boxplot of soil bulk density (g cm^{-3}) by management practice. Soil H horizon (cylinders), 0-15 cm and 15-30 cm depth. Shape refers to block replication. Asterisk symbols are mean values.

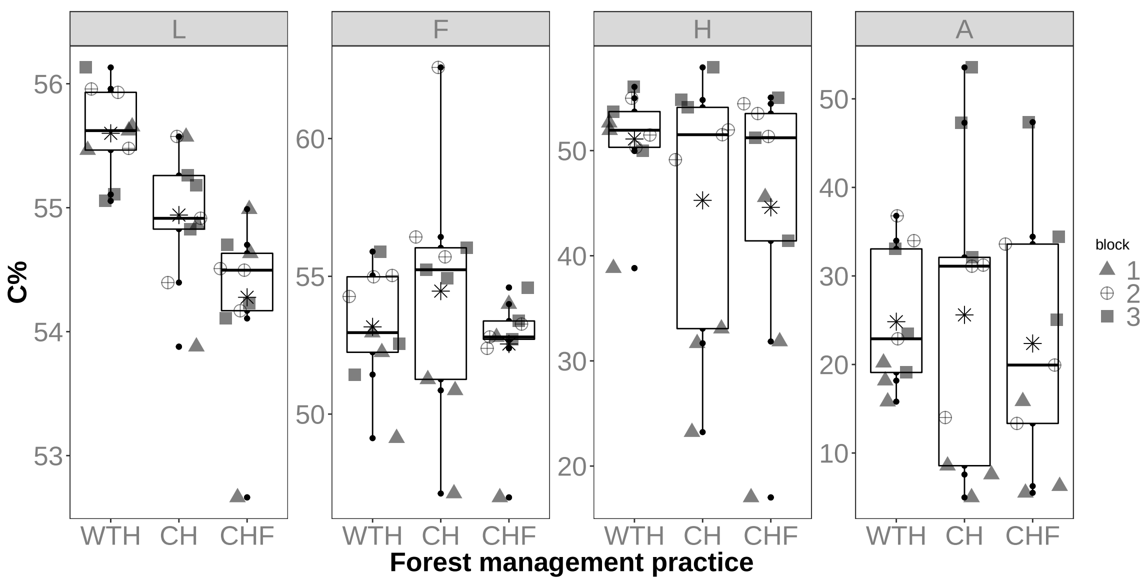

Figure 3.4: Forest of Ae - boxplot of soil C concentration (%) by management practice. L, F, H and A are soil horizons. Shape refers to block replication. Asterisk symbols are mean values. Individuals were bulked into couples, from six to three per block replication during the STSM (see chapter 2.2.2).

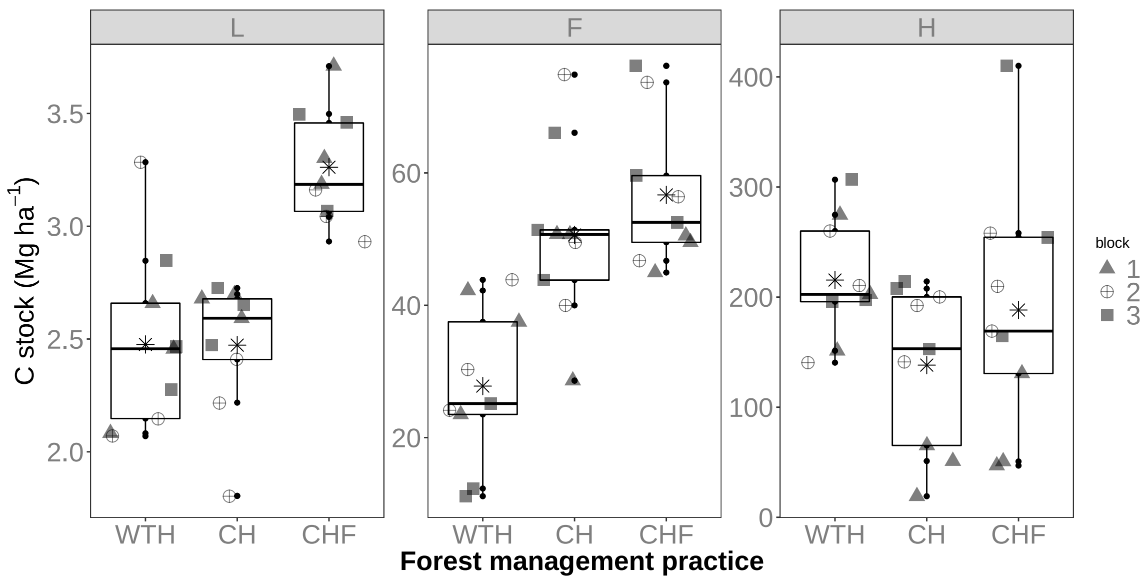

Figure 3.5: Forest of Ae - boxplot of soil C stock (Mg ha^{-1}) by management practice. L, F and H are soil horizons. Shape refers to block replication. Asterisk symbols are mean values. Individuals were bulked into couples, from six to three per block replication.

Table 3.2: Forest of Ae - Pairwise comparisons among estimated marginal means of the treatments for C stock, C concentration, soil field moisture, depth and Bd in the L, F, H, A horizons, the 0-15 and 15-30cm soil depth layers. p-value adjustment: Tukey method for comparing a family of 3 estimates. Degrees-of-freedom method: Kenward-Roger.

var	hor	contrast	estimate	SE	t.ratio	p.value	sign
C stock	L	CH - CHF	-0.79	0.13	-5.87	**9.23e-03**	*
		CH - WTH	-0.00	0.13	-0.02	1.00	
		CHF - WTH	0.79	0.13	5.85	**9.35e-03**	*
	F	CH - CHF	-6.05	6.62	-0.91	0.65	
		CH - WTH	22.84	6.62	3.45	**0.03**	*
		CHF - WTH	28.89	6.62	4.36	**0.01**	*
	H	CH - CHF	-50.04	41.38	-1.21	0.51	
		CH - WTH	-77.26	41.38	-1.87	0.26	
		CHF - WTH	-27.23	41.38	-0.66	0.80	
C concentration	L	CH - CHF	0.66	0.12	5.56	**0.01**	*
		CH - WTH	-0.66	0.12	-5.53	**0.01**	*
		CHF - WTH	-1.32	0.12	-11.08	**8.40e-04**	*
	F	CH - CHF	1.92	1.51	1.27	0.48	
		CH - WTH	1.30	1.51	0.86	0.69	
		CHF - WTH	-0.62	1.51	-0.41	0.91	
	H	CH - CHF	0.67	5.01	0.13	0.99	
		CH - WTH	-5.83	5.01	-1.16	0.53	
		CHF - WTH	-6.50	5.01	-1.30	0.47	
	A	CH - CHF	3.23	6.77	0.48	0.89	
		CH - WTH	0.77	6.77	0.11	0.99	
		CHF - WTH	-2.46	6.77	-0.36	0.93	
Field moisture	L	CH - CHF	1.74	2.71	0.64	0.80	
		CH - WTH	1.49	2.71	0.55	0.85	
		CHF - WTH	-0.24	2.71	-0.09	1.00	
	0-15cm	CH - CHF	-2.69	1.35	-1.99	0.23	
		CH - WTH	-3.21	1.35	-2.37	0.16	
		CHF - WTH	-0.51	1.35	-0.38	0.93	
	15-30cm	CH - CHF	-3.94	3.49	-1.13	0.55	
		CH - WTH	-2.47	3.49	-0.71	0.77	
		CHF - WTH	1.47	3.49	0.42	0.91	
Bulk density	0-15cm	CH - CHF	0.03	0.01	1.86	0.26	
		CH - WTH	0.01	0.01	0.58	0.84	
		CHF - WTH	-0.02	0.01	-1.28	0.47	
	15-30cm	CH - CHF	0.01	0.03	0.36	0.93	
		CH - WTH	0.00	0.03	0.18	0.98	
		CHF - WTH	-0.01	0.03	-0.19	0.98	
Thickness	F	CH - CHF	-1.89	1.36	-1.39	0.40	
		CH - WTH	5.06	1.36	3.73	**0.02**	*
		CHF - WTH	6.94	1.36	5.12	**5.21e-03**	*
	H	CH - CHF	-5.33	2.58	-2.06	0.21	
		CH - WTH	-6.33	2.58	-2.45	0.14	
		CHF - WTH	-1.00	2.58	-0.39	0.92	

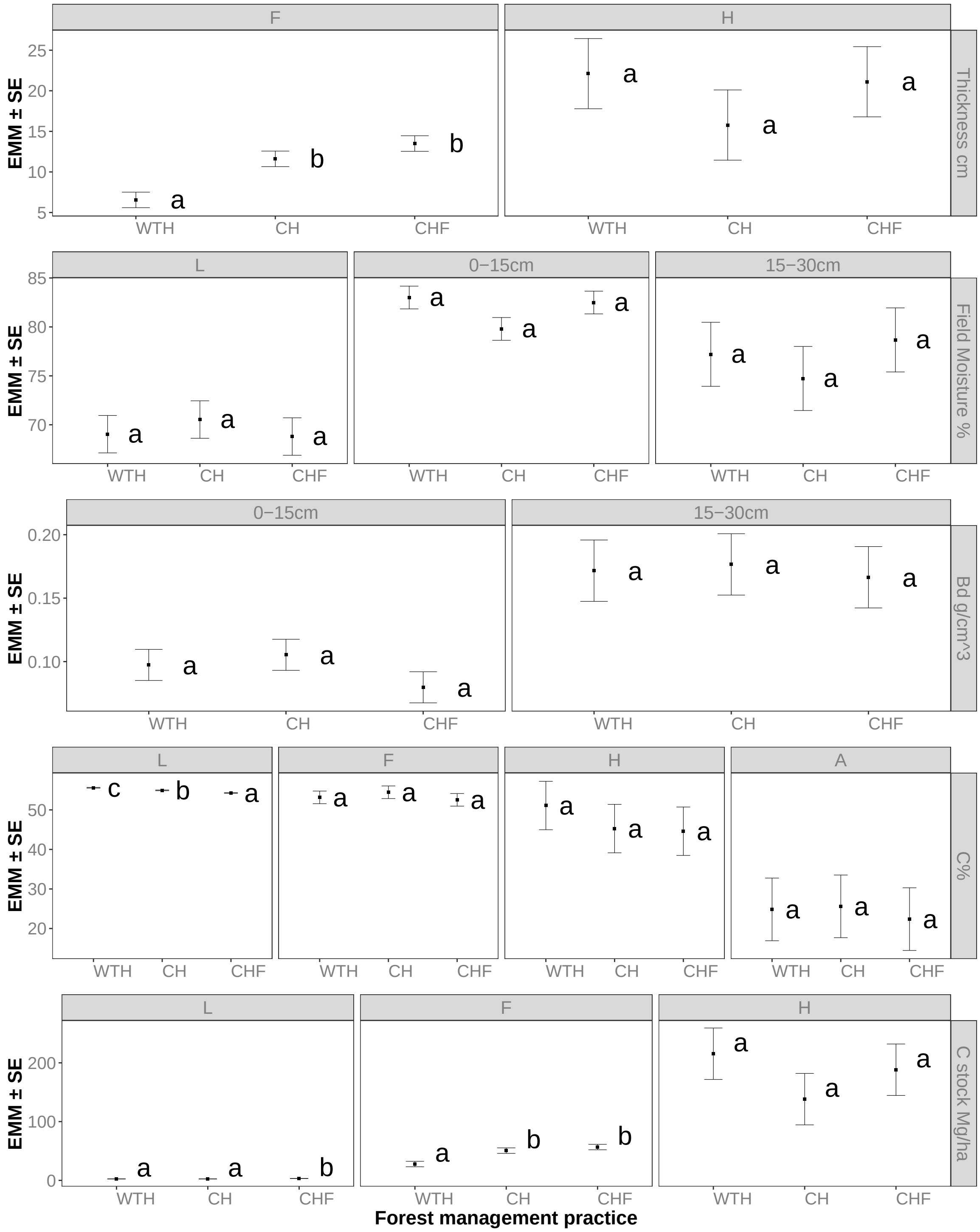

Figure 3.6: Forest of Ae - Estimated marginal means by management practice. Boxes indicate the estimated marginal means. Error bars are estimated marginal mean +/- SE. Means sharing a letter are not significantly different (Tukey-adjusted comparisons).

3.2.2 Continuous-Cover-Forestry trial: Clocaenog

Estimated marginal means for mixed effect model show that the CCF treatment has significantly more C stock in the H horizon when compared to the UN treatment ($p < 0.01$, see table 3.3). A significantly higher Bd was detected in the F horizon of the UN treatment compared to CCF ($p < 0.01$). The H horizon ($p < 0.01$) was significantly thicker in the CCF compared to UN treatment.

Data can be found in the Appendix (tables 6.12, 6.13, 6.14, 6.15). Contrasts between EEM of the treatments are shown in figure 3.12. Refer to figures 3.7 to 3.11 for visual data interpretation.

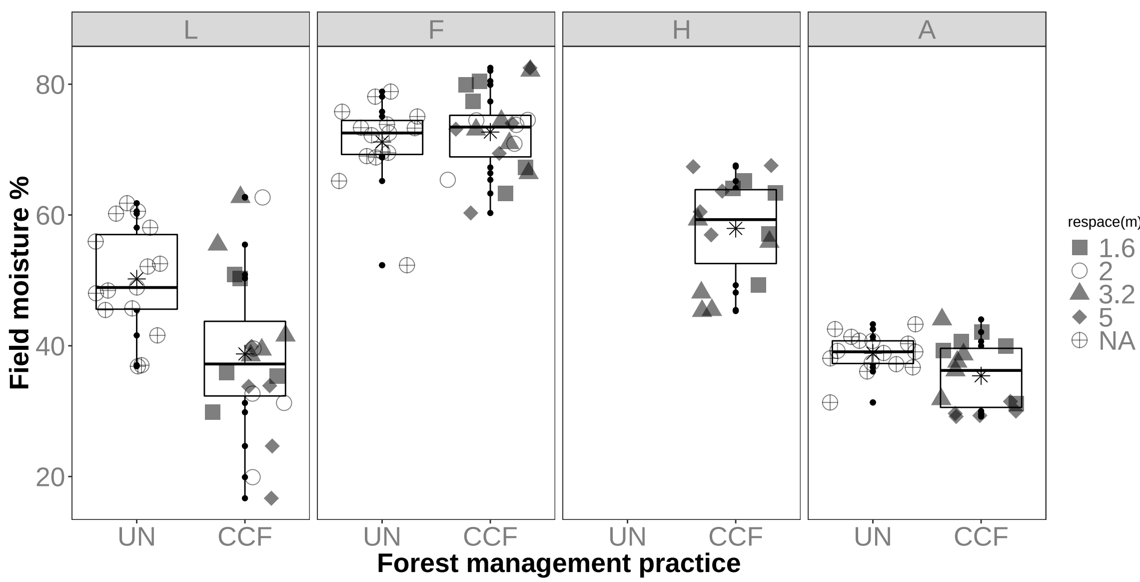

Figure 3.7: Clocaenog Forest - boxplot of soil field moisture (%) by management practice. L,F,H and A are soil horizons. Same shape is same respacing (random variable, m distance between regeneration trees after respacing). Dots are randomly located on the x axis within the boxplot to improve visibility. Asterisk symbols are mean values.

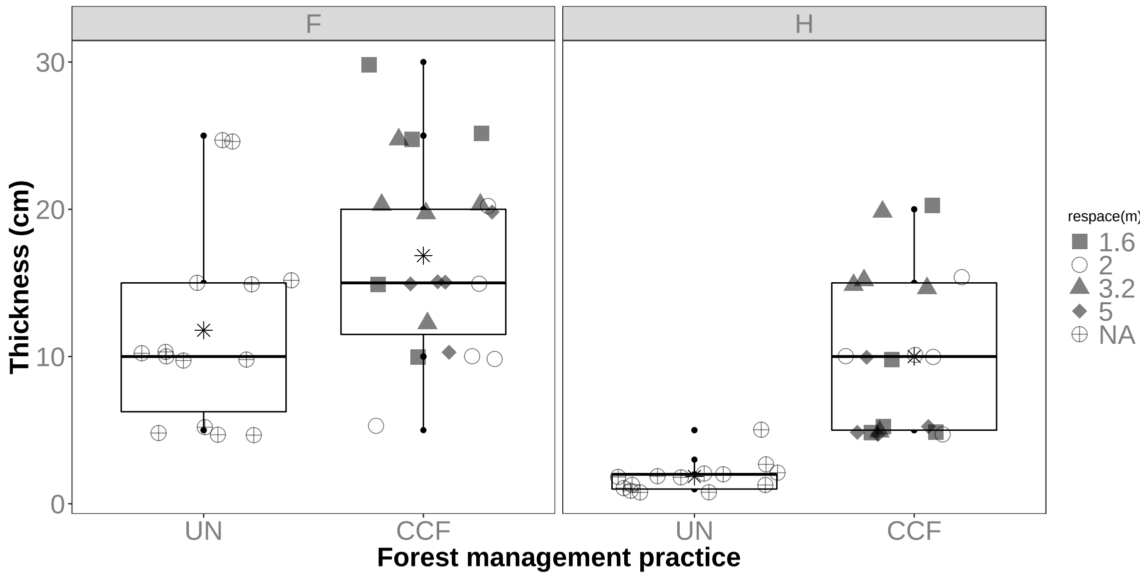

Figure 3.8: Clocaenog Forest - boxplot of soil horizon thickness (cm) by management practice. F and H are soil horizons. Shape refers to respacing (random variable). Asterisk symbols are mean values.

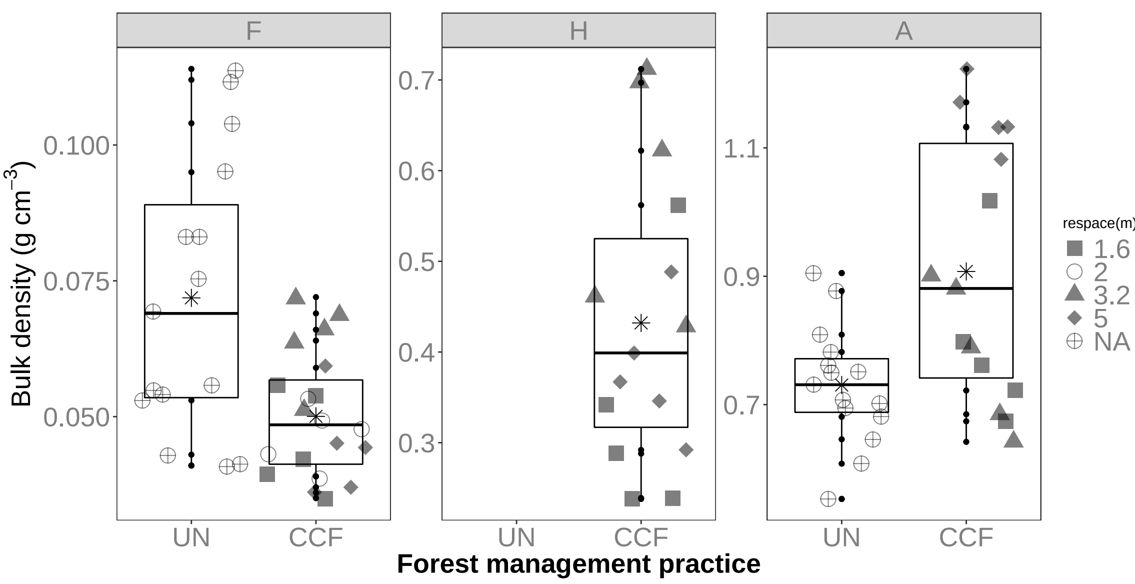

Figure 3.9: Clocaenog Forest - boxplot of soil bulk density (g cm^{-3}) by management practice. F,H and A are soil horizons. Shape refers to respacing (random variable). Asterisk symbols are mean values.

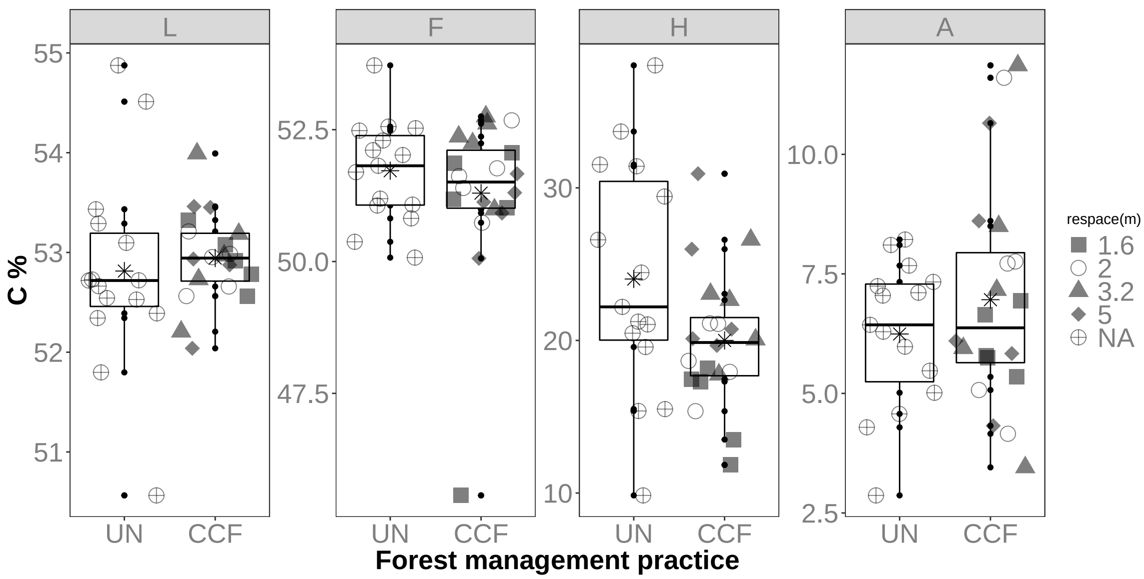

Figure 3.10: Clocaenog Forest - boxplot of soil C concentration (%) by management practice. L,F,H and A are soil horizons. Shape refers to respacing (random variable). Asterisk symbols are mean values.

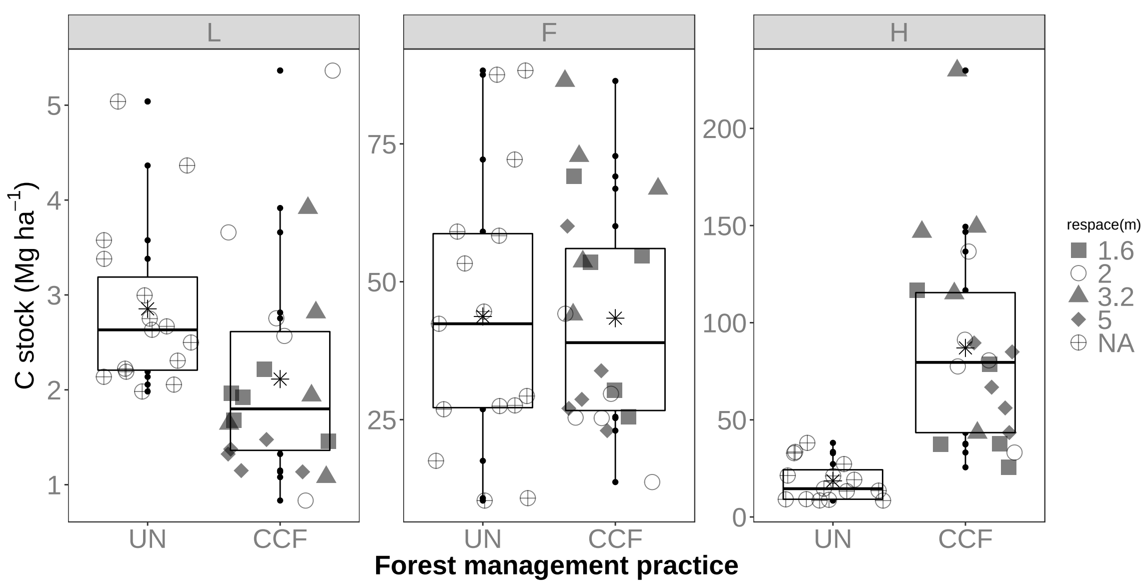

Figure 3.11: Clocaenog Forest - boxplot of soil C stock (Mg ha^{-1}) by management practice. L,F and H are soil horizons. Shape refers to respacing (random variable). Asterisk symbols are mean values.

Table 3.3: Clocaenog Forest. Pairwise comparisons among estimated marginal means of the treatments for C stock, C concentration, soil field moisture, depth and Bd in the L, F, H, A horizons. p-value adjustment: Tukey method. Degrees-of-freedom method: Kenward-Roger. `glmer` model: `emmeans` labels asymptotic results (estimates tested against the standard normal distribution – z tests – rather than the t distribution) as df = 'Inf' (Lenth 2018).

var	hor	contrast	estimate	SE	z.ratio	t.ratio	p.value	sign
C stock	L	UN - CCF	0.69	0.49	1.42	NA	0.15	
	F	UN - CCF	-0.09	0.97	NA	-0.10	0.93	
	H	UN - CCF	-67.28	17.06	-3.94	NA	**8.01e-05**	*
C concentration	L	UN - CCF	-0.13	0.25	-0.53	NA	0.60	
	F	UN - CCF	0.43	0.59	0.73	NA	0.47	
	H	UN - CCF	4.04	2.65	1.53	NA	0.13	
	A	UN - CCF	-0.72	0.66	-1.08	NA	0.28	
Field moisture	L	UN - CCF	11.47	7.17	NA	1.60	0.17	
	F	UN - CCF	-1.51	2.13	-0.71	NA	0.48	
	A	UN - CCF	3.11	3.26	0.95	NA	0.34	
Bulk density	F	UN - CCF	0.02	0.01	3.09	NA	**2.00e-03**	*
	A	UN - CCF	-0.20	0.14	-1.43	NA	0.15	
Thickness	F	UN - CCF	-0.18	0.08	NA	-2.27	0.24	
	H	UN - CCF	-7.88	1.74	-4.52	NA	**6.22e-06**	*

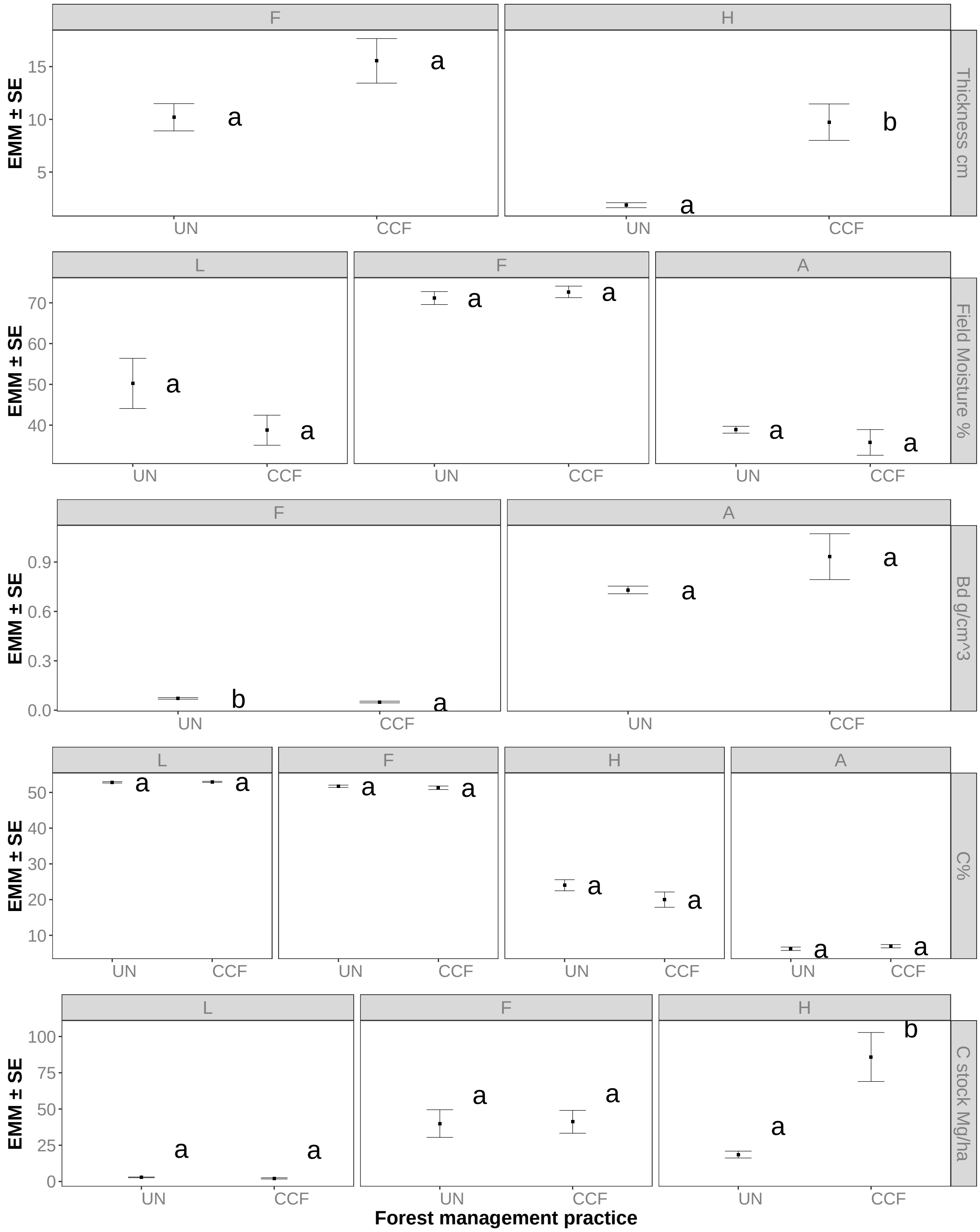

Figure 3.12: Clocaenog trial - Estimated marginal means by management practice. Boxes indicate the estimated marginal means. Error bars are estimated marginal mean +/- SE. Means sharing a letter are not significantly different (Tukey-adjusted comparisons).

3.3 Discussion

3.3.1 Clearfell experiment: Forest of Ae

Utilising the experimental settings at the Forest of Ae and Clocaenog forest limited the effect of influencing variables (climate, temperature, soil type, aspect, acclivity, tree species and age) which were assumed to remain constant. Hence only intra-site comparison between forest management practices were made. This allowed for a robust statistical evaluation of differences between treatments effect of the forest brash, above-ground litter deposition, tree nutrient uptake and fertilization practices[1]. This approach is fundamental to understanding the importance of site, geology, soil and forest management practices in relation to the environmental benefits and availability of biomass production (Vanguelova et al. 2010).

3.3.1.1 Soil field moisture and bulk density

Soil C and N stock can be significantly improved as a consequence of water retention in the organic soil horizons (Vanguelova et al. 2010). In the present experiment, soil field moisture content does not differ between the treatments in any of the horizons or layers under study. This is in contrast with results from Vanguelova et al. (2010) where WTH had significantly higher moisture content in the H horizon.

The bulk density in the H horizon at the Forest of Ae is slightly below average values of the UK Biosoil survey which analysed 66 peaty gley soil plots (cambic stagnohumic gley soils: World Reference Base soil classification: Histic Gleysols (IUSS Working Group WRB 2015)); Results from Vanguelova et al. (2013) highlight a depth-related increase in bulk density within the mineral horizon (from 0.28 to 0.71 g cm^3); results from the present study

[1]Fertilization at the Forest of Ae only

(just below 0.20 g cm^3 on average for all treatments in the H horizon) extend this trend to the H horizon, further confirming the increase in Bd with increased depth in the soil profile.

3.3.1.2 Soil carbon concentration and stocks

Forest ecosystems of the northern temperate climatic zones hold a considerable amount of C below-ground (see chapter 1.1) both as SOM and living biomass.

Analysis of data for soil C concentration (%) highlight significant differences within the L horizon between all of the treatments. WTH held the highest C concentration, followed by CH and CHF; this was in contrast with findings from C stock (see chapter 3.2.2). No difference was found in the F, H and A horizons. The meta-analysis from Johnson and Curtis (2001) found that WTH on average reduces the total soil C concentration in the mineral A horizon by about 6%, while CH increases it by 18% compared to the Control, with differences mainly found in conifer species. This is not reflected in the results at the Forest of Ae, but the WTH treatment included floor removal in the meta-analysis which may have accentuated such differences.

In a recent meta-analysis, with sites mostly based on temperate to cold climate, Achat et al. (2015) found that brash removal significantly affected SOM stock and concentrations, with significant losses from the forest floor amounting from 10% (C stock, WTH) to 45% (more intense bioharvesting). Stock of organic matter in the forest floor decreased with increasing harvest intensity. This is reflected in the present study, where C stock in the L horizon was significantly higher in the CHF treatment compared to the other treatments, while in the F horizons CH and CHF have significantly more C stock than the WTH treatment.

Achat et al. (2015) also found that soil C concentrations decreased significantly (3%) in the forest floor for WTH compared to CH. Differences were more evident in sites with temperate climate. Belanger et al. (2003) found significantly lower organic C concentration in the forest floor three years after WTH on an upland *Picea mariana* stand (Black spruce) compared to CH. In the present study C concentrations in the L horizon had an opposite behaviour (CHF, CH, WTH from the lowest) and were all significantly different between treatments. This suggests that while the L horizon has a limited C contribution in absolute terms, fertilization and brash removal after harvesting may affect the C concentration of relatively fresh fallen leaves, stems, bark, needles and twigs. These findings may be related to a lower C allocation (%) of the CHF treatment to needles and twigs determined by an efficient use of nutrients and C resources to build a higher above-ground C stock[2], although further evidence is needed to confirm these dynamics.

Results from the experiment at the Forest of Ae confirm the potential negative effects of WTH on the C stock, hence atmospheric C sequestration of the L and F horizons as highlighted in the review by Clarke et al. (2015). In the present study the WTH treatment C stock was significantly lower than CHF in the L horizon ($p < 0.01$) and significantly lower than CH and CHF in the F horizon ($p < 0.05$) suggesting that brash left on site at the time of harvesting contributes to C storage more than 20 years after planting. On the other hand, and of high importance to the preservation of most of the C store in peaty soils, was that in the WTH treatment the average C stock in the H horizon[3] was higher when compared to CH and CHF, this difference being non-significant.

While differences in C stock within the H horizon were not significant the higher C stock in the H horizon for the WTH treatment may be associated with priming effect (increased

[2]Above-ground biomass was higher in the CHF and CH treatments compared to WTH (Mason et al. 2012).

[3]The H horizon is by far the horizon that holds the most C stock.

Table 3.4: Forest of Ae. C stock of the OSH by management practice.

			Mg/ha
forest	managem	hor	C stock
	WTH	L	2.48
Ae	CH	L	2.47
	CHF	L	3.26
	WTH	F	27.79
Ae	CH	F	50.62
	CHF	F	56.68
	WTH	H	215.48
Ae	CH	H	138.22
	CHF	H	188.26
	WTH	Total	245.75
Ae	CH	Total	191.32
	CHF	Total	248.19

decomposition of old SOM) caused by brash retention (Wan et al. 2018) and in the case of the present study fertilization practices.

Since degradable substrates increase SOM decomposition (Marschner et al. 2008) substrate limitations of soil microorganisms in WTH treatments may have caused the higher (albeit not significantly) retention of C in the H horizon. This suggests that future activities should be directed towards an assessment of microbial activities, specifically respiration rates, to understand if these dynamics are reflected in the soil organic horizons to better understand the dynamics of C storage.

Another important aspect to consider is that the C stock was affected by the dynamics of C storage in block replication one for treatments CH and CHF (see figure 3.5). Hence, the spatial variability of soil may as well be the most plausible answer to the (non-significant) differences in the H horizon soil C stock between the treatments.

Considering 0.6318 10^6 ha conifer cover on peaty soils in Britain (Vanguelova et al. 2013), projecting average values of C stock from the experiment at the Forest of Ae would result in approximately 0.498 and 0.496 Tg more C stored in the L horizon and sequestered from the atmosphere if the CHF treatment were to be adopted in place of the CH or WTH treatments respectively[4]. These estimates assume all the 0.6318 10^6 ha covered by the treatments. (see table 3.4 with average C sock ha^{-1}). Using the same approach, the benefits in terms of C atmospheric sequestration in the F horizon would be 18.25 and 14.43 Tg when adopting CHF and CH silviculture respectively in place of WTH.

This confirms findings from Nave et al. (2010) suggesting that following harvesting activities significant amount of C stocks can be lost from the forest floor. Nave et al. (2010) meta-analysis considered Control treatments with stand age ranging from 30 years to well over 100 years; Since at the Forest of Ae planting took place in the late 1990s, the present study extends such dynamics to just over twenty years from planting.

While Norway spruce boreal stands subject to CH lead to up to 22 % losses in total C stocks for the organic and mineral layers combined, 15 years after harvesting, the loss was all located in the organic layer, while the mineral C stock was unvaried or increased (Olsson et al. 1996). For this reason, soil type and tree species should be considered in guidelines for forest management. In addition, mixed and coniferous forests have lower decomposition rates within the OSH when compared to broadleaves and are therefore thought to be more recalcitrant (Nave et al. 2010). This highlights the importance of studying the C storage potential within the soil OSH of conifer plantations in upland Britain.

While the Gartzia-Bengoetxea et al. (2009) study focussed on clearfell and forest floor removal combined, therefore more intense bioharvesting when compared to WTH, the study found that on a *Pinus radiata* chronosequence the forest floor was still missing three years after establishment. Even after 16 years this was still approximately half the mass when

[4]Results are approximations due to the uncertainties associated with forest cover, the distribution of peaty soil as well as the depth of the horizons under study. Further analysis of the uncertainties and variabilities associated with the above values will need to be carried out to validate these results.

compared to the mature stand. This is attributable to the reduced litter input and quicker decomposition after harvesting. Similar dynamics may be ongoing at the Forest of Ae given the significantly lower C stock in the F horizon of the WTH treatment compared to CH. Findings from the present study in the F horizon contrast with results from Vanguelova et al. (2010) at Kielder forest on a second rotation, 28 year-old Sitka spruce plantation on peaty-gley soil. Vanguelova et al. (2010) found that soil F horizon C stocks in WTH, CH and CHF were not significantly different. The same study found significantly different C stock in the H horizon between all treatments, with WTH having the highest C stock, followed by CHF and CH. While the same pattern is reflected in the present study, differences are not significant. Vanguelova et al. (2010) suggested that WTH on highly organic soils can significantly improve the soil C and N stock when compared to CH and CHF as a consequence of lower rate of mineralisation and increased water retention in the organic soil horizons. Brash retention was claimed to be the reason for increased mineralization of soil N and C stock on organic soil. Research at Beddgelert Forest (Wales) conducted in the early 1980s compared second rotation Sitka spruce under whole-tree harvesting (WTH) and conventional harvesting (CH) management practices (Walmsley et al. 2009). While the results did not provide significant evidence, tendency of higher soil organic matter content in the O horizon of the WTH treatment was found in three out of the four blocks under study, which is in line with results from the present study and Vanguelova et al. (2010).

Saarsalmi et al. (2010) found some evidence (at one of two sites) of significantly lower organic C in WTH compared to CH in the soil organic layer of a Scots pine plantation.

The soil C stock from the OSH measured at the Forest of Ae essentially agrees with recent findings. Vanguelova et al. (2019) study was based on a 100 year Sitka spruce chronosequence on peaty-gley soils in the north of England. This found that the L horizon

C stock on a 10 to 15 degree slope varies between 2.5 and 7.5 Mg ha^{-1}. Soil C stock in WTH and CH in the present study are on the lower edge of this range; all of the treatments fall below the 95 % confidence interval highlighted in Vanguelova et al. (2019). Within the F horizon, the same study provided lines of best fit to compare the first and second rotation of Sitka spruce in terms of C stock accumulation. This was claimed to be affected by both rotation and time since afforestation. Results from the Forest of Ae suggest that while the WTH treatment is in line with results for C stock accumulation on a second rotation Sitka spruce provided in Vanguelova et al. (2019), results from the CH and CHF treatments are even higher than the upper 95 % confidence interval of the > 30 year-old first rotation. This suggests a much more significant effect of management practice (specifically brash retention and fertilization) when compared to rotation and time since afforestation. It additionally provides relevant evidence to studies which focus on forest management as a way to tackle climate change by lowering atmospheric CO_2 emissions. Finally, H horizon results are in line with typical C stock accumulation for similar site elevations, with average values from the WTH and CHF treatments falling within the 95 % confidence interval highlighted in Vanguelova et al. (2019).

Wan et al. (2018) meta-analysis of studies on mineral soils only found significantly higher C stocks in the CH treatments compared with WTH for both broadleaves and conifers. The study attributed this to the effects of brash left on site at the time of harvesting in the CH treatment. Similar dynamics may be ongoing at the experimental site at the Forest of Ae. This being the case, it would confirm the trend of soil C stock depletion in more intense bioharvesting practices such as WTH. Research should be extended to the soil mineral horizons to confirm this and to follow the likely vertical translocation of C.

3.3.2 Continuous-Cover-Forestry trial: Clocaenog

3.3.2.1 Soil field moisture and bulk density

The experiment took place after a week of dry and sunny weather. Results from soil field moisture highlight that while the field moisture content was lower on average for the CCF treatment in the L horizon (see figure 3.7), this was not significant. In any case, median values of field moisture content in the L horizon for the UN treatment are around 50%, while for CCF this is down to about 40%. The evident diversity in canopy structure highlighted in figure 2.4 (which is likely to have an impact on the canopy water interception and to increase evapotranspirations losses) resulted in lower water content within the uppermost CCF horizon which may have affected the turnover of C in this horizon. The SOM turnover may also have been affected by higher temperature on the ground (Jandl et al. 2007) resulting from large openings within the CCF treatment.

Bulk density was significantly higher in the F horizon of the UN treatment compared to the CCF treatment. The causes of this are not clear, particularly considering the thinning activities in the CCF treatment over the last fifteen years (see chapter 2.1.2) as opposed to the UN treatment, which were thought to increase Bd values in the CCF treatment (Basal area is 58 and 26 for UN and CCF respectively, refer to table 2.2). At the same time, water content which was found to be negatively related to bulk density (Benham et al. 2012; Vanguelova et al. 2013) was not different between treatments in the F horizon. H horizon Bd for the UN treatment is not available, but while not significant the CCF treatment has higher mean and median values of Bd in the A horizon (> 0.8 g cm^3) when compared to the UN (> 0.7 g cm^3) although this could be attributed to thinning and grazing.

Table 3.5: Clocaenog forest. Mean and SD of C concentration by management practice and horizon. managem: forest management practice; hor: soil horizon.

managem	hor	C concentration	SD
UN	L	52.813	1.018
CCF	L	52.944	0.443
UN	F	51.721	0.963
CCF	F	51.296	1.526
UN	H	24.025	7.733
CCF	H	20.000	4.451
UN	A	6.243	1.540
CCF	A	6.960	2.349

3.3.2.2 Soil carbon concentration and stocks

The average C concentration of the soil H horizon is just above minimum levels to be classified as an organic horizon (Zanella et al. 2011) (table 3.5). According to the 20% C concentration rule, the 1.6 m distance between regeneration trees after respacing sub-plot of the CCF treatment as a whole (and on average also the 2 m respacing subplot) would more appropriately be classified as organo-mineral H horizon (see figure 3.10 and table 6.15). C concentration within the H horizon of the CCF treatment increases on average with increased distance between regeneration trees after respacing, although this is attributable to the microvariability within the soil.

The second rotation Sitka spruce experimental site at Clocaenog forest investigating the effects of transition to irregular shelterwood compared to conventional forestry practices is now approaching 70 years since planting. Management practices differentiated the two treatments only from 2002 onwards; yet results highlight a highly significant larger C stock within the H horizon of the CCF treatment compared to the UN treatment. This is the single finding within the present research which has the largest bearing on the soil C accumulation within the OSH. Under the assumption that differences in soils were the result of forest management practice and not the soil variability at local scale (measures were taken to prevent this by identifying the best experimental plots based on slope and aspect - see chapter 2.1.2), then the ability of the OSH to store C under the UN treatment would be compromised. In the CCF treatment the OSH as a whole stores 203.42% of the UN treatment C stock (see figure 3.11). This increases to 468.1% if only the H horizon is considered. This is mainly the result of the shallower H horizon in the UN treatment since comparison between the treatment for C concentration were non-significant. Considering a conifer woodland cover on peaty soils in Britain (peaty gleys and podzols) of 0.6318 10^6 ha (Vanguelova et al. 2013) and assuming that such an area is dedicated to the treatments, differences in C stock within the H horizon alone would account for a further 43 Tg C sequestration from the atmosphere for the CCF treatment. This may be seen as a simplistic projection with too many assumptions (tree species, topography, site and climate are not considered), among which the unknowns regarding soil mineral horizons. Nevertheless, results from the present study have highlighted the beneficial effects as a C sink of transitioning practices to irregular shelterwood when compared to even-aged, conventionally harvested plantations.

While Bd is significantly higher in the F horizon of the UN treatment (median values UN $\sim$ 0.070, CCF $\sim$ 0.050 g cm^{-3}), the F horizon is non-significantly thicker in the CCF treatment (median values UN $\sim$ 10 cm, CCF $\sim$ 15 cm depth). For this reason, differences in the F horizon C stock are not significant. In his study on the effects of silvicultural systems (CH, shelterwood and group selection) and utilization intensity on forest floor and mineral soil, Jang et al. (2016) found that thirty-eight years after harvesting the amount of woody debris resulted higher on average in the medium utilization (unburned) of the group selection system compared to the untreated Control treatment (213 vs. 200 Mg ha^{-1}). Hence, results from Jang et al. (2016) are in line with the present research findings in the H horizon. CCF systems such as the selection system and irregular shelterwood may be able to promote enhanced C storage when compared to more intensive harvesting practices (Puhlick et al. 2016), and this is confirmed by results from the present study.

One recent study from Cheng et al. (2017) found that the concentration of light and heavy fractions[5] (the latter accounting for up to 97% of total SOC) did not change between different thinning regimes on a 15 years old CH site (brash retained) *Cunnimghamia lanceolata* stand in eastern China on an orthic Acrisol soil. Results from Cheng et al. (2017) suggest that C stocks between the UN and CCF treatment in the mineral horizon for the present study may be similar. This would confirm the beneficial effects of the CCF treatment when all of the soil profile is considered. To confirm this, future research should concentrate on the effects of forest management practices on C stock and nutrient dynamics in mineral horizons and deeper in the soil in order to complete the entire soil profile and be able to suggest the full GHG mitigation potential and long term C sequestration for different forest management practices. Analysis of C stocks in the organo-mineral A and mineral horizons underneath the OSH may further differentiate the soil C storage potential between the treatments; or they may even counterbalance the significant differences in the H horizon. One report has suggested the potentially mitigating effect of the soil mineral horizons (Nave et al. 2010) but this is not always the case (Wan et al. 2018). A review carried out by Clarke et al. (2015) highlights that differences between forest management practices are more often found in the organic layer. Hence, future studies will need to include both organic and mineral soil horizons.

The C balance of the forest ecosystem would not be complete without considering the

[5]Heavy fraction organic C: Protected from decomposition through mineral association. SOM-rich with slow turnover (Cheng et al. 2017); Light fraction organic C: Moderately decomposed fraction from plant litter and animal tissues, which is promptly affected by management activities. The light fraction is usually associated with rapid turnover (Cheng et al. 2017).

above-ground growth and biomass of tree stems, branches and twigs, leaves and needles. Hence, before delving into the the key findings of the present experiment, the next chapter will highlight some of the latest results concerning the above-ground contribution in terms of C storage which are of relevance to the treatments and conditions discussed in the present thesis.

3.3.3 Above-ground biomass

The C storage potential of forest soils is partly the result of the harvesting intensity adopted (Clarke et al. 2015). Soil C storage is affected by forest growth in subsequent rotations, tree nutrient uptake and input derived from harvesting residues. Therefore, scarcity of brash-derived nutrients in the soil over time could potentially cause a decrease in growth (Mason et al. 2012) leading to reduced above-ground biomass and above and below-ground litter production.

The above-ground conifer growth in northern Europe is limited by the presence of N; fertilization is practised to increase forest production (Bergholm et al. 2015).

The experiment carried out by Mason et al. (2012) focussed on diameter and height of 10 year old Sitka spruce stands; this was conducted on the same experimental site of the present study, the Forest of Ae. Mason et al. (2012) claims that while the effects of WTH are site and soil specific, the effects of brash removal on tree height and diameter may be delayed to at least 10 years after plantation occurred. Results from this study indicate lower height (5 to 9 %) and diameter growth (5 to 19 %) when brash is removed after harvesting compared with brash left on site. Mason et al. (2012) reported that during the first stages of growth the effect of fertilization is not evident; this is claimed to be caused by the fertilizing effect of brash from the previous rotation. The same reports studies in Britain where WTH has negative effects on tree growth, such as a 9 - 10 % reduction in diameter and 16 % reduction in basal area in the third decade after planting. Mason et al. (2012) also reported simulations on peaty gley soils in Kielder forest where WTH lead to a decrease of 20 % in height when compared to CH, although such simulations raise questions on how site and soil specificity have been taken into account. Clarke et al. (2015) reports several studies that found reductions in tree growth of WTH sites compared to CH.

Studies conducted in boreal regions reported potential long term detrimental effects on site productivity of WTH experimental sites (against CH; CHF), although thinning intensity before harvesting and final harvesting did not affect Norway spruce stands growth both in the 20 years leading to the final harvest and ten years after replanting of the new generation (Kaarakka et al. 2014). The same study also reports little or no effects of WTH on tree seedlings growth from a series of studies conducted in the last 20 years, suggesting that when differences are present, these are likely to be caused by the C stock within the residues removed from the site and the amount of nutrients in the OSH (Saarsalmi et al. 2010).

Results on the ways WTH affects forest growth are contrasting; there is currently not unanimous solid evidence in support of the effects of soil fertility on tree growth, although the answer to this may be found in soil type, depth of the organic horizons (Hazlett et al. 2014) and the tree species adopted (Clarke et al. 2015).

Puhlick et al. (2016) conducted research on the above-ground C allocation under continuous cover forestry. Puhlick et al. (2016) analysed the long-term effects of alternative forest management treatments with diverse, mixed tree species composition. This study found that overstory C resulted higher in the shelterwood treatment (similar to the selection system) when compared to CH. Puhlick et al. (2016) also found that harvested wood in Mg C ha^{-1} did not significantly vary between treatments. Results suggest that maintaining a more diverse forest structure in terms of age (and species) may also be beneficial for the purpose of storing C above-ground.

Model simulation comparing temperate mixed forests clearfell, shelterwood, selection systems and unmanaged treatments found that the above ground contribution to the total C storage is negatively affected ($p = 0.05$) under any of the forest management practices when compared to the unmanaged treatment (Nunery and Keeton 2010). Also, lower harvesting frequency and structural retention contributed to a higher above-ground C storage.

In light of the above findings, future research activities at the Clocaenog experimental site should be conducted in order to understand if long term benefits of C storage for the CCF treatment can also apply above-ground, or if the UN treatment more closely reflects dynamics of above-ground C storage similar to the unmanaged treatment discussed by Nunery and Keeton (2010). Particularly for the CCF treatment in Clocaenog, the total ecosystem C stock will have to incorporate the HWP resulting from thinning operations.

3.4 Conclusions

The clearfell experiment at the Forest of Ae on a second rotation, 22 year old Sitka spruce plantation highlighted significant difference is soil C stock (Mg ha^{-1}) in the uppermost soil OSH (L and F). Specifically, the fertilized CHF treatment resulted in significantly higher C stock in the L horizon compared with the CH and WTH treatments. Based on the 0.6318 10^6 ha conifer cover on peaty soils in Britain, the CHF treatments would improve the L horizon C storage potential by about 0.498 and 0.496 Tg compared to CH and WTH respectively.

The treatment that removed brash (WTH) resulted in significantly lower C stock in F horizon compared with CH and CHF treatments which was determined by a significantly lower thickness in the F horizon. Results suggest that the beneficial effects in terms of soil C storage have been quantified in 18.25 and 14.43 Tg for the CHF and CH treatment respectively.

Nor organic horizon field moisture content or Bd were significantly different between the treatments. This was not surprising since the experimental area is fenced, thereby eliminating the effects of grazing on soil compaction. Slope, aspect, soil type, tree species and age did not vary by design, which may have contributed towards non-significant differences in soil field moisture content. Consequently, it is more plausible that differences in C stock were a direct consequence of brash management and fertilization.

C concentration in the L horizon had the opposite behaviour (all differences being significant with WTH the highest, followed by CH and CHF). This could be the result of better access to soil nutrients and consequent nutrient uptake from the treatments where brash was left on site at the time of harvesting. More so for the CHF treatment where fertilization was also applied. This being the case, CH and CHF treatments would have a more nutrient rich litter horizon (although this will need to be confirmed) but a lower C % compared to WTH, and also a larger redistribution of C in above-ground biomass as measured in (Mason et al. 2012).

The experiment at Clocaenog forest on a second rotation 70 year old Sitka spruce plantation highlighted a highly significant difference in soil C stock in the soil H horizon between UN and CCF treatments. The CCF treatment, which underwent regular thinning operations aiming at achieving irregular shelterwood silviculture, stored significantly higher C stock compared to the unthinned (since early 2000s) UN Control treatment. This difference is not only highly significant, but it is of the highest importance in the C balance of forest ecosystems on a peaty gley soil since the H horizon stores the most C in these types of soils. Results suggest that the benefits in terms of C storage if the CCF treatment would be adopted in place of the UN treatment over the entire peaty soils in Britain would be in the region of 43 Tg.

Field moisture content did not vary between treatments and while the BD of the F horizon was significantly higher in the UN treatment, the soil F horizon in the CCF treatment was thicker on average; hence, differences in C stock were not significant in the F horizon.

In order to better understand the dynamics of soil C stock accumulation both for the forest of Ae and Clocaenog forest, it is important to assess the role of the quality of C. The next chapter will focus on investigating differences in N dynamics (N concentration, available N and C:N ratio) and proximate C pools (Lignin, holocellulose and cell solubles) with different requirements of activation energy[6] to understand if these can affect the C stock potential within the soil OSH.

[6] The energy necessary to degrade compounds such as lignins, hemicellulose and other C pools.

Chapter 4

Forest management impacts on soil C quality

4.1 Introduction

SOC pools vary in a biochemical continuum from those that are stable, formed with the interactions with mineral aggregates and particles within the soil to liable C in fresh biomass. Studies suggest that mitigation mechanisms such as Reducing Emissions from Deforestation and forest Degradation program (REDD+) should put more emphasis on the different residence times of SOC by dividing it into pools with different stability (Lützow et al. 2007). Biogeochemical models could then be implemented for predicting the effects of vegetation, climate and parent material on the turnover of SOC pools. While considerable fractionation work (either physical or chemical) has been carried out to relate C pools in SOM to different turnover times (Moinet et al. 2016) the chemistry and distribution of organic compounds within the OSH of temperate forests has not been fully investigated (Gartzia-Bengoetxea et al. 2009). Nevertheless, their importance is known to affect the stability of SOM as well as the microbial activities and consequent stabilisation processes. For example, litter lignin content is known to affect microbial decomposition. Lignin:N ratio, the ratio of lignin:cellulose and the lignocellulose index (LCI) are regarded as common indexes for estimating the decomposition rates, with higher ratio values indicating slower decomposition (Moorhead et al. 2013). In coniferous forests, lignin content was also found to be the primary control of litter rates of decomposition (Kleber, 2010). The initial concentration of N and lignin are related (positively and negatively respectively) to the decomposition rates of forest litter. Current research generally agrees on the importance of such variables to control decomposition rates in several ecosystems (Melillo et al. 1982; Moorhead et al. 1996; Schmidt et al. 2011; Dinakaran et al. 2014; Sariyildiz 2015; Luo et al. 2017).

The dynamics of SOM turnover are affected by a number of factors. These can be summarised as:

- Organo-mineral association characterised by the interaction of SOM with minerals and its protection or arrangement within the mineral matrix (sorptive interactions: adsorption, desorption) see also chapter 4.1.1.1 (Kleber 2010; Schmidt et al. 2011; Schrumpf et al. 2013; Lehmann and Kleber 2015; Muller and Linhares-Juvenal 2016).

- SOM occlusion or incorporation within soil aggregates (Kleber 2010; Schrumpf et al. 2013; Lehmann and Kleber 2015; Muller and Linhares-Juvenal 2016).

- Soil oxidation - reduction state (Kleber 2010; Schmidt et al. 2011; Lehmann and Kleber 2015).

- Presence of potential decomposers and their interactions with the mineral surfaces (physical separation from degraders and enzymes) (Schmidt et al. 2011; Lehmann and Kleber 2015).

- Temperature and moisture condition of the soil (Schmidt et al. 2011; Lehmann and Kleber 2015).
- Soil acidity status (Schmidt et al. 2011).
- Bulk chemical composition (eg. N content or the fraction of plant residue that requires more enzymatic steps to release a C atom as C dioxide (lignin) (Schmidt et al. 2011).
- The longer permanence of tree root C in the soil compared to litterfall (Schmidt et al. 2011), the fast turnover of fine roots and their contribution to the terrestrial C reservoir and C cycle (Lukac and Godbold 2010).
- SOM quantity and quality (Vanguelova et al. 2010).

Forest soils show marked differences in C pool size, chemical characteristics and turnover times at different depths; OSH (see chapter 1.3) could more easily be affected by management and disturbance when compared to the mineral horizons (Nave et al. 2010; Thiffault et al. 2011; Hume et al. 2018). For instance, when the C stock in the forest floor is larger compared to the mineral soil, disturbance could cause high C losses in absolute terms. For instance, when the C stock in the forest floor is smaller compared to the mineral soil, small reductions in absolute terms could cause a proportionally high C loss. The forest floor is also the most dynamic pool of SOC stock; hence understanding the dynamics of forest floor disturbance will help predict and optimize its C balance (Lal 2005). In addition, studies highlighted how critical the presence of the organic layer is as a buffer against disturbance of the mineral horizons during harvesting, as well as its importance in the slow release of nutrients (Thiffault et al. 2011) and the consequent challenges in understanding the interactions between OSH, mineral soil, and silvicultural systems (Jang et al. 2016). According to estimates, up to 25% of the C within mineral horizons may be in the form of DOC that derives from above-ground biomass and litter (Wan et al. 2018). Turnover times of forest soil C become progressively delayed with soil depth as a result of increased recalcitrance or protection of the subsoil SOM; chemistry becomes more complex with soil depth (Marschner et al. 2008). At the same time, the high presence of labile organic substrates or nutrients may trigger a swifter response of the r-strategist[1] microorganisms (this also referred to as 'positive priming effect') as a consequence of harvesting operations or other disturbance events (Ekschmitt et al. 2005; Brady and Weil 2008).

The objective of the present study is to understand the effects of forest management practices (conventional clearfell, whole-tree harvesting, fertilization and in transition to continuous-cover forestry, see chapter 1.2 for an introduction on the treatments) on the soil proximate C pools and N dynamics of forest soil OSH and organo-mineral horizons in upland Britain.

4.1.1 Soil fractionation techniques: advantages and limitations

SOM is difficult to characterise, and this is mainly caused by the stabilization mechanisms involved (Marschner et al. 2008). Bulk soil is divided into fractions through a number of techniques. These are represented by chemical, physical (size, density) and combined techniques. Extraction procedures being part of such efforts are certainly subject to a

[1]k-strategists and r-strategists are microorganisms responsible for the organic decay within the soil. k-strategists maintain a low but stable population; these microorganisms are dominant in poor soil conditions (low levels of easily digested organic materials). r-strategists are instead microorganisms that awake form dormancy when new food supplies become available (eg. sugars, starches, aminoacids). These overtake the k-strategists with high levels of reproduction and growth resulting in higher production of CO2. This may stimulate the breakdown of 'recalcitrant' materials (this being the priming effect). Depletion of the food supplies will follow, leading to the starvation and consequent reduction in r-strategists (Brady and Weil 2008).

number of critiques mostly relating to the claimed inefficiency in correctly measuring the pools of C. It is claimed that there is evidence of incomplete extraction of C pools from the soil which may cause a miscalculation of the microbial or plant-derived residues; it is reported that more than 50 % of the soil mineral-associated lignin phenols could not be extracted (Castellano et al. 2015) and 50 to 70% of the SOC which is then categorized in the fraction 'humin'(Lehmann and Kleber 2015). Lehmann and Kleber (2015) reports how the extraction in alkali, an 18th century procedure unchanged in principle, is selective and with a tendency to produce artefacts. The addition of OH- in solution (pH 13) causes the so called 'humic acid' to precipitate in solution, while the part of organic matter called 'fulvic acid' remains in solution after acidification; 'humin' is the remaining 'pool'. The pools become less meaningful if we consider the mentioned limitations. Additionally, the way in which the literature refers to fractions is cause for further confusion. Furthermore, the high pH involved in this methodology is nothing similar to the soil pH range and moreover, the extraction in alkali may actually have pushed this body of research to concentrate more on humic substances (whose definition is not clear). Humic substances have different connotations, from result of extraction methods for the identification of 'humins', 'fulvic acids' and 'humic acids' to a 'material that is not an operational construct'. More surprisingly different branches of research refer to 'humic substances' in different ways (Kogel-Knabner et al. 2008; Lehmann and Kleber 2015):

- "Small fragments"; "compounds of different composition and mass"; "large molecular mass"; "relatively high molecular weight substances"; "stable fraction of SOM".

It is still unclear which fractionation method leads to a more accurate estimate of the C fractions. The technique that has been utilized for this current study is fibre analysis, also referred to as 'forage fibre analysis' (Ryan et al. 1990; Van Soest et al. 1991a). This method is utilized in nutrition research and feedstuff analysis. Because of the potential to reduce labour costs, this has been recently tested against the results from the Association of Official Analytical Chemists (AOAC International 2007; Marichal et al. 2011). The fibre Ankom200 analyser (Ankom Technology Corporation, Macedon, New York, USA) uses filter bags that are placed in a reaction vessel for solvent extraction. Results suggest a reasonable degree of agreement between the AOAC procedure and the Ankom fibre analysis procedure. Forage fibre analysis was also tested against a more complex fractionation analysis developed for the forest products industry (forest products analysis) in which a series of digestions determines the proximate C fractions. Proximate carbon fractions, nonpolar extractives (fats, oils, and waxes), polar extractives (simple sugars and polyphenols), acid-soluble products (cellulose), and lignin were determined gravimetrically. Simple sugars, phenolics, and hydrolysed carbohydrates (cellulose plus hemicellulose) were quantified colorimetrically. Findings on samples subject to different decomposition stages suggest that while the forest product analysis seems to more closely estimate the rate of decomposition, and to be more sensitive with regards to lignin changes during decomposition, proximate C fraction estimates from the forage fibre analysis can be used to accurately measure the proximate C fractions cell solubles, hemicellulose, cellulose and lignin (Ryan et al., 1990).

4.1.1.1 The Forage fibre technique

While SOM chemistry is very complex, it is possible to separate the organic compounds in large fractions or pools (such as cell solubles, hemicellulose, cellulose lignins) which differ in the number of enzymatic steps required to release as CO_2 a C from an organic compound (Kleber 2010). The previous definition may be the most accurate way to describe the difference between soil C pools because it does not rely on the concept of recalcitrance, but on activation energy. While C is the dominant element (about 50% ash-free) of the pools, these are not strictly defined. Proximate C fractions is another way to refer to these pools which highlight the variability of such fractions in terms of organic chemistry introduced by plant species and litter types (Ryan et al., 1990). More specifically, SOM can be divided into three broad categories (Goering and Van Soest 1970; Moorhead et al. 1996; Hobbie et al. 2006; Bani et al. 2018):

1. Cell solubles (extractives), the soluble component. This nutrient-rich, high-quality substrate for microbial growth can be divided into:
    - Nonpolar compounds - mainly fatty acids and lipids.
    - Polar compounds - sugars and phenolics.
2. Acid-soluble fractions: these are polymer carbohydrates, otherwise called holocellulose and divided into:
    - Cellulose-hydrogen bonds hold 1,4-linked D-glucose in chains and create a crystalline structure that confers rigidity to cell walls. Cellulose is the most abundant natural polymer (30 to 50 % dry-weight of the plant).
    - Hemicellulose and some bound proteins; the amorphous structure of hemicellulose is mainly composed of mannans, xyloglucans and xylans with branched, short oligomers and monomers.
3. Aromatic acid-insoluble compounds, or lignins. The aromatic matrix of lignin confers rigidity and strength to plant cell wall and function.
4. Acid insoluble ash, mainly silica.

Among the pedogenic factors affecting SOM quality and quantity, vegetation through plant litter (both above- and below-ground) modifies the amount of organic compounds such as waxes, tannins and lignin. These contribute to the early dynamics of decomposition and eventually, the turnover of SOM (Catoni et al. 2016). This is affected by the presence or absence of specific decomposers which in turn are driven by resources (e.g. N and macronutrients). At the same time, the soil parent material affects organo-mineral association (driven by chemical bonds i.e. ligand exchange such as carboxyl groups and hydroxy groups on mineral surfaces, Van der Waals interactions and cation bridges) by influencing the mineral phase and eventually the SOM stabilization potential.

The forage fibre analysis technique is a detergent system of fibre fractionation that was originally developed to estimate forage quality; it was applied in the present experiment to investigate decomposition dynamics of the forest floor. The neutral detergent fibre (NDF) procedure is used to estimate the soluble and available constituents (cell solubles) by dividing this pool from the rest that is subject to microbial fermentation[2] (Goering and Van Soest 1970).

$$Cell\ solubles = 100 - NDF \tag{4.1}$$

The Acid detergent fibre (ADF) procedure estimates the amount of lignocellulose by separating the original material with H_2SO_4 and cetyltrimethylammonium bromide, this being a modification of the original procedure resulting from the toxicity of previously adopted chemicals (Ryan et al. 1990). The procedure is useful for determining the hemicellulose fraction:

[2]Values in the following formulas are expressed as %

$$Hemicellulose\ (and\ some\ proteins\ attached\ to\ cell\ walls) = NDF - ADF \tag{4.2}$$

ADF is also a preparatory procedure for cellulose and lignin determination, as it removes acid-bound substances and proteins that would otherwise affect the subsequent procedures. The Acid detergent lignin (ADL) allows the estimation of cellulose and lignins:

$$Cellulose = ADF - ADL \tag{4.3}$$

$$Lignin = ADL \tag{4.4}$$

All fractions corrected for the presence of ash, (see equation (2.8)).

The LCI was calculated as follows:

$$LCI = lignin/(lignin + holocellulose) \tag{4.5}$$

where holocellulose is the sum of the two proximate C pools of hemicellulose and cellulose (Moorhead et al. 2013).

4.2 Results

Please refer to chapter 2.2.1.3 for a description of the statistical methods utlised in this chapter.

4.2.1 Clearfell experiment: Forest of Ae

Estimated marginal means for mixed effect model show significantly higher C:N ratio in the F horizon in the CH and WTH treatment compared to CHF ($p = 0.05$ and $p < 0.05$ respectively, see table 4.1). Available N in the form of nitrate is significantly higher in the H horizon ($p < 0.05$) for CHF compared to WTH.

In the proximate C pools, the hemicellulose in the H horizon is significantly higher in WTH compared with CHF ($p < 0.05$). The amount of cellulose in the L horizon is significantly lower in the CH treatment compared with both WTH and CHF ($p < 0.05$). When considering LCI, the F horizon was significantly higher in CHF compared to WTH ($p < 0.05$). Significantly more ash was found in the L horizon of the CHF treatment compared to WTH ($p < 0.05$). Results for ash content from the thermogravimetric analyser were in line with the results from the muffle furnace after forage fibre analysis (correlation +0.985, data not shown). This is in line with the significantly higher C concentration in the WTH treatment compared to the CHF.

Contrasts between EMM of the treatments are shown in figures 4.6 and 4.7 (refer to figures 4.1 to 4.5 for visual data interpretation).

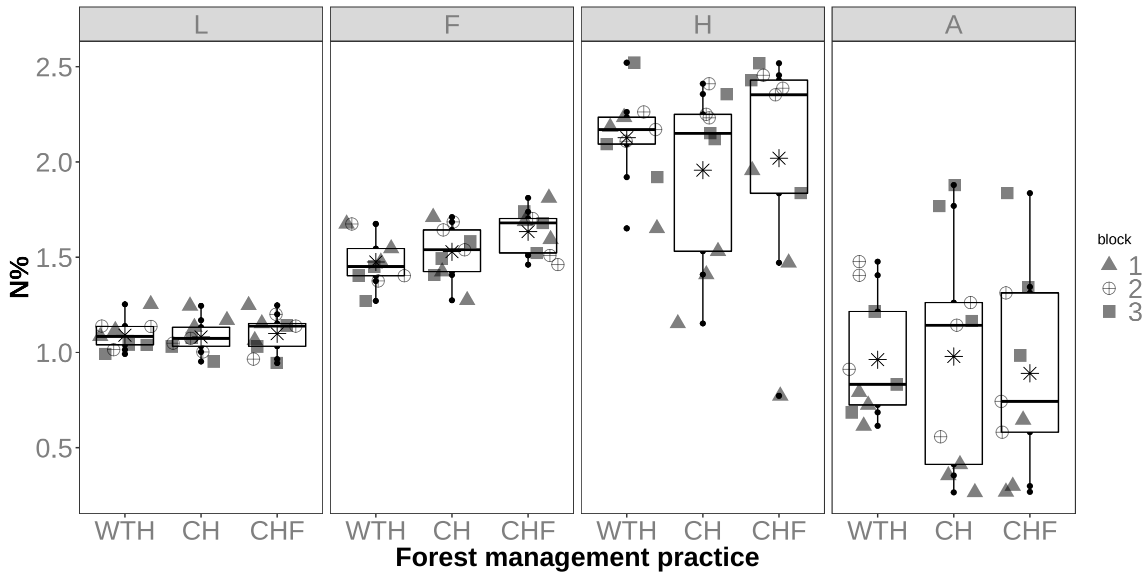

Figure 4.1: Forest of Ae - boxplot of soil N concentration (%) by management practice. L,F,H and A are soil horizons. Black dots refer to observations that may be outliers according to the rule ± 1.5 * interquartile range (Kabacoff 2015). Shape refers to block replication. Individuals were bulked into couples, from six to three per block replication. Asterisk symbols are mean values.

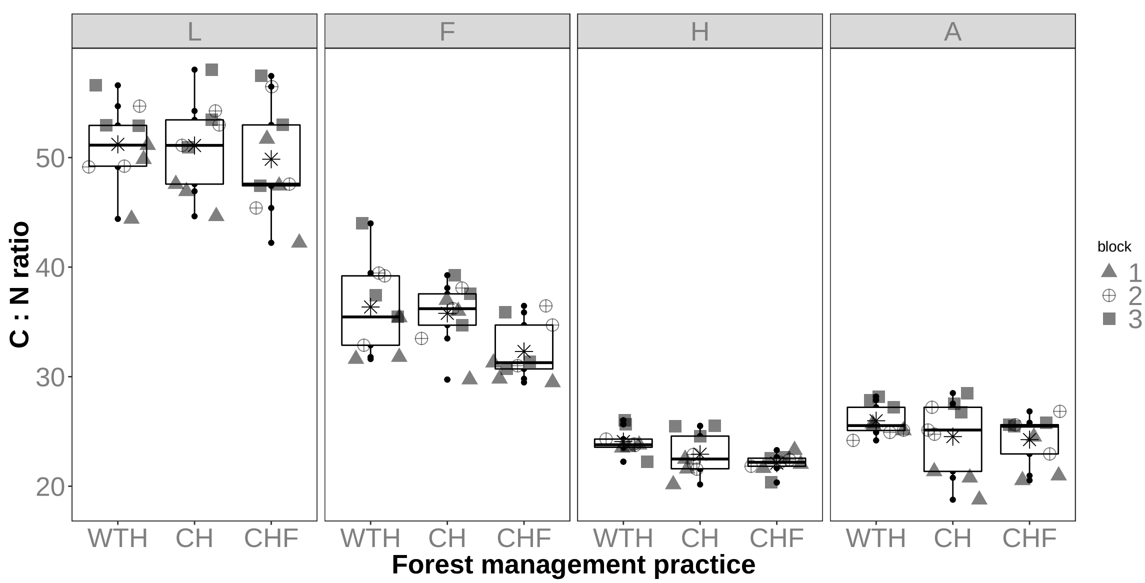

Figure 4.2: Forest of Ae - boxplot of soil C : N ratio by management practice. L,F,H and A are soil horizons. Shape refers to block replication. Individuals were bulked into couples, from six to three per block replication. Asterisk symbols are mean values.

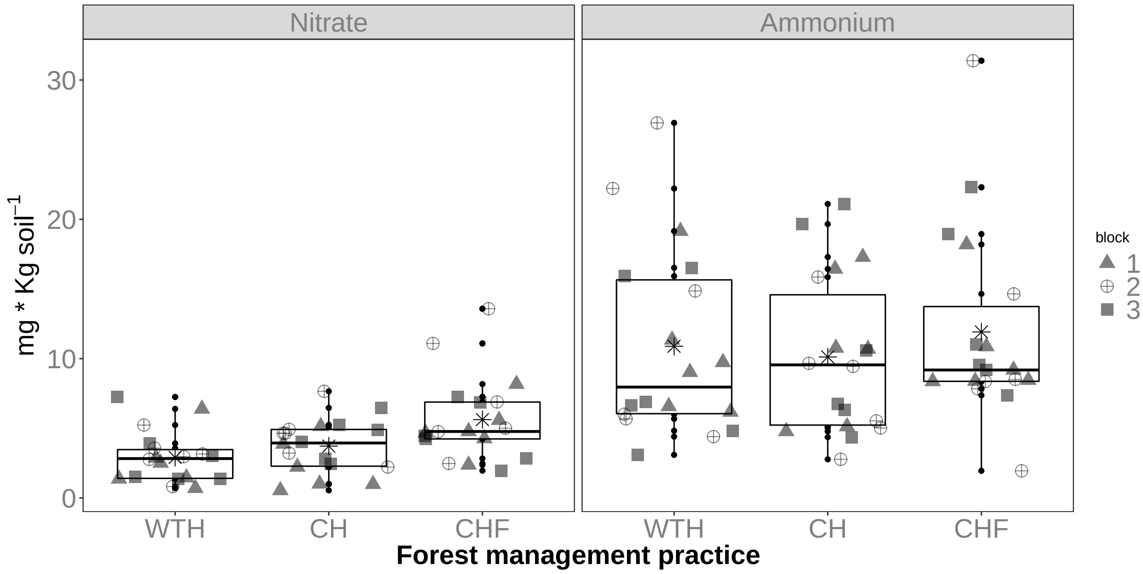

Figure 4.3: Forest of Ae - boxplot of soil H horizon available N by management practice. Plots are nitrate and ammonium. Shape refers to block replication. Asterisk symbols are mean values.

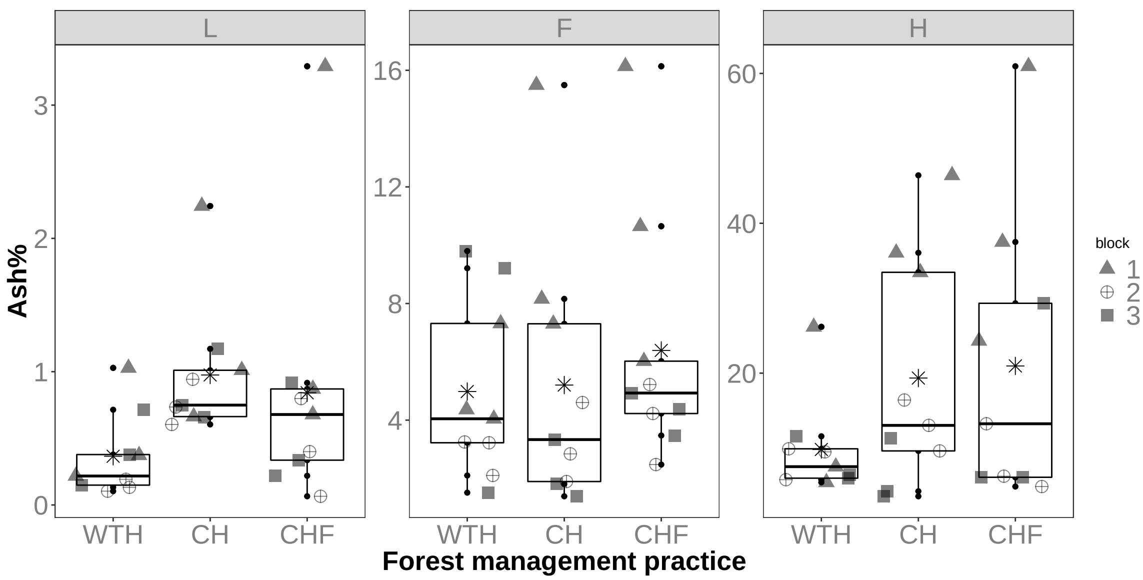

Figure 4.4: Forest of Ae - boxplot of soil ash content (%) from the thermogravimetric analyser by management practice. L,F and H are soil horizons. Shape refers to block replication. Individuals were bulked into couples, from six to three per block replication. Asterisk symbols are mean values.

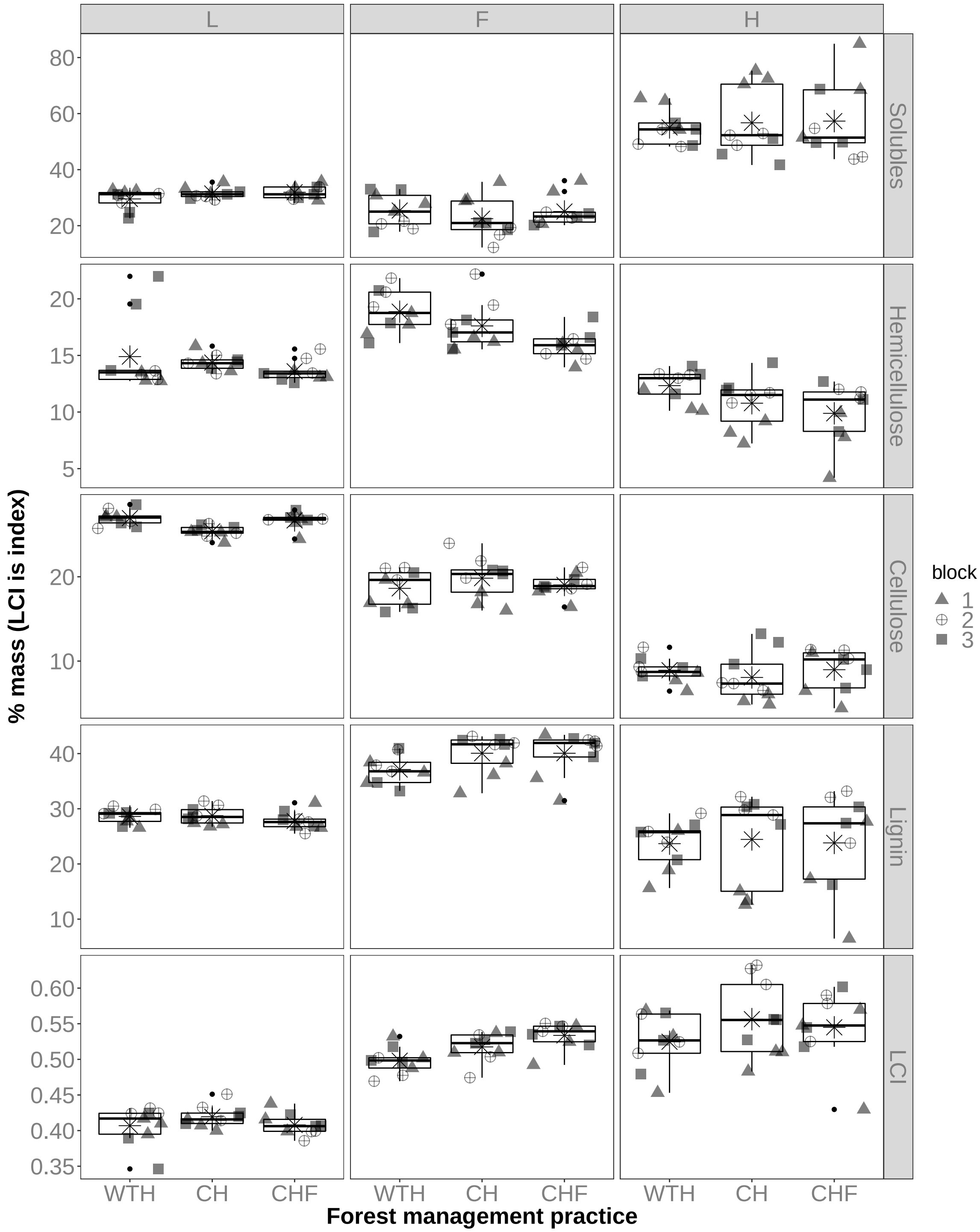

Figure 4.5: Forest of Ae - boxplot of soil proximate C pools (% - on ash-free dry-mass basis) and LCI (expressed as index) by management practice and horizon. Shape refers to block replication. Asterisk symbols are mean values.

Table 4.1: Forest of Ae. Pairwise comparisons among estimated marginal means of the treatments for N concentration, C:N ratio, Nitrate, Ammonium, cell solubles, hemicellulose, cellulose, lignin, LCI and ash in the L, F, H and A horizons. p-value adjustment: Tukey method for comparing a family of 3 estimates. Degrees-of-freedom method: Kenward-Roger.

var	hor	contrast	estimate	SE	t.ratio	p.value	sign
N concentration	L	CH - CHF	-0.02	0.02	-0.82	0.71	
		CH - WTH	-0.01	0.02	-0.45	0.90	
		CHF - WTH	0.01	0.02	0.37	0.93	
	F	CH - CHF	-0.11	0.07	-1.55	0.34	
		CH - WTH	0.05	0.07	0.79	0.72	
		CHF - WTH	0.16	0.07	2.34	0.13	
	H	CH - CHF	-0.06	0.21	-0.30	0.95	
		CH - WTH	-0.17	0.21	-0.82	0.71	
		CHF - WTH	-0.11	0.21	-0.52	0.87	
	A	CH - CHF	0.09	0.26	0.34	0.94	
		CH - WTH	0.02	0.26	0.07	1.00	
		CHF - WTH	-0.07	0.26	-0.28	0.96	
CN ratio	L	CH - CHF	1.25	0.89	1.40	0.42	
		CH - WTH	-0.11	0.89	-0.12	0.99	
		CHF - WTH	-1.36	0.89	-1.52	0.38	
	F	CH - CHF	3.48	0.98	3.57	**0.05**	*
		CH - WTH	-0.58	0.98	-0.59	0.83	
		CHF - WTH	-4.06	0.98	-4.16	**0.03**	*
	H	CH - CHF	0.81	0.93	0.87	0.68	
		CH - WTH	-1.15	0.93	-1.24	0.50	
		CHF - WTH	-1.97	0.93	-2.11	0.20	
	A	CH - CHF	0.27	1.41	0.20	0.98	
		CH - WTH	-1.45	1.41	-1.03	0.60	
		CHF - WTH	-1.72	1.41	-1.23	0.50	
Nitrate	H	CH - CHF	-1.90	0.72	-2.63	0.12	
		CH - WTH	0.82	0.72	1.13	0.55	
		CHF - WTH	2.72	0.72	3.76	**0.04**	*
Ammonium	H	CH - CHF	-1.80	1.48	-1.21	0.49	
		CH - WTH	-0.77	1.48	-0.52	0.87	
		CHF - WTH	1.03	1.48	0.69	0.78	
Cell solubles	L	CH - CHF	-0.43	1.27	-0.34	0.94	
		CH - WTH	1.96	1.27	1.54	0.37	
		CHF - WTH	2.39	1.27	1.88	0.26	
	F	CH - CHF	-2.56	2.75	-0.93	0.65	
		CH - WTH	-2.90	2.75	-1.05	0.59	
		CHF - WTH	-0.34	2.75	-0.12	0.99	
	H	CH - CHF	-0.60	4.40	-0.14	0.99	
		CH - WTH	1.64	4.40	0.37	0.93	
		CHF - WTH	2.24	4.40	0.51	0.87	
Hemicellulose	L	CH - CHF	0.77	1.49	0.52	0.87	
		CH - WTH	-0.52	1.49	-0.35	0.94	
		CHF - WTH	-1.30	1.49	-0.87	0.68	
	F	CH - CHF	1.75	1.02	1.72	0.31	
		CH - WTH	-1.26	1.02	-1.23	0.50	
		CHF - WTH	-3.01	1.02	-2.95	0.09	
	H	CH - CHF	0.89	0.67	1.34	0.45	
		CH - WTH	-1.55	0.67	-2.33	0.16	
		CHF - WTH	-2.45	0.67	-3.68	**0.05**	*
Cellulose	L	CH - CHF	-1.30	0.34	-3.81	**0.04**	*
		CH - WTH	-1.57	0.34	-4.60	**0.02**	*
		CHF - WTH	-0.27	0.34	-0.79	0.73	
	F	CH - CHF	0.80	1.01	0.79	0.73	
		CH - WTH	1.21	1.01	1.19	0.52	
		CHF - WTH	0.41	1.01	0.40	0.92	
	H	CH - CHF	-0.92	1.55	-0.59	0.83	
		CH - WTH	-0.86	1.55	-0.55	0.85	
		CHF - WTH	0.06	1.55	0.04	1.00	
Lignin	L	CH - CHF	0.96	0.92	1.05	0.59	
		CH - WTH	0.14	0.92	0.15	0.99	
		CHF - WTH	-0.82	0.92	-0.90	0.67	
	F	CH - CHF	-0.00	1.45	-0.00	1.00	
		CH - WTH	2.95	1.45	2.03	0.22	
		CHF - WTH	2.95	1.45	2.03	0.22	
	H	CH - CHF	0.63	2.73	0.23	0.97	
		CH - WTH	0.77	2.73	0.28	0.96	
		CHF - WTH	0.14	2.73	0.05	1.00	
LCI	L	CH - CHF	0.01	0.01	0.92	0.65	
		CH - WTH	0.01	0.01	1.01	0.60	
		CHF - WTH	0.00	0.01	0.09	1.00	
	F	CH - CHF	-0.02	0.01	-1.56	0.33	
		CH - WTH	0.02	0.01	1.87	0.23	
		CHF - WTH	0.04	0.01	3.42	**0.03**	*
	H	CH - CHF	0.01	0.02	0.50	0.88	
		CH - WTH	0.03	0.02	1.37	0.43	
		CHF - WTH	0.02	0.02	0.88	0.68	
Ash	L	CH - CHF	-0.68	0.33	-2.04	0.22	
		CH - WTH	0.53	0.33	1.58	0.35	
		CHF - WTH	1.21	0.33	3.62	**0.05**	*
	F	CH - CHF	-2.43	1.90	-1.27	0.48	
		CH - WTH	-0.45	1.90	-0.24	0.97	
		CHF - WTH	1.97	1.90	1.04	0.60	
	H	CH - CHF	-0.02	8.49	-0.00	1.00	
		CH - WTH	10.86	8.49	1.28	0.48	
		CHF - WTH	10.88	8.49	1.28	0.47	

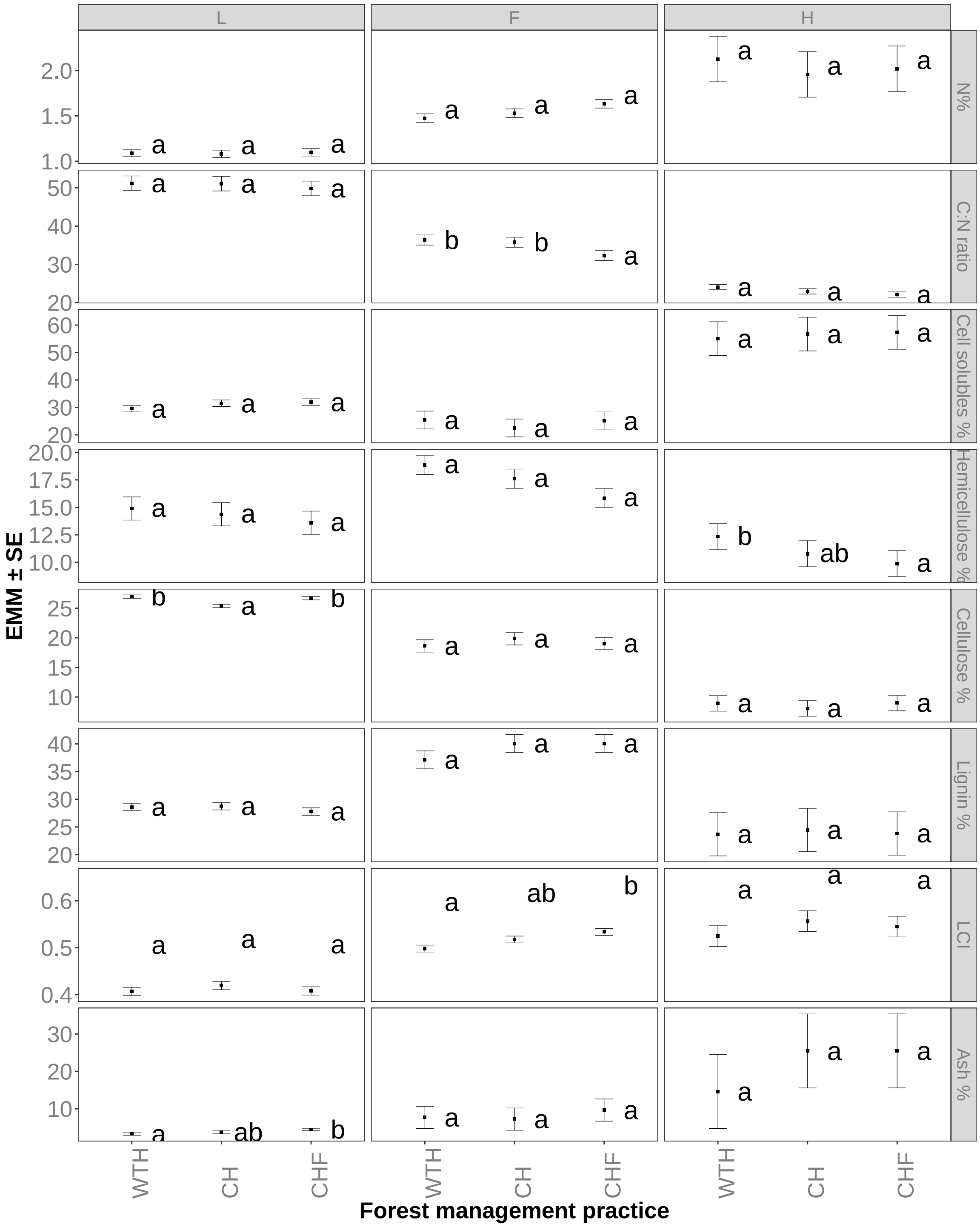

Figure 4.6: Forest of Ae - C quality: Estimated marginal means by management practice. Boxes indicate the estimated marginal means. Error bars are estimated marginal mean +/- SE. Means sharing a letter are not significantly different (Tukey-adjusted comparisons). N%, C:N ratio, proximate C pools, LCI and ash content.

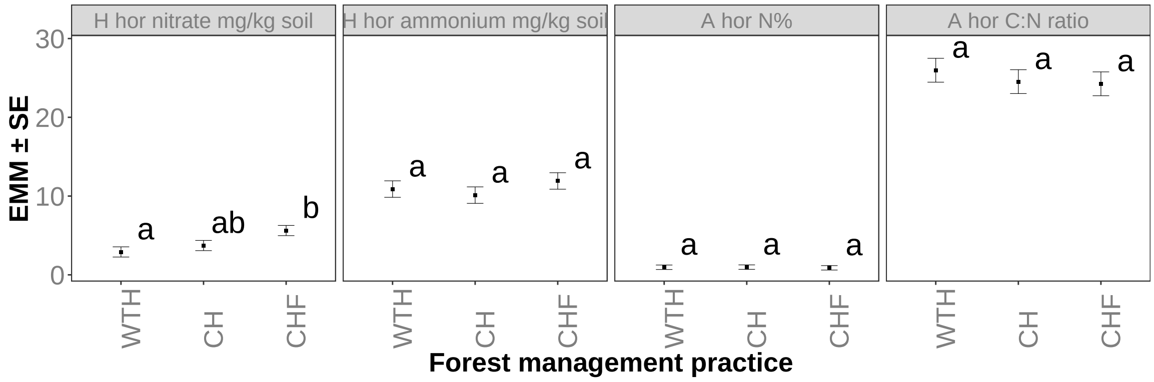

Figure 4.7: Forest of Ae - C quality: Estimated marginal means by management practice. Boxes indicate the estimated marginal means. Error bars are estimated marginal mean +/- SE. Means sharing a letter are not significantly different (Tukey-adjusted comparisons). H horizon available N and A horizon N% and C:N ratio.

4.2.2 Continuous-Cover-Forestry trial: Clocaenog

Estimated marginal means for mixed effect model show a significantly higher total N concentration (%) in the UN treatment compared to CCF for L ($p < 0.05$), F ($p < 0.05$) and H horizons ($p < 0.01$), see table 4.2. C:N ratio chiefly reflect these values; results highlight significantly lower values in the L ($p < 0.01$), H ($p < 0.05$) and A ($p < 0.01$) horizons of the UN treatment. Available N in the form of ammonium found in the H horizon was significantly higher in the UN treatment ($p < 0.05$). The proximate C pools in the H horizon showed that the pool of cell solubles was significantly lower in the UN treatment ($p < 0.05$). Hemicellulose was significantly lower in the F horizon of the UN treatment ($p < 0.01$), while H horizon lignin was significantly higher in the UN treatment ($p< 0.05$) compared to CCF treatment. L horizon Ash content was significantly higher for the UN treatment ($p < 0.05$) compared to CCF treatment. This was not reflected by soil C concentration in chapter 3 which provided non-significant results within the L horizon.

Contrasts between EMM of the treatments are shown in figures 4.13, 4.14 and 4.15 (refer to figures 4.8 - 4.12 for visual data interpretation).

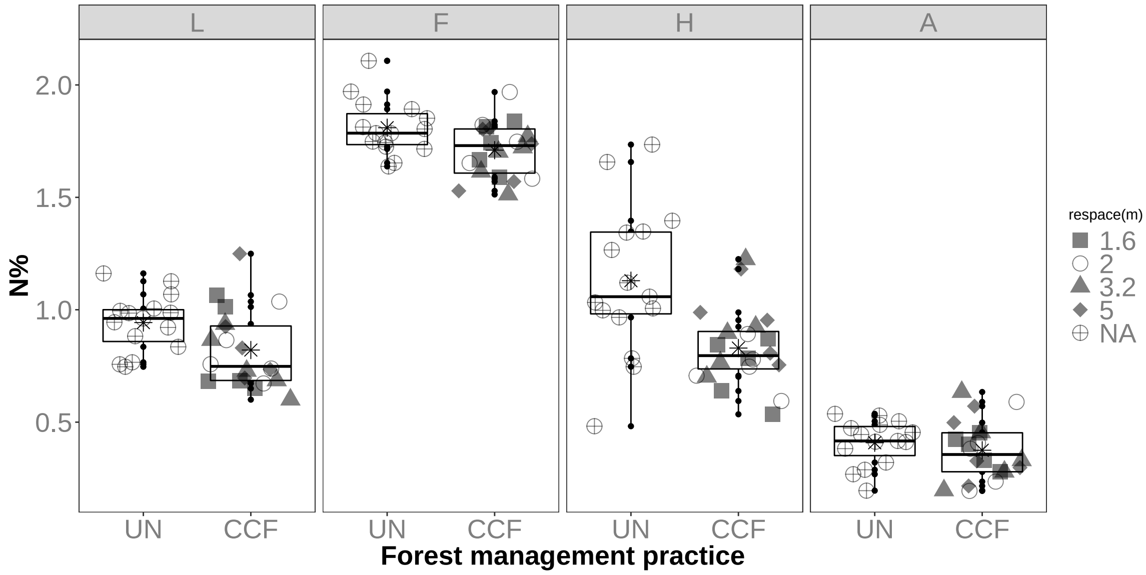

Figure 4.8: Clocaenog Forest - boxplot of soil N concentration (%) by management practice. L, F, H and A are soil horizons. Shape refers to respacing (random variable). Asterisk symbols are mean values.

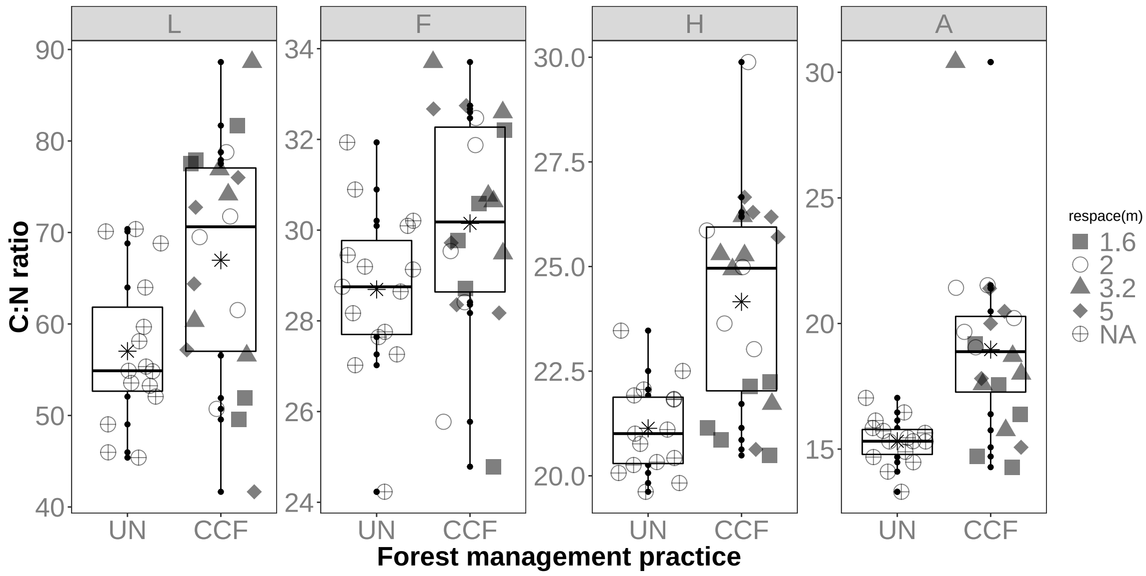

Figure 4.9: Clocaenog Forest - boxplot of soil C:N ratio by management practice. L, F, H and A are soil horizons. Shape refers to respacing (random variable). Asterisk symbols are mean values.

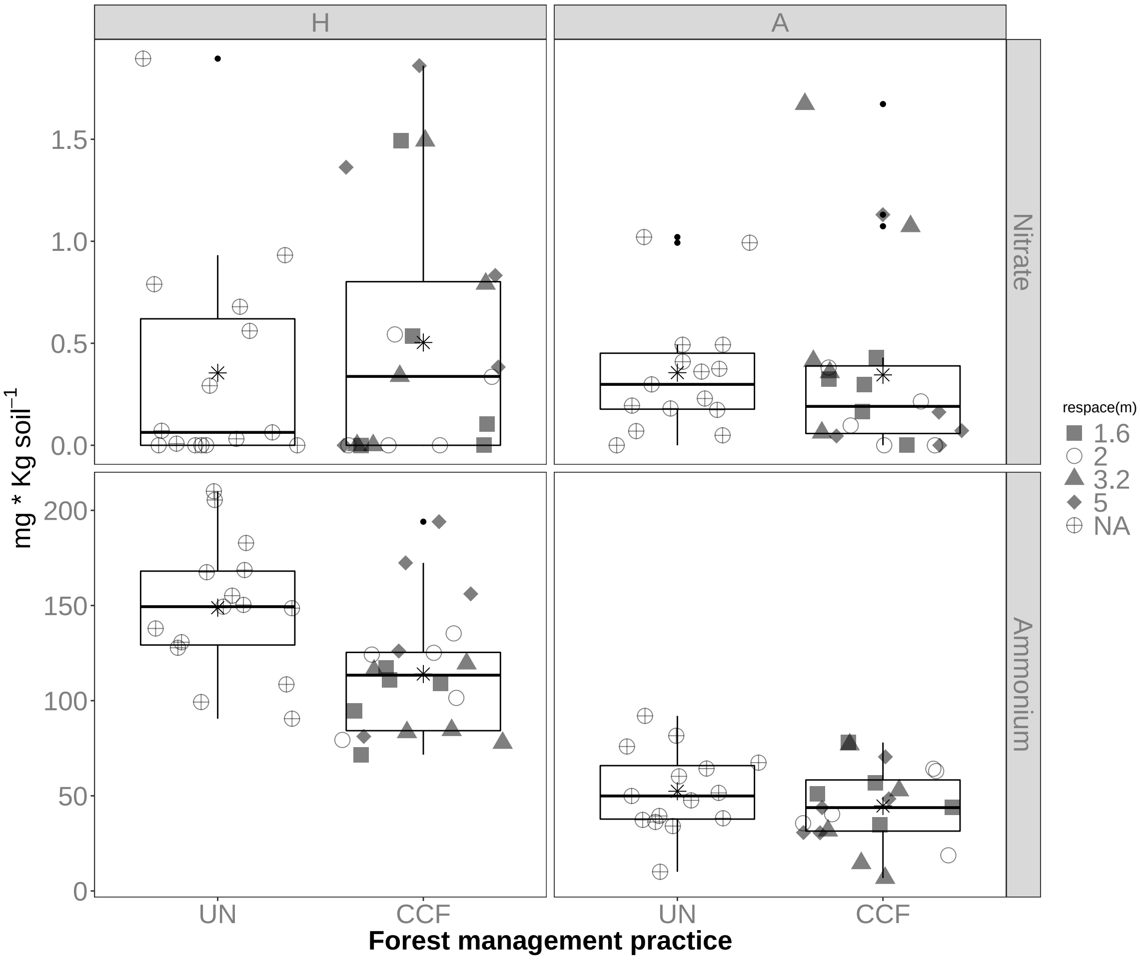

Figure 4.10: Forest of Clocaenog - boxplot of soil available N (nitrate and ammonium) by management practice. Shape refers to respacing (random variable). Asterisk symbols are mean values.

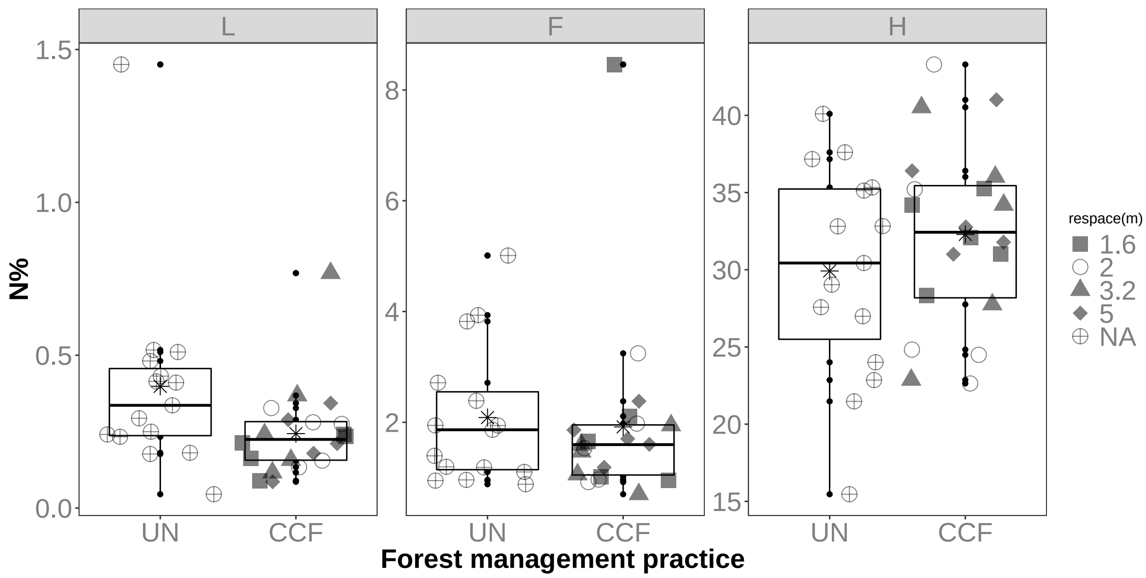

Figure 4.11: Clocaenog Forest - boxplot of soil ash content after forage fibre analysis, by management practice. L, F and H are soil horizons. Shape refers to respacing. Asterisk symbols are mean values.

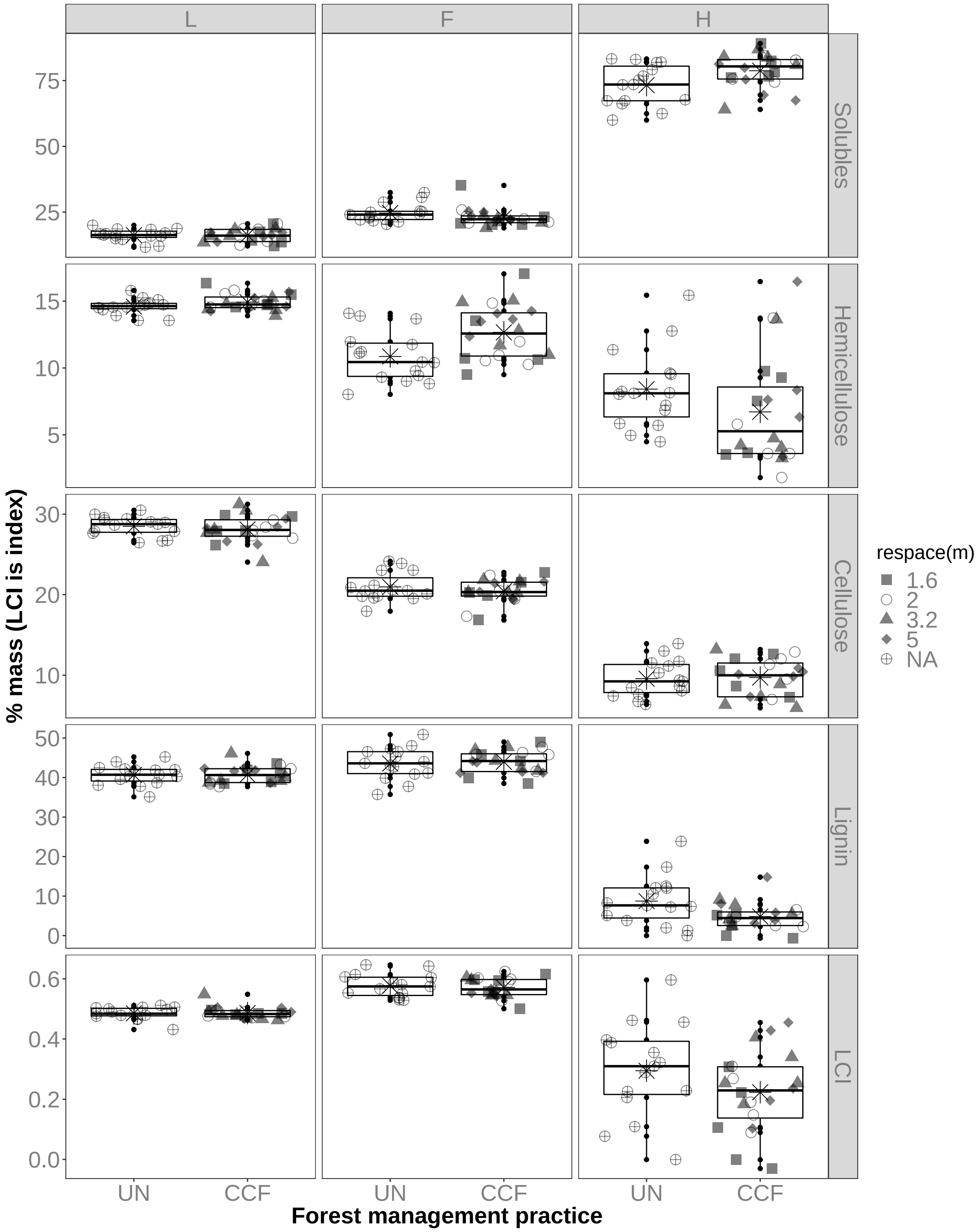

Figure 4.12: Clocaenog Forest - boxplot of soil proximate C pools (% on ash-free dry-mass basis) by management practice. L, F and H are soil horizons. Shape refers to respacing. Asterisk symbols are mean values.

Table 4.2: Clocaenog Forest. Pairwise comparisons among estimated marginal means of the treatments for N concentration, C:N ratio, Nitrate, Ammonium, cell solubles, hemicellulose, cellulose, lignin, LCI and ash in the L, F, H and A horizons. p-value adjustment: Tukey method. Degrees-of-freedom method: Kenward-Roger. `glmer` model: `emmeans` labels asymptotic results (estimates tested against the standard normal distribution - z tests, rather than the t distribution) as df = 'Inf' (Lenth 2018).

var	hor	contrast	estimate	SE	z.ratio	p.value	sign
N concentration	L	UN - CCF	0.12	0.05	2.35	**0.02**	*
	F	UN - CCF	0.10	0.04	2.49	**0.01**	*
	H	UN - CCF	0.30	0.09	3.19	**1.41e-03**	*
	A	UN - CCF	0.03	0.04	0.80	0.42	
CN ratio	L	UN - CCF	-9.94	3.58	-2.78	**5.45e-03**	*
	F	UN - CCF	-1.45	0.79	-1.83	0.07	
	H	UN - CCF	-3.09	1.22	-2.53	**0.01**	*
	A	UN - CCF	-3.66	1.23	-2.99	**2.81e-03**	*
Nitrate	H	UN - CCF	-0.31	0.29	-1.06	0.29	
Ammonium		UN - CCF	34.70	15.46	2.24	**0.02**	*
Nitrate	A	UN - CCF	-0.03	0.13	-0.21	0.83	
Ammonium		UN - CCF	7.74	8.14	0.95	0.34	
Cell solubles	L	UN - CCF	0.01	0.84	0.01	0.99	
	F	UN - CCF	1.68	1.08	1.56	0.12	
	H	UN - CCF	-5.47	2.39	-2.28	**0.02**	*
Hemicellulose	L	UN - CCF	-0.33	0.24	-1.41	0.16	
	F	UN - CCF	-1.80	0.67	-2.68	**7.45e-03**	*
	H	UN - CCF	1.70	1.26	1.35	0.18	
Cellulose	L	UN - CCF	0.38	0.50	0.76	0.45	
	F	UN - CCF	0.54	0.54	1.00	0.32	
	H	UN - CCF	-0.12	0.83	-0.15	0.88	
Lignin	L	UN - CCF	-0.06	0.79	-0.07	0.94	
	F	UN - CCF	-0.41	1.19	-0.35	0.73	
	H	UN - CCF	4.03	1.67	2.42	**0.02**	*
LCI	L	UN - CCF	-0.00	0.01	-0.13	0.90	
	F	UN - CCF	0.01	0.01	0.51	0.61	
	H	UN - CCF	0.07	0.05	1.36	0.17	
Ash	L	UN - CCF	0.16	0.07	2.27	**0.02**	*
	F	UN - CCF	0.20	0.43	0.47	0.64	
	H	UN - CCF	-2.37	2.19	-1.08	0.28	

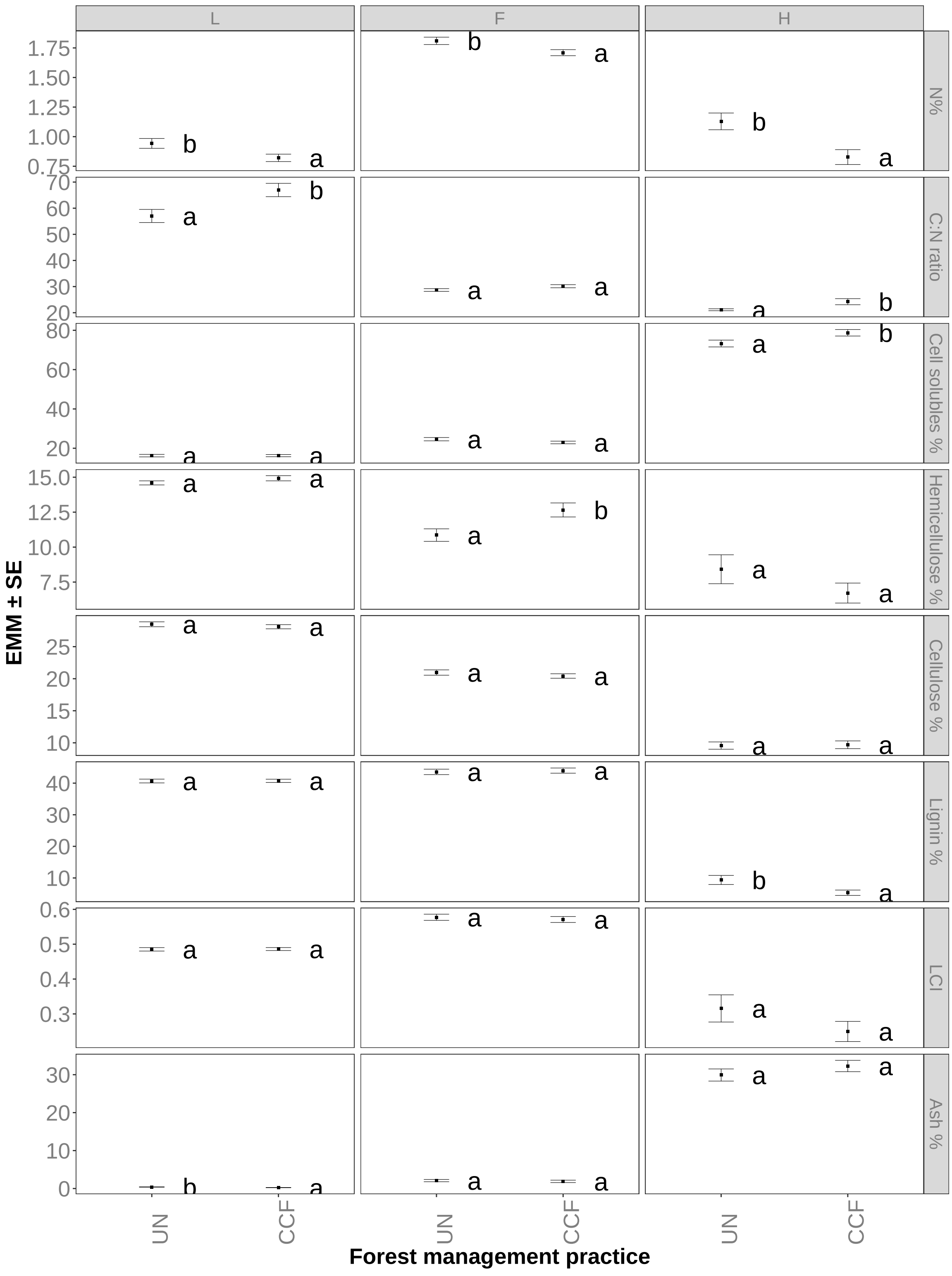

Figure 4.13: Clocaenog Forest - C quality: estimated marginal means by management practice. Boxes indicate the estimated marginal means. Error bars are estimated marginal mean +/- SE. Means sharing a letter are not significantly different (Tukey-adjusted comparisons). N%, C:N ratio, proximate C pools, LCI and ash content.

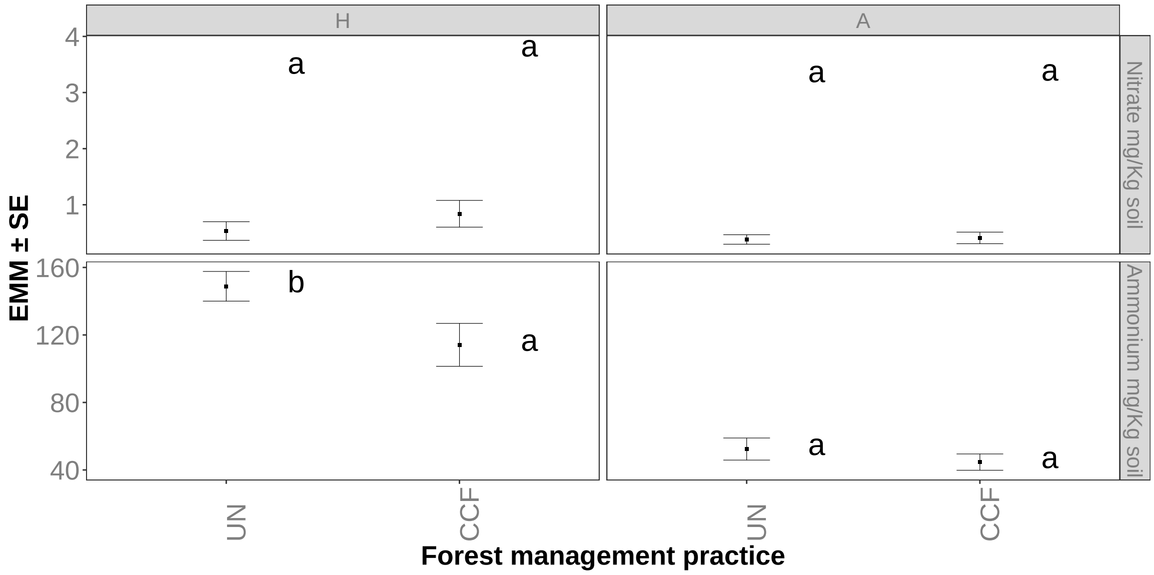

Figure 4.14: Forest of Clocaenog - C quality: Estimated marginal means by management practice. Boxes indicate the estimated marginal means. Error bars are estimated marginal mean +/- SE. Means sharing a letter are not significantly different (Tukey-adjusted comparisons). H and A horizons available N.

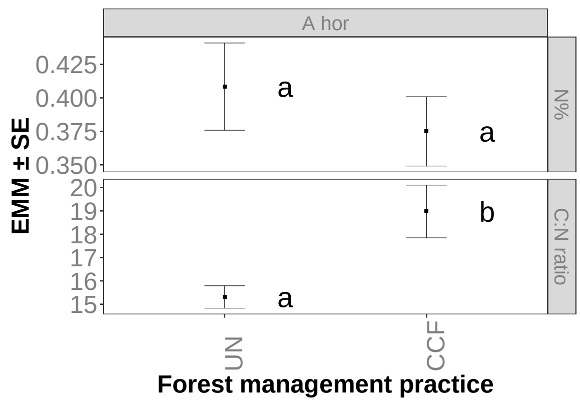

Figure 4.15: Forest of Clocaenog - C quality: Estimated marginal means by management practice. Boxes indicate the estimated marginal means. Error bars are estimated marginal mean +/- SE. Means sharing a letter are not significantly different (Tukey-adjusted comparisons). A horizon C concentration and C to N ratio.

4.3 Discussion

4.3.1 Clearfell experiment: Forest of Ae

4.3.1.1 N concentration, C:N ratio and available N

Results from N concentration (%) in the present research found no difference between the treatments in any of the horizons under study twenty-two years after planting. This suggests a limited role of N% relating to within-horizon soil C stock[3] accumulation between the treatments. While N% in the F horizons increases on average (WTH, CH, CHF from the lowest) differences between the treatments were not significant; this may reflect the cumulative fertilizing effect of brash (CH, CHF) and fertilization (CHF). This study highlighted a higher N% independently of treatment from the L to H horizon which is linked to the stage of decomposition of the material and a lower N% in the organo-mineral A horizon (figure 4.1).

With the exception of the L horizons (results ≥ 50, see figure 4.2) the remaining soil organic horizons under study (F and H) resulted in C:N values between 13 and 44. These are typical values reported in a study conducted in 4000 European forest plots which analysed the factors determining C:N ratios of forest floor and peat top soil (Cools et al. 2014).

C:N ratio results from the current study indicate significant lower values in the F horizon of the CHF treatment compared with WTH and CH. This did not negatively affect the C stock of the horizon which instead was significantly higher in CHF and CH compared to WTH. This may be the result of both fertilization and brash retained after harvesting, where litter deriving from forest canopies would have been enriched in N compared to other

[3]Soil C stock as the single, most important variable in the experiment to ultimately measure the potential of the treatment to mitigate the effect of climate change.

treatments. While the WTH treatment in the soil H horizon displays a slightly higher C:N ratio compared to the other treatments, it was not significant. Results are in line with findings from Smolander et al. (2008). This reports higher C:N ratio and lower C mineralization rates in the H horizon of a litter decomposition experiment with mesh bags as a consequence of WTH thinning when compared to CH after 10 years on a relatively fertile Norway spruce stand.

C:N ratio decreased from the L to the H horizon independently of treatment as found in previous studies (Gartzia-Bengoetxea et al. 2009; Cools et al. 2014) and increased in the A horizon. The A horizon of the WTH treatment had the highest mean and median values (25 or above), while CH and CHF had non-significant lower values. With reference to C:N ratio values, all treatments of the soil H horizon fall below the threshold value of 25 denoted as an indicator for potential nitrate leaching (Vanguelova and Pitman 2019). In particular, WTH treatment showed a higher median value of ~ 24, followed by CH (> 22) and CHF (~ 22).

Vanguelova et al. (2010) in a very similar experimental setting in terms of soil and tree species at Kielder forest (but on a 27 years of second rotation Sitka spruce plantation) found differences in N stock in the L and F horizon where CHF resulted in significantly higher N stock compared to WTH and CH. Significant differences were also found in the H and A horizons with highest values in the WTH treatment. Kaarakka et al. (2014) found no difference in C:N ratio of the organic layer (O_{fh}) and mineral soil between WTH, CH and CHF (P 40 and N 150 kg ha^{-1}) during thinning practices and ten years after final harvesting on a fertile Norway spruce experiment.

The meta-analysis from Johnson and Curtis (2001) found that WTH on average reduces the total soil C and N concentration in the A horizon (-6% and -10%), while CH increases both C and N of 18% compared to the Control, although the WTH treatment included floor removal in the meta-analysis which may have accentuated such differences.

One study found that in mixed forested watershed sites in eastern Maine (USA) eight years of bimonthly ammonium sulphate application significantly reduced the C:N ratio of the forest floor (from over 30 to over 23) (Parker et al. 2001). Fertilization treatment also had reduced N and C stock compared to the reference treatment. The study from Vanguelova et al. (2010) in Kielder forest, north of England found significantly lower C:N ratio values in the CH treatment in the F horizon, while no difference was found in the H horizon. The present study found significantly lower C:N ratio in the CHF treatment compared with WTH and CH, which reflects the effects of both brash retainment at the time of harvesting and fertilization.

The meta-analysis from Achat et al. (2015) primarily based on temperate to cold climate analyses a range of forest management practices, from CH to intense bioenergy harvest (stem, branches foliage and forest floor removal). This found that utilization intensity significantly reduced the quantity of soil nutrients. Soil N losses were significantly affected by forest management practice: total soil N stock in the forest floor was significantly reduced (-12.1%) when compared to CH, while N concentrations were lower but not significant in WTH. Similar significant reductions were also found for Ca and P. Overall, N outputs from the forest caused by the removal of stem and branches were 37% higher compared with stem-only harvest, while the further removal of foliage (WTH) led to 87% more N outputs, which raised to 117% when also stump and roots were removed. Changes in the nutrient balance were more evident in conifer species; differences in total N were more evident in sites with temperate climate.

In the present study, available N results from the H horizon found significantly higher concentrations of nitrate in the CHF treatment compared to WTH. This was reflected in the C stock of the H horizon for WTH (see figures 3.5 and 4.3 and tables 3.2 and 4.1), which was the highest among the treatments, suggesting that forest brash retention and fertilization may increase the rate of mineralisation of existing soil organic C and N stocks in the longer term, but for now differences are not significant[4]. However in Vanguelova et al. (2010) in a 28 years second rotation of Sitka spruce the significant reductions in water content and total soil N and C concentrations in the H and A horizons for the CH treatment compared to WTH point towards an increase in the rate of mineralization of the stock of N and C for CH as a result of the retention of forest residues on the forest floor. This was supported by a significantly higher available nitrate in the CH compared to the WTH treatments in Vanguelova et al. (2010). No difference in ammonium between the treatments was found in the H horizon, and this is also reflected in the study from Vanguelova et al. (2010). Results contrast with the meta-analysis from Achat et al. (2015); this only found significant differences in available N for more intense bioenergy harvesting practices (forest floor removal) when compared to CH.

Significant losses in water content and soil N and C concentrations in the CH treatment when compared to WTH are claimed to be the result of the increased rate of mineralization of SOC and N stocks caused by higher tree uptake and residue retention as found in Vanguelova et al. (2010). This would be justified by the higher available N in the CH and CHF treatments. Additionally, intensity of forest residue harvesting has been shown to result in reduced microbial activity and lower available N (Hassett and Zak 2005).

Available N in the form of nitrate in the soil can be easily leached, affecting streams and groundwater (Nieminen 2004; Bergholm et al. 2015). It is also claimed that plant available

[4] See also the variability of block replication discussed in chapter 3.3.1

N may be more sensitive to forest management practice than total N (Tamminen et al. 2012). The main ions associated with CEC in soils are the exchangeable cations calcium, magnesium, sodium and potassium, or base cations. When nitrification occurs[5], the soil acidifies. As a consequence, base cations are replaced by other cations (hydrogen, aluminium and manganese) which may result in a decrease in long term site productivity, with potential repercussions on the soil C storage. Brash retention on site after harvesting operations, as well as higher levels of nitrate are often associated with increased rates of SOC and N stock mineralization (Vanguelova et al. 2010).

Smolander et al. (2008) found a non-significant, yet lower rate of C mineralization for the H horizon associated with higher C:N ratio in WTH compared to CH ten years after treatment in a 40-year-old Norway spruce stand on relatively fertile podzol and mor humus in Finland.

The experiment at a “moist-cool forest” in north-western Montana (Jang et al. 2016) subject to pacific maritime climate on a loamy-skeletal isotic Andic Haplocryalfs soil (USDA 2014) found no difference in total soil C, N and nutrients within the forest floor between utilisation intensities (among which the untreated Control treatment, medium and high utilization) 38 years after harvesting, suggesting these had little long-term impacts on soil C and OM. Since the present study found significant differences in total C and N % between utilization intensities, these may be explained by differences in soil type, climate and tree species (Pacific maritime with European larch and Douglas fir as major overstory tree species in the case of Jang et al. (2016)).

N fertilization has been recommended as a management practice to increase the stock of SOC (Lal 2005; Finn et al. 2016). While the L horizon is usually accounted for aboveground C, results from the present study suggest that there is an evidence of increased C stock in

[5]Nitrification is the conversion of ammonium to nitrate. This creates H cations that acidify soils.

the L horizon when comparing CHF to CH. This suggests a potential for the L horizon to increase SOC stock when decomposition processes move the C in the lower horizons. However, horizons F and H did not show significant differences between CHF and CH and results suggest that C from the L horizon did not contribute to a difference in C in lower organic horizons. The C costs of extracting, processing, transporting and applying fertilisers are not quantified in the present study. These should ideally be included in the C balance of the fertilization treatment.

C stock and N concentration of all soil horizons combined exhibit polynomial regression with C stock as quadratic term and N % as response variable (see model formula (4.6)).

$$lm(N \sim C_{stock} + (C_{stock})^2) \tag{4.6}$$

This model was a better fit and resulted in a significant improvement compared with the linear model N $\sim C_{\mathrm{mass}}$ (Anova F test $p < 0.01$) providing evidence of curvature in these data. The regression provided a very good fit ($R^2 = 0.936$, adj$R^2 = 0.931$).

These results suggest that consistently, the soil H horizon of block replication one for the CH and CHF treatments resulted in lower C %, N % and C stock values on average, even by looking at the sub-replicates level (see figures 3.4, 3.5, 4.1). The CH and CHF treatments in block one are adjacent, separated only by a corridor and in close proximity to the road which suggests that they may share similar past land utilization (figure 2.2 and 2.1). Both plots had similar values of H horizon C stock as did the average F horizon C stock, but also similar values of N concentration. This suggests that in this experiment, under the specific site conditions at the Forest of Ae, C stock may be utilized as a proxy to estimate N concentration in the OSH, and vice-versa (see figure 4.16, and table 4.3). This would save the time-consuming and labour-intense processes (in both field and laboratory) of having to measure soil C stock from soil cores and pits as this would be all done with Dutch auger. The prediction equation is:

$$N = 1.092 + 0.009523 * C_{stock} + (-1.963e - 05) * C_{stock}^2 \quad (4.7)$$

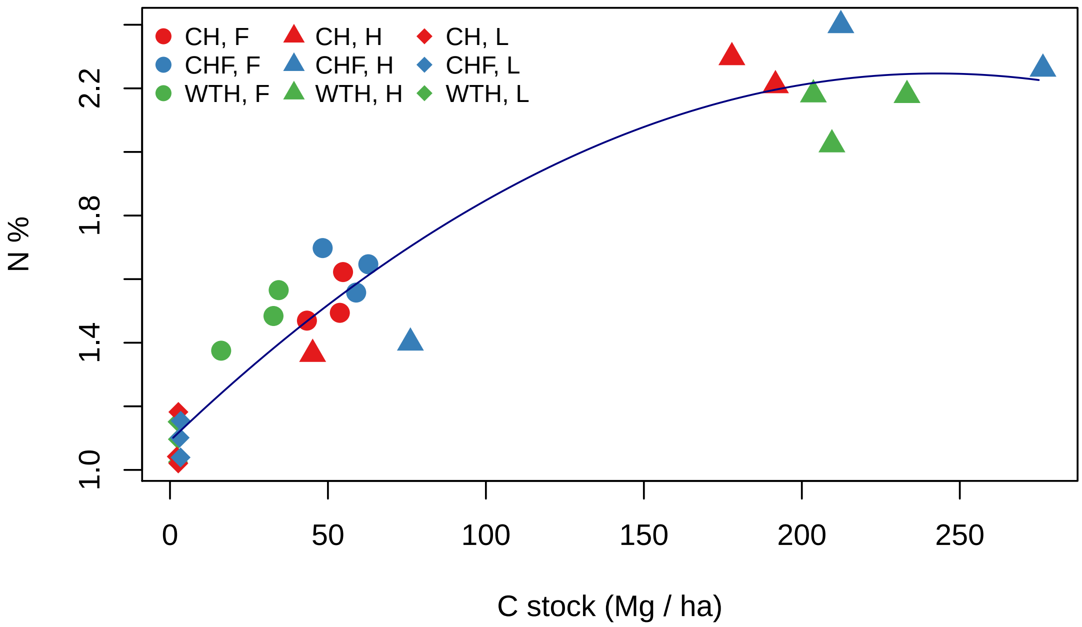

Figure 4.16: Forest of Ae. Polynomial regression of C stock and N concentration (%) for soil L, F and H horizons. lm (N ~ C_{stock} + C_{stock}^2). $R^2 = 0.936$, adjR^2= 0.931. See prediction equation (4.7). Legend: the first term defines the treatment, the second the soil horizon.

As pointed out in chapter 4.3.1.1, C:N ratio values for treatments in the H horizons are all below the threshold of 25, indicating potential soil N leaching, particularly for the CH and CHF treatments. This, coupled with plateauing levels of N concentration for all the treatments and non-significant differences in C stocks suggest that retention of forest residues

Table 4.3: Polynomial regression results of fitting the quadratic equation. Both regression coefficients are significant at $p < 0.01$ level. The significance of the squared term ($t = -4.373$, $p < .001$) suggests that inclusion of the quadratic term improves the model fit.

attribute	Estimate	Std. Error	t value	Pr(>|t|)
intercept	1.09	0.04	28.90	**3.68e-20**
Cstock	0.01	0.00	8.62	**8.23e-09**
CstockSquared	-0.00	0.00	-4.37	**2.04e-04**

on site and fertilization practices may increase the rate of mineralisation of existing SOC within the H horizon. As mentioned earlier in the chapter, the C:N ratio is significantly lower in the CHF compared to the other treatments in the F horizon, and the concentration of nitrate is significantly higher in CHF compared to the WTH treatment. All these aspects may promote a greater N uptake and above-ground C capture for CH and more so for the CHF treatment. In this respect, the study from (Mason et al. 2012) on the same experimental site at the forest of Ae found that ten years after planting WTH resulted in lower height (up to 9 %) and diameter growth (up to 19 %) when compared to treatments where brash was left on site and fertilisation applied.

Brash left on site lead to a significantly higher C stock in the F horizon (CH and CHF) and fertilization lead to significantly higher C stock in the L horizon (CHF). Coupled with results from above-ground growth (Mason et al. 2012) the present study highlights the need to retain brash on site after harvesting and fertilisation, confirming that the deleterious effect of the WTH treatment on both below- and above-ground C capture continues more than twenty years after planting. While the contribution of the L horizon in terms of C stock within the OSH is limited, fertilization practices may be recommended on soils with poor nutrient regimes. This is also supported by above-ground results from Mason et al. (2012) consistently pointing towards taller and larger diameters trees in the fertilized plots, compared to the removal of brash and conventionally harvested plots.

4.3.1.2 Soil proximate carbon pools and fractions

No significant differences in the proximate cell solubles pool were observed between treatments.

In the F horizon Lignocellulose index (LCI) values (for formula see equation (4.5)) were significantly higher in the CHF treatment (median 0.54) compared with WTH (median $<$ 0.50). In this instance, the soil C stock in the F horizon was significantly higher in the CHF and CH compared to WTH[6], supporting reports of decreases in rate of decomposability with higher LCI values (Moorhead et al. 2013). The higher LCI and higher amount of C stock in the F horizon for the CHF compared with the WTH treatment may have been caused by the fertilization; since in terrestrial ecosystems N deficiency can limit forest productivity above- and below-ground (Pennock and VanKessel 1997; LeBauer and Treseder 2008), the physical removal of forest brash may have exacerbated litterfall accumulation in the WTH treatment caused by soil nutrient unbalance in the forest floor.

The amount of hemicellulose was significantly higher in the H horizon[7] for WTH compared to CHF. The cellulose pool of C was significantly lower in the L horizon for CH (median around 25%) compared to the other two treatments (medians around 27%). The pool of lignin did not result in any difference between treatments, although for the L horizon it was lower on average ($<$ 28%) in the CHF treatment when compared to CH and WTH ($>$ 28%). Median values were $>$ 29%, $>$ 28% and $<$ 28% for WTH, CH and CHF respectively. The F horizon lignin was lower in the WTH treatment (median around 37%) when compared to CH and CHF (medians around 42%); this reflects LCI results pointing to higher decomposition

[6]F horizon C stock was lower on average, but not significantly in CH compared to CHF. F horizon LCI was higher on average, but not significantly in CHF compared to CH.

[7]Refer to chapter 4.3.1.2 for a discussion on the limitations of the forage fibre analysis technique on the H horizon.

rates in the F horizon for WTH.

This study has highlighted some of the limitations of the forage fibre analysis when applied to soil with particle size smaller than the porosity of the filter bag in the fibre analyser (25μm). By observing figures 4.5 and 4.12, the H horizon loses a comparatively high amount (%) of material in the first cycle of the fibre analyzer (NDF, see from chapter 2.2.2.4), this being more evident in the Clocaenog experiment. When the soil H horizon was included in a batch of the forage fibre analyser, the results had to be adjusted[8] as the blanks confirmed the slippage of material from the filter bags. This did not occur in batches with L and F horizons only. The usage of the forage fibre analysis technique for humic and mineral horizons is therefore inadvisable.

In a litter bag experiment, Hobbie et al. (2006) found that microbial rates of litter decomposition were weakly positively related (p=0.06) with mean annual soil temperature and significantly negatively related with litter lignin. The same study suggests that because soil community and physical environment may be affected by plant taxonomy, ultimately tree species are responsible for the microbial decomposition rates through their effects on litter lignin and Ca content. This indicates that plant genera such as *Picea* or *Abies* affect the decomposition rates by lowering the soil temperature and rate of decomposition, suggesting how interspecificity may be a driver in soil decomposition and Sitka spruce stands such as the ones used in the clearfell and CCF experiments may be subject to slow overall C turnover. Hence, results from Hobbie et al. (2006) suggest that the weak differences in the proximate C pools between the treatments in the present study may be justified by both within-species comparison between the treatments as well as well as the low disturbance of the treatments which, with the exception of the CHF treatment have

[8]Specifically, results had to be reduced.

not incurred in any change since planting took place in 1996-97.

Brash management in WTH, CH and WTH with forest floor removal treatments on a 4-20 year old *Pinus radiata* stand (Huang et al. 2011), caused the C stock in the heavy fraction to be significantly higher in WTH and CH when compared with WTH with floor removal in one of the forests under analysis, while in the other forest only CH had significantly higher soil C mass in the heavy fraction. CH management also showed higher cutin- and lignin-derived C than the other treatments. Huang et al. (2011) argues that the 'recalcitrant' C within the heavy fraction that is returned to the sites depends on the amount of residue returned. This would confirm recent research findings suggesting that the 'effective C saturation' by which soil C saturation may be affected by climate and also by the management practice adopted could affect the soil C stabilization potential (Castellano et al. 2015). Huang et al. (2011) concentrates on the mineral soil horizons. Nevertheless it provides evidence of dynamics of C accumulation underneath the OSH that are in favour of CH practices, leading to higher C stocks when compared with more intense harvesting regimes. While further research is needed to confirm this, similar dynamics may be undergoing at Clocaenog forest.

4.3.2 Continuous-Cover-Forestry trial: Clocaenog

4.3.2.1 N concentration and C:N ratio

Soil N concentrations were higher in the UN treatment compared to the CCF, with significant differences between treatments for the L, F and H horizon. The C:N ratio reflected these results, with the L, H and A horizons in the UN treatment having significantly lower values compared to CCF. A recent study conducted in 190 plots in temperate European mixed forest (Maes et al. 2019) found that litter quality is a strong driver of topsoil conditions, and the chemistry of litter (e.g. C:N ratio, exchangeable base cations and total P) can affect the humus layer and its biological activity (De Wandeler et al. 2018). This ties in with statistical analysis results of C stock calculations in the present study, where the higher presence of N in the UN treatment for all of the horizons may exert negative effects on the C stock within the H horizon. This would be particularly important if in order to store more C in the soil, litter C can be diverted to humus through biochemical and microbial activities (e.g. enzyme inhibition and formation of novel recalcitrant compounds) rather than allowing it to decompose (Prescott 2010). One study claims that in European forest soils, C:N ratio within the forest floor is mostly affected by tree species (Cools et al. 2014). The present study highlights the effects of forest management practices on the soil OSH C:N and the potential for this to affect the dynamics of OSH C storage. Since forest management practices have been shown to reduce microbial biomass, enzyme activity and soil N cycling (Hassett and Zak 2005) further research is now necessary to understand if the results from Clocaenog indicating significant reduction in soil C stock for the H horizon of the UN treatment are attributable to the same dynamics.

In their meta-analysis of studies conducted on temperate and boreal forests, Hume et al. (2018) compared CH, WTH and partial harvesting with uncut Control. Hence, the treatments covered in the study can be relevant for both the clearfell site at the Forest of Ae and the CCF trial at Clocaenog. Hume et al. (2018) found that WTH had the largest negative effect on forest floor N and C concentrations, with the CH treatment resulting in only marginal decreases. C:N ratios decreased in the WTH and CH treatments when compared to the Control, but not in the partial harvest treatment (differences were not significant). Conifer forests were the most negatively affected in terms of soil C concentration, N, C:N and P. With regards to the C concentration, the WTH treatment in the study at the Forest of Ae resulted in opposite dynamics, showing significantly higher C % in the WTH treatment compared to CH. Hume et al. (2018) also showed an increase in C:N ratio in the partial harvest treatment compared to Control, albeit results were not significant. Although it is not possible to underpin the exact role of the partial harvest given the inherent variability of the meta-analysis approach, results appear to agree with those in the present study (CCF Clocaenog) where C:N ratios were consistently higher in the CCF treatment compared to UN. Emmett et al. (1995) found that when mature Sitka spruce stands in upland Wales are subject to soil N deposition in excess of N ecosystem critical loads it can lead to high levels of N leaching. In addition, the same study investigated the age effect of Sitka spruce in unlocking N leaching and determined that this point is reached in mature Sitka spruce plantation. This suggests that by opening the canopy to encourage regeneration the CCF treatment may have further beneficial effects on N cycling by delaying the process of soil N saturation and leaching. Additionally, the leaching of nitrate may deplete base cations; these are mobilized by the release of hydrogen during the nitrification process and may result in a decrease in long term site productivity and consequent decrease in C storage above- and below-ground. This suggests that an analysis of base saturation may be needed to reveal differences in site productivity between silvicultural systems (Hume et al. 2018).

Future efforts should extend to long-term studies in the effects of CCF silvicultural systems on the overall quality of OSH since the latter is known to affect nutrient sustainability and tree growth (Jandl et al. 2007; Vanguelova et al. 2010). For instance, effects of harvesting on soil C and N are comparatively well researched; by contrast the effects of geochemically-controlled P are less known, despite its potentially limiting effects on forest productivity in temperate forest soils and its apparent decouple from the N and C cycle, these being subject to atmospheric N deposition and C emissions respectively (Hume et al. 2018).

By looking at the C stock and N scatterplot (figure 4.17), dynamics of soil C storage in relation to N availability are more complex when compared to the clearfell site at the Forest of Ae (figure 4.16), there seems not to be a clear role of N on the OSH as a whole.

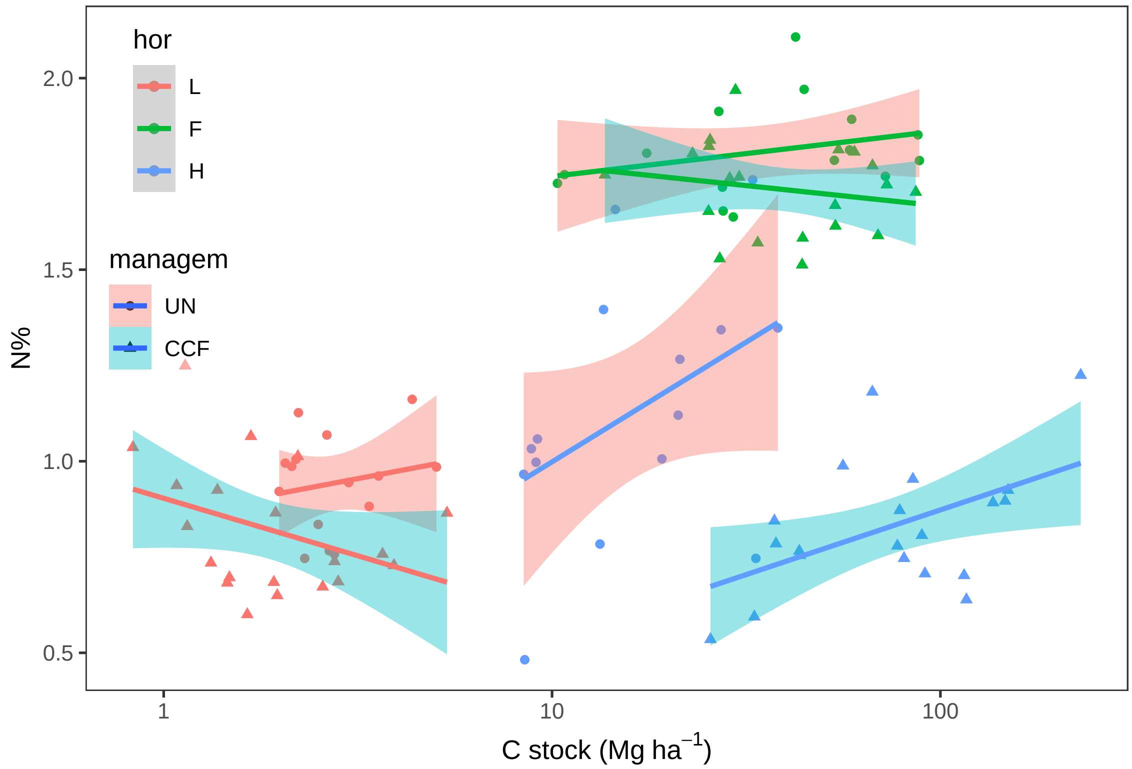

Figure 4.17: Clocaenog Forest. Scatterplot of soil C stock (on a $\log_{10}$ scale, Mg ha^{-1} y^{-1}) by total soil N % divided by soil horizon. Within horizon N concentration is positively related to C stock for the UN treatment and the H horizon of the CCF treatment. N concentration is negatively related to the amount of soil C in the L and F horizon of the CCF treatment. Linear model fitted with confidence interval (0.95). "hor": soil horizon; "managem": forest management practice.

Contrary to the Forest of Ae, the N concentration of Clocaenog decreases in the H horizon compared to the F horizon. In particular, while total N concentrations and C stock for the L and F horizons are in line between the two sites, the H horizons at Clocaenog are comparatively N and C stock depleted and it was not possible to build a regression line that describes the dynamics of C stock in relation to total N concentration for the OSH as a whole.

It is possible to affirm that, by looking at figure 4.17, the H horizons within both treatments still respond positively in terms of C stock to the concentration of N (see trend lines). The H horizons at Clocaenog forest did not plateau as for the Forest of Ae, suggesting that the treatments at Ae may be approaching steady-state conditions. At Clocaenog forest, results suggest contrasting C dynamics between the two treatments in the soil H horizon. Significantly higher accumulation of soil C in CCF compared to UN treatment may result from higher and more diverse C inputs from both mature Sitka spruce in addition to the second storey of Sitka spruce regeneration, together with rich herbaceous layers which are found at the CCF, but not under the UN treatment. Forest floor C dynamics may also be different under CCF as a result of a much higher above-ground biodiversity compared to monoculture and even aged Sitka spruce stand in the UN treatment. On the other hand, the UN treatment soil C in the H horizon does not accumulate and it is more likely to be mineralized (Castellano et al. 2015); this may be a consequence of the significantly higher concentration of N in the UN treatment in all but the A horizon (this being higher on average for the UN treatment albeit not significantly).

Differences in soil C stock within the H horizon may also be the result of a higher water table and water content in the CCF treatment, although differences in depth of the water table within the H horizon cannot be confirmed as the UN treatment water content was not measured due to the shallow depth. Nevertheless, the occasional formation of a gley horizon underneath the H horizon for the CCF treatment (in which case it is more appropriately described as an O horizon (see chapter 1.3), and not occurring in the UN treatment) suggests that this may be the reason (compare diversity of soil pits between and within treatment on figure 2.16 and figure 4.18). Additionally, previous studies at Clocaenog forest demonstrated that soils under CCF (uniform shelterwood) have a significantly higher water holding capacity (8 and 5% higher for organic and mineral soils respectively) when compared to conventional clearfell managed forest stands (Pitman et al. 2011). The variability of soils highlighted in table 2.2 was more evident in CCF treatment.

Figure 4.18: Clocaenog forest: CCF treatment. Left: soil pit in one of the respacing sub-plots showing diffuse transition (Zanella et al. 2011) of the H horizon over the organo-mineral A horizon. Contrary to the soil pit shown in 2.16 there is no gley formation; right: detail of the gley horizon in sub-plot '5 m distance between regeneration trees after respacing'.

The cause may be related to diversity at micro scale which lead to a different stratification of the soil profile (although measures were taken to prevent this by identifying the best experimental plots based on slope and aspect, see chapter 2.1.2) both within and between the treatments. Another reason could be higher tree water uptake and potential evapotraspiration in the UN treatment resulting from the higher above-ground biomass (see table 2.2) and water interception in the lower canopy of the CCF treatment.

Available N in the form of ammonium increased with soil C concentration (%). As a whole, linear regression of soil ammonium content in the H and A horizons (see figure 4.19 and prediction equation (4.8)) had a regression coefficient of 4.8 ($p < 0.01$, see table 4.4).

$$ammonium = 20.26 + 4.806 * C_{concentration} \tag{4.8}$$

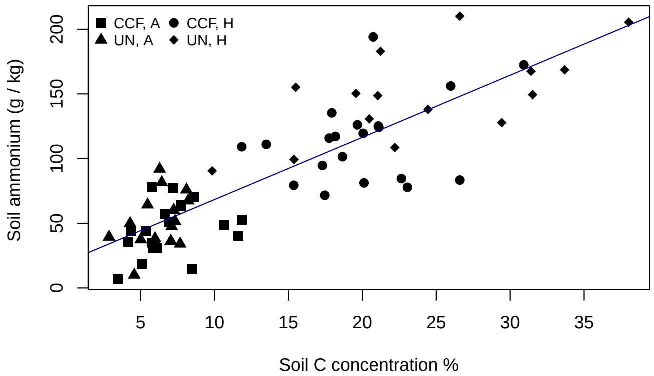

Figure 4.19: Linear regression of soil ammonium and soil C concentration (%) in the H and A horizon.

Table 4.4: Summary table of the linear regression for soil ammonium and soil C concentration.

Attribute	Estimate	Std. Error	t value	Pr(>|t|)
Intercept	20.26	6.17	3.28	**1.63e-03**
C conc	4.81	0.37	13.01	**3.95e-20**

The model accounts for 71% of variance in ammonium (R^2 = 0.714, adjR^2= 0.709). Ammonium content in the soil H horizon was significantly lower in the CCF treatment compared to UN. Nevertheless, C % is not significantly different between the two treatments in the H horizon, although it is lower on average for CCF (figure 3.10). The higher available ammonium under UN in the H horizon ties in with the significantly lower C:N ratios in the L, H and A horizons and lower C:N ratio on average in the F horizon for UN treatment (table 4.2). This can potentially exacerbate N mineralization (Vanguelova et al. 2010) and increase cation leaching. At the same time the UN treatment may exacerbate the rate of mineralization of SOC which results in lower levels of C accumulation in the H horizon. Being the H horizon the OSH that by far stores the most C in the UN treatment, the effects of forest management practices on soil N dynamics may greatly affect the ability of the soil to stock C.

4.3.2.2 Soil proximate carbon pools and fractions

Similar to results in the clearfell site at the Forest of Ae, the role of soil OSH proximate C pools in relation to forest management practice is unclear. Results confirm a significantly higher amount of cell solubles in the H horizon[9] of the CCF treatment. The hemicellulose pool of C is significantly higher in the F horizon of the CCF compared to the UN treatment (median values: CCF $<$ 11%, UN $>$12%). Percentage differences in hemicellulose values are minimal; the reason for the significant results may be attributable to differences between respacing subplots in the CCF treatment and model-handling of differences within the random effects. There was no difference in cellulose and LCI values values between treatments.

Proximate lignin pool was significantly lower in the H horizon of the CCF treatment. It is known that more energy is required to degrade compounds such as lignin (lignin polymers are oxidised using fifteen exo-enzymes, (Ekschmitt et al. 2005)) when compared to cellulose. Therefore, lignin requires more enzymatic steps to release a C atom as CO_2 and it is considered of low quality (poor quality for microbial growth, and high activation energy). However, it is also true that adapted decomposer organisms use enzymes to cope with energy problems in metabolic pathways (Marschner et al., 2008). Organisms produce a great number of enzymes that catalyse the decomposition of any stabilising substances (i.e. keratin, peptidoglycan, melanin, beta-glucan, polyphenols, cutin, lignin, hemicellulose and cellulose) in the immediate environment (Moorhead et al. 1996; Ekschmitt et al. 2005; Gartzia-Bengoetxea et al. 2009). Therefore, results from the present study suggest that the lower presence of N as nutrient in the CCF treatment may have caused the microbial

[9]Refer to chapter 4.3.1.2 for a discussion on the limitations of the forage fibre analysis technique on the H horizon.

community to degrade the proximate, lower-quality and higher-activation-energy lignin pool in the H horizon.

4.4 Conclusions

The clearfell experiment at the Forest of Ae on a second rotation 22 year old Sitka spruce plantation highlighted C:N ratios that suggested higher decomposition rates in the F horizon of the CHF treatments (a significantly lower C:N ratio in the CHF compared to the other treatments). However, higher decomposition does not necessarily translate into lower C stock and mitigation potential. This is because the balance of soil C stock is not only the result of SOM decomposition but also the inputs of fresh litter on the forest floor (Todd-Brown et al. 2013; Bradford et al. 2016) and the brash left on site at the time of harvesting (Gartzia-Bengoetxea et al. 2009). Referring back to chapter 3, while decomposition rates in the F horizon of the CHF treatment may be significantly higher (microbial respiration rates would be necessary to confirm this), the higher presence of brash and litter production of the CHF treatment may have contributed to a higher C stock. The CHF treatment resulted in significantly higher presence of nitrate (H horizon) compared to the WTH treatment. The H horizon, or soil OSH with the highest C stock did not result in significant differences between treatments. Nevertheless, lower C stocks on average for CHF compared to WTH treatments suggested that fertilization may, in the long term, promote soil C and N mineralization, lowering the atmospheric C sequestration potential of the forest management treatment.

The forage fibre analysis resulted in non-significantly, lower-on-average lignin values for the WTH treatment in the F horizon. This (albeit to a lesser extent when compared to brash left on site and litter production) may have contributed to the significantly higher C stock accumulation within the F horizon for CH and CHF treatments, since lignin is the pool of C with the highest activation energy. Additionally, significantly higher results for

LCI in the CHF treatment compared to WTH suggest lower decomposability of the CHF treatment in the F horizon compared with WTH. This is in agreement with results from lignin concentration and C stock accumulations.

The experiment at Clocaenog forest on a second rotation 70 year old Sitka spruce plantation highlighted a consistently higher, primarily significant N% (L,F and H horizons) in the control, unthinned UN treatment and a consistently lower, primarily significant C:N ratio (L,H and A horizons). Together with significantly higher ammonium within the H horizon of the UN treatment, all results point to a higher soil C mineralization rate. This is reflected in soil C stock results from chapter 3 where the CCF treatment was significantly higher in the H horizon, with nearly 70 Mg C ha^{-1} more than the UN treatment. This translates to a much higher mitigating effect for the CCF in transformation to irregular shelterwood compared to conventionally managed forest.

The higher lignin content found in the H horizon of the UN treatment suggest lower decomposition rates and is in contrast with significantly higher presence of N (both as N% and ammonium) in the UN treatment which would suggest higher decomposition rates. It also has to be pointed out that the forage fibre technique was an inappropriate method for analysing the proximate C pools of the H horizons due to slippage of soil material from filter bags.

The next chapter will focus on understanding whether the contribution to soil C stock from Sitka spruce biomass and necromass, growth and turnover of fine roots is affected by the adopted management practice.

Chapter 5

Forest management impacts on tree fine root C

5.1 Introduction

5.1.1 Overview

Globally, roots contribute up to 40% of the total biomass in forest ecosystems (Brunner and Godbold 2007). Research activities associated with roots are generally regarded as labour-intensive and with methodological issues (cost, accuracy and time efficiency) which makes root studies one of the least-covered areas in terrestrial ecosystems. As a result, often only the above-ground contribution of litter is reported; hence, fine roots[1] are poorly represented in forest ecosystem models (Godbold and Lukac 2011; Addo-Danso et al. 2015; Donnelly et al. 2016). For these reasons, knowledge of the response of fine roots to increasing temperatures and levels of CO_2, as well as soil nutrient regimes and forest management is

[1] defined as roots with Ø $\leq$ 2mm, (Luo 2003; Guo et al. 2004; Strand et al. 2008; Hobbie et al. 2010; Shen et al. 2017)

very limited (Brassard et al. 2009), with recent findings pointing to a decrease in fine and absorptive root biomass with increasing soil temperatures (Shen et al. 2017; Parts et al. 2019; Wang et al. 2019). Forest management practices in particular are known to modify the production of fine roots, as well as their distribution (Andreasson et al. 2016). Yet, the contribution of fine roots (Ø < 2mm) to the below-ground C is essential, with turnover estimated in 0.5 to 3 Mg ha^{-1} y^{-1}, despite the great variability in turnover time, ranging from less than 2 to 18 years and alleged to be driven by methodological differences (Endrulat et al. 2010; Brunner et al. 2012). The variability is also intra-specific; a significant difference in biomass partitioning between and within Sitka spruce clones was found, with competitive interactions affecting fine root length and the root surface area (Donnelly et al. 2016). The dynamics of root biomass are claimed to be fundamentally important for a better understanding of C storage and allocation in terrestrial ecosystems (Helmisaari et al. 2007). SOC may be largely derived from fine roots, whose biomass was reported to contribute up to 67% of the annual primary productivity and being one to many times larger than litterfall-derived SOC (Jackson et al. 2017). Roots contribute from 30-46% of overall forest litter inputs (Andreasson et al. 2016). Nutrients and SOM resulting from the turnover of fine roots are therefore considered an influential source for soil C and a contribution from 20 to 80 % to soil nutrient turnover (Wang et al. 2014). Hence, their influence extends to the biological properties of the soil, as well as to the soil chemical and physical processes that affect productivity. This calls for an accurate estimation of fine roots production and turnover to better understand SOC dynamics and C cycling (Brunner et al. 2012; Wang et al. 2014; Neumann et al. 2020). In addition, understanding and quantifying the effects of driving factors for fine roots changes such as climatic changes and forest management is vital in order to predict SOC dynamics.

The process of fine root turnover is continuous throughout the development of a stand (Brassard et al. 2009). Fine roots are the means by which plants relocate C and energy from above-ground to below-ground; the high C fluxes associated with this, coupled with the short lifespan of fine roots makes it one of the larger C pathways in forestry. For these reasons, C reporting for climate change mitigation needs reliable and realistic data on fine root production and turnover to help parametrise forest ecosystem models, thereby optimizing current estimates of SOM response to management practice and global warming (Strand et al. 2008).

Forest management practices that promote uneven-aged structures with the recruitment of trees into successive age classes over time may improve forests C storage and resilience against climate change (Blasko et al. 2020). Fine root production is one of the critical factors affecting soil CO_2 fluxes in forest ecosystems (Peng et al. 2008) and fine roots play an essential role in C and nutrient cycling and plant growth. Knowledge about the effects of forest management practices is still limited (Shen et al. 2017).

The objective of the present study is to understand the effects of forest management practices (conventional clearfell, whole-tree harvesting and fertilization, see chapter 1.2 for an introduction on the treatments) on the dynamics of tree fine root production and turnover of typical British upland forest ecosystems.

5.2 Results

Please refer to chapter 2.2.1.3 for a description of the statistical methods utilised in this chapter.

Estimated marginal means for mixed effect model show significantly higher necromass in the 15 - 30 cm soil depth for CHF when compared to WTH ($p < 0.05$, see table 5.1). This was the only significant result in the present experiment (refer to figures 5.1 to 5.4 for visual data interpretation).

For the purposes of statistical analysis, data were averaged by block replication. For fine root turnover, median values were utilised. Data can be found in the Appendix (tables 6.10, 6.11). Contrasts between EEM of the treatments are shown in figure 5.5.

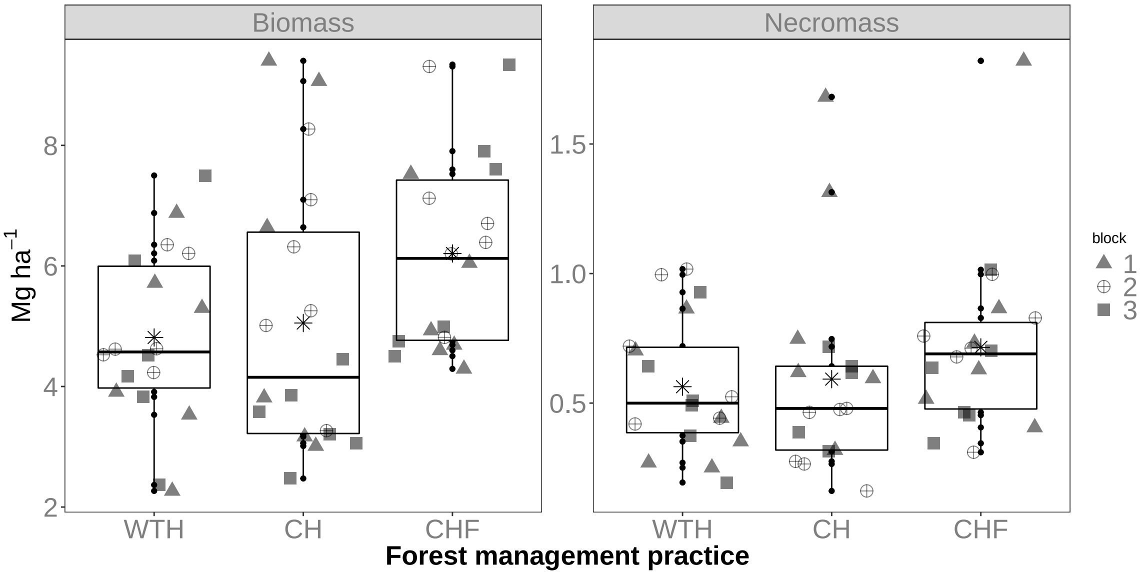

Figure 5.1: Forest of Ae - boxplot of fine root standing biomass and necromass (Mg ha^{-1}) within the 0-15 cm soil depth. Black dots refer to observations that may be outliers according to the rule ± 1.5 * interquartile range (Kabacoff 2015). Shape refers to block replication. Dots are randomly located on the x axis within the boxplot to improve visibility. Asterisk symbols are mean values.

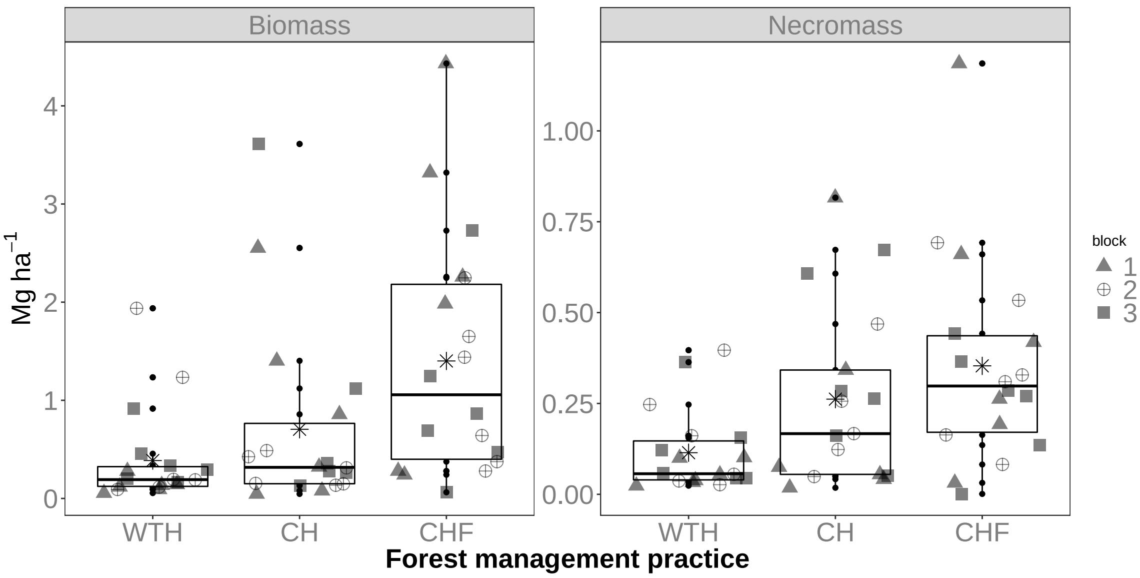

Figure 5.2: Forest of Ae - boxplot of fine root standing biomass and necromass (Mg ha^{-1}) within the 15-30 cm soil depth. Shape refers to block replication. Asterisk symbols are mean values.

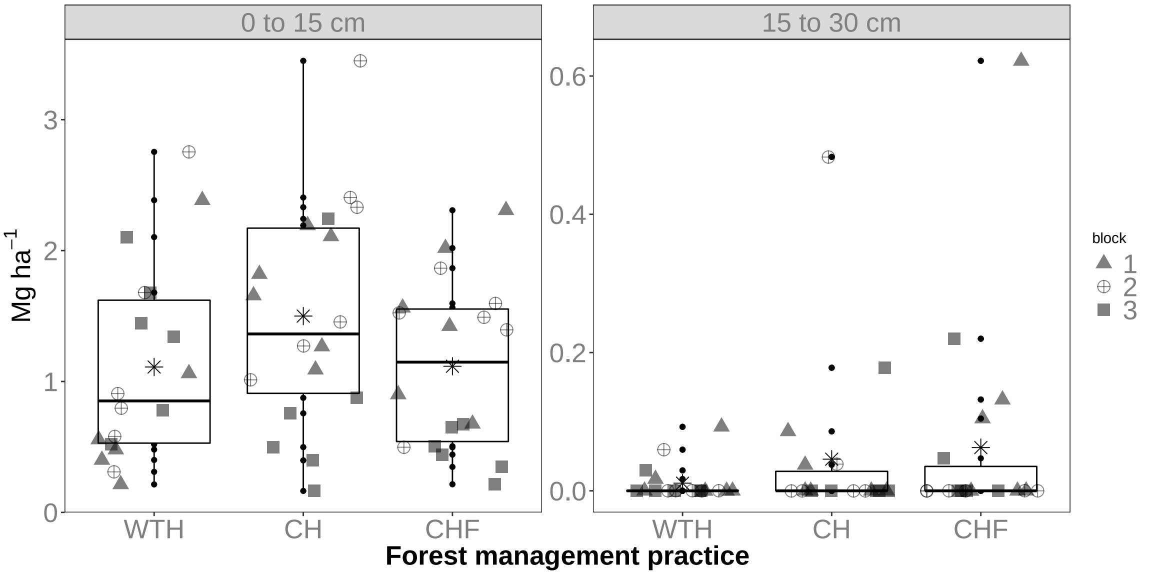

Figure 5.3: Forest of Ae - boxplot of fine root production (Mg ha^{-1}) within the 0-15 and 15-30 cm soil depth with the RIN technique. Shape refers to block replication. Asterisk symbols are mean values.

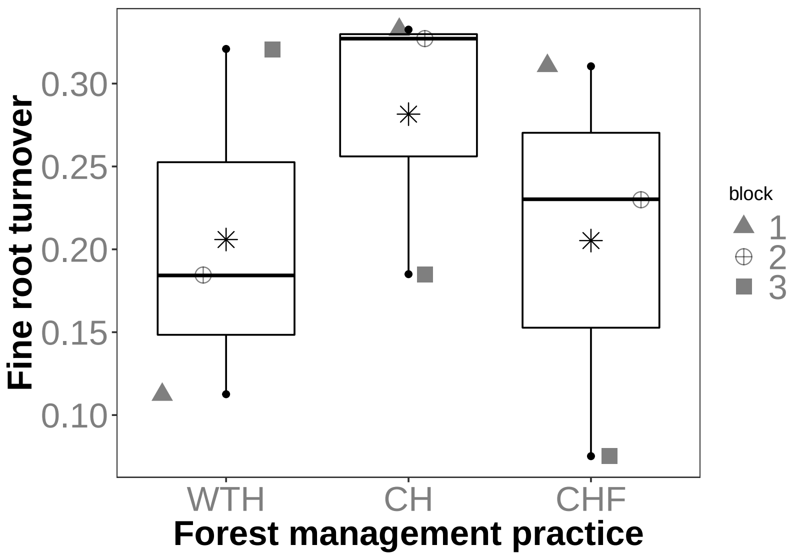

Figure 5.4: Forest of Ae - boxplot of fine root turnover within the 0-15 soil depth. Shape refers to block replication. Asterisk symbols are mean values.

Table 5.1: Forest of Ae. Pairwise comparisons among estimated marginal means of the treatments for fine root biomass and necromass in the 0 to 15 and 15 to 30 cm soil depth, fine root production and turnover in the 0 to 15 cm soil depth. p-value adjustment: Tukey method for comparing a family of 3 estimates. Degrees-of-freedom method: Kenward-Roger.

var	hor	contrast	estimate	SE	t.ratio	p.value	sign
Biomass	0-15cm	CH - CHF	-1.15	0.76	-1.52	0.35	
		CH - WTH	0.24	0.76	0.32	0.95	
		CHF - WTH	1.39	0.76	1.84	0.24	
Necromass		CH - CHF	-0.13	0.15	-0.86	0.68	
		CH - WTH	0.03	0.15	0.18	0.98	
		CHF - WTH	0.15	0.15	1.04	0.58	
Biomass	15-30cm	CH - CHF	-0.70	0.35	-1.99	0.20	
		CH - WTH	0.32	0.35	0.91	0.66	
		CHF - WTH	1.01	0.35	2.89	0.06	
Necromass		CH - CHF	-0.09	0.06	-1.48	0.36	
		CH - WTH	0.14	0.06	2.27	0.14	
		CHF - WTH	0.24	0.06	3.75	**0.02**	*
Production	0-15cm	CH - CHF	0.38	0.36	1.05	0.59	
		CH - WTH	0.39	0.36	1.07	0.58	
		CHF - WTH	0.01	0.36	0.01	1.00	
	15-30cm	CH - CHF	-0.02	0.04	-0.44	0.90	
		CH - WTH	0.03	0.04	0.90	0.66	
		CHF - WTH	0.05	0.04	1.33	0.43	
Turnover	0-15cm	CH - CHF	0.08	0.08	0.90	0.66	
		CH - WTH	0.08	0.08	0.89	0.67	
		CHF - WTH	-0.00	0.08	-0.01	1.00	

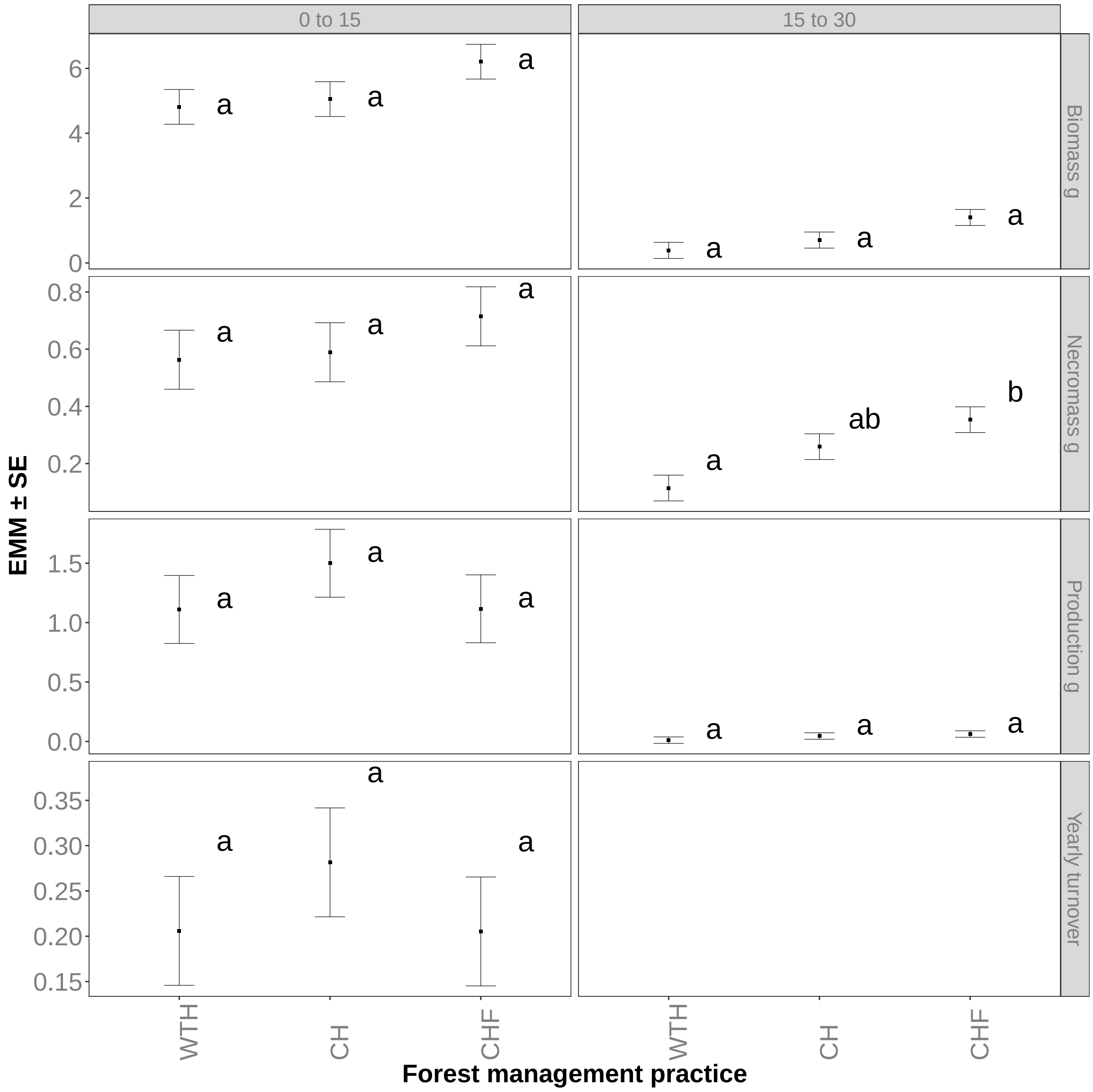

Figure 5.5: Forest of Ae - Estimated marginal means by management practice. Boxes indicate the estimated marginal means. Error bars are estimated marginal mean +/- SE. Means sharing a letter are not significantly different (Tukey-adjusted comparisons). 0 to 15: 0 to 15 cm soil depth; 15 to 30: 15 to 30 cm soil depth; biomass: fine root biomass (g); necromass: fine root necromass(g); production: fine root production (g); turnover: fine root turnover. Statistical analysis for the fine root turnover of the 15 to 30 cm was not calculated.

5.3 Discussion

While fine roots (Ø $<$ 2mm) represent the smaller pool of roots, some studies divide this further to identify the "very fine" pool. This is because it is claimed that roots with Ø $<$ 0.5 mm are shorter in longevity, as well as a fast growing pool (Montagnoli et al. 2014). In the same study, Montagnoli et al. (2014) found that soil water content influenced the length and dry mass of fine roots regardless of root diameter. In contrast, soil temperature was responsible for root mass and length of very fine roots only (fine roots peaked in one occasion at 8°C). These results lead the study to conclude that the radial growth of fine (0.5 to 2 mm) roots may be driven by soil water content, while longitudinally-developing very fine roots (<0.5 mm) are prone to the effects of soil temperature (Montagnoli et al. 2014).

In the present study only fine roots were measured ($<$ 2mm diameter); therefore investigating the dynamics of the thinner fine root pool is not the scope of this experiment. The fine root pool as a whole (Ø 0 - 2mm) remains important given the results reported in the above studies. Results show that soil field moisture content and fine root production did not vary significantly between the treatments (refer to table 3.2). The role of field moisture content in root production is not clear; as a whole, linear regression shows a decreasing trend in fine root production with increasing soil field moisture content, but this has a low fit (see figure 6.1, Appendix). One hypothesis could be that lower fine root production results from high levels of moisture in peaty soils. This would be an opposite behaviour compared to the mineral soil. With low and limiting moisture content for growth, mineral soil may benefit in terms of fine root production when moisture content increases, as opposed to peaty soils. Such findings relate well to studies investigating the SOC decomposition rates which are much slower in peaty soils due to waterlogging

Table 5.2: Forest of Ae. Table of mean values for the treatments for fine root standing biomass, production, turnover and field root count.

		Mg/ha					Mg/ha		
forest	managem	Biomass015	Necromass015	Biomass1530	Necromass1530	FieldCount	Production015	Production1530	Turnover015
Ae	WTH	4.81	0.56	0.39	0.11	20.39	1.11	0.01	0.21
Ae	CH	5.05	0.59	0.70	0.26	28.94	1.50	0.05	0.28
Ae	CHF	6.21	0.72	1.40	0.35	20.78	1.12	0.06	0.21

Note:
Biomass: standing biomass of fine roots; Necromass: standing necromass of fine roots; 015 / 1530: 0 to 15 / 15 to 30 cm soil depth; FieldCount: number of fine roots crossing the meshes at the time of mesh harvesting; Production: fine root production.

conditions compared to better drained mineral soils.

5.3.1 Fine root biomass

The dynamics of soil C are affected by the growth of fine roots, and this is in turn affected by soil fertility (Lal 2005). The present study found significantly higher fine root standing necromass in the 15 to 30 cm soil depth in the CHF treatment compared to WTH.

Whilst results are not significant ($p = 0.062$, see table 5.1 and figure 5.2) within the same soil layer CHF has a tendency to hold more C stock in fine root standing biomass compared to the WTH treatment. The benefits in terms of C storage in fine roots for the CHF treatment compared to WTH considering 0.6318 10^6 ha conifer forest cover on peaty gleys and podzols (Vanguelova et al. 2013) in Britain would amount to 150.97 Gg C. Average values by treatment (Mg ha^{-1}) are summarised in table 5.2.

The linear relationship found between biomass of the fine roots crossing and occupying the virtual parallelepiped around the net and the number of inclusions counted at the time of harvesting shows that in addition to root count also root diameter (0 to 2 mm) is likely to contribute to fine root mass (figure 5.6). Similar findings were also reported in (Lukac and Godbold 2010). While field root counts cannot be utilized to predict the biomass of fine roots with certainty, results from linear regression indicates that the model explains over 60

% of the variation ($p < 0.01$); field root count can therefore give a first indication in terms of fine root production.

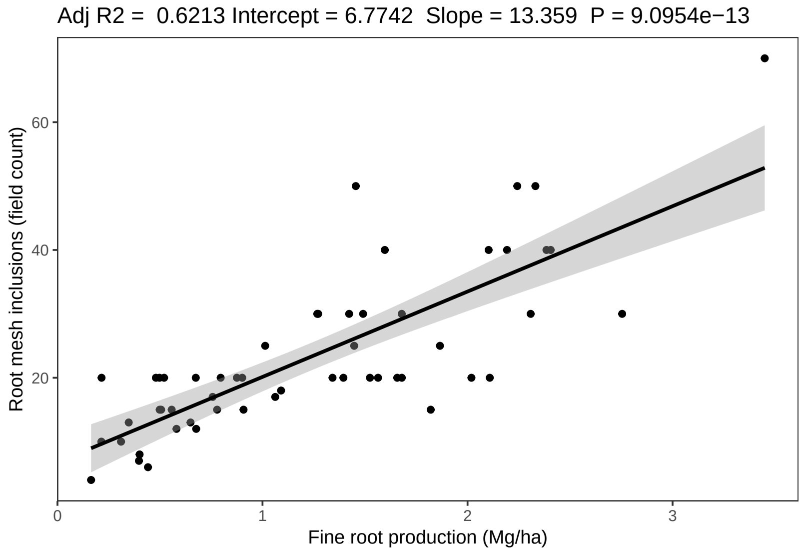

Figure 5.6: Forest of Ae. Linear regression of net fine root inclusions (field count) and fine root production in the 0 to 15 cm soil depth. Data was grouped together as differences in fine root production between treatments were not significant.

A study comparing varying intensity thinning practices as part of a WTH management practice did not lead to significant differences compared to the Control (unthinned) in terms of fine root biomass in a *Picea crassifolia* plantation in the Quilian mountains (China) (He et al. 2018). Wang et al. (2014) analysed the effects of stand age and fine root production methods in a *Larix principis-rupprechtii* temperate forest in northern China and found that fine root standing biomass measured with soil cores fluctuates throughout the season and is significantly affected by the stand age. From the study conducted by Neumann et al. (2020) on model recalibration based on 454 European plots[2], temperate coniferous forests fine root necromass is on average 2.88 ± 2.72 Mg ha^{-1}. The present study found average values for fine root necromass between 0.67 to 1.07 Mg ha^{-1} within the 0 to 30 cm soil depth (see table

[2]Given the variability in sampling depth between studies, fine root biomass and production on the entire rooting depth was estimated with observed fine root data, sampling depth and a coefficient determining the shape of the rooting profile.

5.2).

Neumann et al. (2020) also found that temperate coniferous forests fine root biomass averages 3.29 ± 2.23 Mg ha^{-1}. In addition, Lukac and Godbold (2010) reported fine root biomass of Norway spruce in boreal climate of 2.88 and 3.54 Mg ha^{-1} (measured 2002 and 2004 respectively) within the first 20 cm soil depth. A database of 186 studies on boreal, temperate and tropical forest environments reported average values of fine root standing biomass estimates at 3.27 ± 1.96 Mg ha^{-1} (mean sampling depth 37.2 cm) for temperate climates (Finér et al. 2011).

Therefore, with average values for the 0-15 cm soil depth spanning from 4.81 to 6.21 Mg ha^{-1} (see table 5.2) the present study sits at the high end of the fine root production range; this may reflect the high water content level of peaty soils and the cold climatic conditions of the experimental site. These results reflects average values from temperate forest biomes. Necromass values in the same soil layer spanning 0.56 to 0.72 Mg ha^{-1} are also high, although necromass for the 0-15 soil depth for Douglas fir in Lozanova et al. (2019) study represented 19.98 and 9.87 % of the total fine root mass (biomass + necromass) within the 0-15 cm soil layer. In the present study this was found to be 10.43, 10.46 and 10.39 % for the WTH, CH and CHF treatments respectively. In this respect the biomass:necromass ratio can be considered similar.

In the 15-30 cm soil depth, fine root necromass for Douglas fir represented 22.36 and 10.83 % of the total root mass in Lozanova et al. (2019), while in the present study this was 22, 27.08 and 20 % for WTH, CH and CHF respectively. Perhaps the reason for diverging results could be that Lozanova et al. (2019) experiment was carried out in two different plantations leading to high inter-variability, specifically in terms of tree species and soil type. Hence, the present study found a higher presence of necromass on average within the lower 15-30 cm soil layer, where water content levels and consequent slower decomposition of dead root mass may have further contributed towards the accumulation of C within the H horizon. Since the present study found no significant differences in C stock between treatments in the H horizon, it is not possible to affirm that the higher presence of necromass in the 15-30 cm layer for CHF compared with the WTH treatment have influenced the ability of soil to sequestrate atmospheric C. On the other hand, the WTH treatment has higher-on-average C stock in the H horizon which, as mentioned in chapter 4 suggests that N dynamics may control soil C mineralization.

5.3.2 Fine root production

Fine root nets were harvested in August 2018, 20 months from installation. Since experiment setup in November 2016, meshes remained in the soil for two growing seasons. Nevertheless, fine root production was assumed as annual production. This is because the setup of the root nets introduced disturbance to the soil; this was thought to result in an underestimate in fine root production at the end of the first growing season. The second reason is that literature suggests different residence times for the nets; in this instance 21 months permanence sits somewhere in between what is thought to be an ideal time for the roots to recolonize the soil occupied by the nets[3]. Fine root production results were not different between the treatments although these varied between 1.11 (WTH) and 1.50 (CH) Mg ha^{-1} within the 0

[3]Research suggests that the accuracy of the fine root production measurement is commensurate to the time that the meshes are left in the soil (so to minimize root death) and the climatic condition of the site. An agreement on the best possible time for meshes to be left in the soil is therefore necessary (Lukac and Godbold 2010; Wang et al. 2014). Lukac and Godbold (2010) suggests an incubation time of over one year for its experiment located in a boreal forest (Russia), where the study found no presence of dead roots. The incubation time should be shortened if this is necessary to avoid the decomposition, hence disappearance of the roots from the meshes, hence underestimate root production. Andreasson et al. (2016) tested the effects of meshes (36mm^2 pore) with the RIN (20 x 50 cm, installed at 15 cm) and the ingrowth core technique (Ø 8 cm x 15 cm depth). This found that RIN production estimates for *Pinus pinaster* stands and understory species peaked mostly after 36 months and in a few cases after 24 months (9, 24 and 36 month incubation were tested). Within the RIN technique, fine root production showed significantly higher biomass after 24 and 36 months, these being not significantly different.

to 15 cm soil depth and between 0.01 (WTH) and 0.06 (CHF) Mg ha^{-1} in the 15 to 30 cm soil depth.

The meta-analysis from Addo-Danso et al. (2015) reports average values of fine root production in temperate, continental and tropical climates calculated with ingrowth core (of which root inclusion net is defined as a modification), sequential coring and minirhizotrons (2.06, 3.84 and 3.81 Mg ha^{-1} y^{-1} respectively). Results were found to be lower for the ingrowth core, but differences were non-significant ($F = 2.851$, $p = 0.061$); the author also supports the findings with a series of reviews highlighting the same patterns. A database of 186 studies (Finér et al. 2011) found that fine root production in forest temperate environments is on average 3.37 ± 2.56 Mg ha^{-1}. The study by Neumann et al. (2020) on model recalibration based on 454 European plots found that temperate coniferous forests fine root production averages at 1.73 Mg ha^{-1}. These findings are in line with findings from the present research.

5.3.2.1 Root inclusion net: observations after the experiment

Andreasson et al. (2016) found 69–89 % lower root production with a recorded maximum of 0.45 against 1.94 Mg ha^{-1} in a 3-year timespan under *Pinus pinaster* and understory species with the RIN technique when compared to ingrowth cores. A lower root production (67–85 %) was also found with the RIN for the understory species. Andreasson et al. (2016) also found a significantly lower specific root length with the RIN. The same study also claims that the level of disturbance was not reduced with the RIN because of the large mesh size adopted also affected the setup. Experience from the present study suggests that the insertion of mesh in the slit for the RIN technique had to be aided by basic yet reliable tools. Andreasson et al. (2016) a spade was utilized to push a large mesh (50 x 20 cm) into a soil depth of 15cm. Borrowing from previous research (Lukac and Godbold 2010; Wang et al. 2014) the present study may have improved this method by applying a spade to create the slit, after which a metal sheet with front blade was utilized to manually setup the mesh. In addition, smaller meshes were adopted both in terms of pore size, which according to Andreasson et al. (2016) could potentially yield different results. The present study utilised a 1 mm^2 woven mesh allowing for the expansion of the root, yet able to capture and retain small roots. Mesh size was limited to 10 x 30 cm, the longer size representing the depth. This experiment confirms the suitability of small-sized meshes for the quantification of fine root standing biomass, although biomass and necromass should be quantified with different meshes and harvested at different times of the year.

5.3.3 Fine root turnover

The present study found turnover rates of 0.21 (WTH and CH) and 0.28 (CHF), see formula (2.11) corresponding to turnovers of 4.76 and 3.57 years respectively, differences between the treatments being non-significant.

The Lukac and Godbold (2010) study in a boreal climate in NW Moscow estimated the fine root turnover of Norway spruce stands and mixed forest sites to be 0.1 to 0.24 y^{-1}. Interestingly, the study also calculates the relationship between biomass of the roots and the number of root inclusions in the net, although results do not closely fit the regression line and seem to confirm a high variability in space. Lukac and Godbold (2010) also reported Norway spruce studies where root turnover was 0.28 to 1.0 y^{-1} (temperate climate, pH 3.6 to 5, Germany), 0.67 y^{-1} (Belgium, loamy brown acid forest soils), and 0.76 y^{-1} and 1.3 y^{-1} (boreal climate).

One study found that rate of turnover in fine roots increased with soil depth, while mortality rate (amount of fine root mortality to the average fine root biomass) was higher in the 0-10 cm soil depth, with significantly lower differences in lower soil layers (Wang et al. 2014). These findings suggest that the fraction of necromass in 15 to 30 cm soil depth at the forest of Ae that could not be extracted due to its friable nature may affect the turnover rate of fine roots at this depth. Further research is needed to understand the dynamics of fine root at this depth. Sequential coring may achieve this by estimating the fine root standing biomass at different times of the year, while at the same time allowing the sampling of the fraction of necromass that present research could not estimate. However, this would require a significant increase in the amounts of labour and resources. Results of turnover rates in Wang et al. (2014) were 1.12, 0.61, and 0.51 y^{-1} of increasingly older *Larix principis-rupprechtii* stands (13, 22 and 38 years old). Turnover contributed to a 0.52, 0.58, and 0.94 Mg C ha^{-1} y^{-1} to the soil of increasingly older stands. Contribution of the fine root in terms of C to the soil organic C pool was estimated in $<0.01\%$. Differences between the present study and Wang et al. (2014) can be related to a series of factors, such as the cold climatic conditions and high soil water content at the Forest of Ae, as well as differences in soil type.

In the present study, fine root meshes were collected exclusively from one point in time[4]. This method may have introduced limitations in estimated fine root production, therefore turnover rates, particularly if seasonality affected average annual values of fine root biomass and production. Future research should therefore concentrate on the dynamics of root growth through the seasons. This information, coupled with data from fine root standing biomass may reveal different dynamics of root turnover. As previously mentioned, the recent study from Lozanova et al. (2019) points out how fine root mass differed significantly between sampling plots (with same tree species planted) rather than between the forest types

[4] Mostly dictated by time and resource constraints.

(with different tree species planted). In this instance, the experimental design at the forest of Ae was concerned with finding differences between forest management practices utilizing a 2^3 factorial design (Proe et al. 2001) from a previous experiment (see figure 2.2). All plots were concentrated in an area of approximately 1 ha in size under the assumption that other variables did not affect the plots. While further research is required to confirm this, findings from Lozanova et al. (2019) suggested that the Forest of Ae could be interpreted as one plot, with different forest types (treatments) within. This would confirm the plot (implying parent material, climate, organisms, time and relief) more than forest type is responsible for the dynamics of fine roots. Future research could therefore concentrate on aspects other than, or not exclusively forest management practice to better understand the dynamics of fine root C. Contextually, future analysis of fine roots for C concentration could reveal differences in forest management practices that did not prove significant when using fine root standing biomass.

5.3.4 Considerations from field and laboratory activities

Development of fine roots at the Forest of Ae concentrated on F horizons; rarely was the H horizon explored by fine roots, which were mostly confined within the first 10 cm soil depth as confirmed by other studies on second rotation Sitka spruce, peaty-gley soils in upland England (Ball et al. 2011). Nevertheless, the H horizon (within the 15 to 30 cm soil core) appeared to be populated by necromass in an advanced stage of decomposition which could not be sampled due to its friable nature (particularly within the soil cores collected in November 2016). This is also confirmed in a recent study from (Lozanova et al. 2019) on the vertical distribution of roots in European beech forests and Douglas Fir plantations in Bulgaria, where the highest values of necromass were recorded in the spring, while the lowest were in the summer season. At time of harvesting the root meshes during August 2018, many nets slipped out of the H horizon mostly root-free. This may suggest a high turnover of roots that could not be captured by meshes and could potentially result in undersampling of fine roots within the 15 to 30 soil depth in terms of fine root production and standing biomass within this soil layer. Another reason could be the slow growth of fine roots in these layers, together with the presence of a substantial amount of dead matter subject to very slow rates of decomposition. Consequently, median values of fine root production within the 15 to 30 cm soil layer were mostly null values; hence statistical analysis of fine root turnover was limited to the 0 to 15 cm soil depth. An additional reason, but a potential limitation of the RIN technique could be that seasonal fluctuations in fine root growth cannot be detected if not by repeat measurements throughout the seasons; implying more labour, time and economical constraints.

Regarding the root meshes, the space explored by the roots occasionally ended abruptly within the F horizon, while at other times these clearly faded with increased depth within the F horizon (see figure 5.7). Root exploration of the F horizon may have been hindered by a shallow F horizon or a higher water table, although the experimental site was located on a slope (see table 2.1). At the time of harvesting the root meshes as part of the RIN technique for fine root production estimates, the depth of soil horizons in proximity to the mesh was not collected. As seen in chapter 3, the F horizon, where most of the root growth occurred, was significantly shallower in respect to the WTH treatment compared to CH and CHF. Information on depth of soil horizons around the meshes could confirm if the abrupt root ending is limited by the shallowness of the F horizon, which in turn is a result of brash removal for the WTH treatment. The likely exclusion of roots from the H horizon was perhaps related to high water content and consequently poor oxygen levels that prevented root growth (e.g. soil conditions within the F horizon were more suitable for root growth compared to the H horizon).

Figure 5.7: Forest of Ae. Fine root development within the F horizon. Left: gradual ending of fine roots. The net was inserted with the short side (at left) up; right: abrupt ending of fine roots clustered in less than 1 cm thickness (zoomed detail).

One apparent limitation found when processing root meshes in the laboratory was a difficulty in figuring out the exact position of the root within the virtual parallelepiped around the mesh. This method does not allow to know what the position of the root was in the soil with respect to the mesh; this can potentially affect the final value of fine root production because the direction of the root departing from the mesh affects its length within the virtual parallelepiped.

5.4 Conclusions

The values of fine root turnover coupled with those of fine root standing biomass led to a fine root biomass contribution to the soil of 1.01, 1.41 and 1.3 Mg ha^{-1} y^{-1} for the WTH, CH and CHF respectively. Overall, the yearly contribution of fine roots to the soil OSH C stock using turnover rates from the 0 to 15 cm soil depth was 0.005, 0.008, and 0.005 % for WTH, CH and CHF respectively. Since the grand majority of roots grew in the L and F horizons, when only these two are considered the contribution of fine roots grows substantially to 0.04, 0.03, and 0.02 for WTH, CH and CHF respectively. The C stock within the F horizon was significantly higher for CHF and CH compared to WTH, this resulting from a significantly thicker F horizons. Results suggest that fine root C stock contribution of WTH to the soil is proportionally higher (less volume to explore but comparatively more roots on an equal-volume base), followed by CH and CHF. Additional results from fine root turnover do not confirm suggestions of a negative relationship between fine root age and fertility (Solly et al. 2013).

Recent research has found that fine root biomass between different diameter classes of fine roots (< 0.5, 0.5 to 1 and 1 to 2mm) was higher ($p < 0.01$) in a moderately thinned (15% basal area removed) treatment compared to the Control (unthinned) on an over forty year old *Pinus massoniana* plantation subject to sub-tropical temperate climate and on a slightly steep slope (Shen et al. 2017). The thinned plot in particular resulted in a 46.1 (59.5% increase), 88.9 (35.4%), and 170.9 g m^{-2} (47.8%) for the three diameter sizes. This suggests that the experimental site at Clocaenog forest and its CCF and UN treatments may reveal dynamics of C accumulation in fine root production that are in line with findings from Shen et al. (2017). Similar research activities to those conducted at the forest of Ae should be undertaken at Clocaenog forest in order to understand if fine roots dynamics are influenced by CCF as found in other studies.

Results from the present study using the RIN technique suggest that future research concentrating on this part of the soil where most of the tree fine roots are confined - the F horizon - could lead to an understanding of whether nutrient depletion is at the base of the apparent limited above-ground C allocation.

Findings from the Forest of Ae experiment suggest that fine root necromass was significantly higher in the 15 to 30 cm soil depth of the CHF compared to the WTH treatment, and a potential increase in C storage in soil contributed by fine roots C input of 150.97 Gg C. This assuming a complete cover by the treatments of all 0.6318 10^6 ha conifer cover on peaty soils in Britain.

Chapter 6

Final conclusions

The following chapter is a summary and discussion of findings and conclusions from the research chapters on soil C quantity, quality and the C dynamics of fine roots.

The research objectives of the thesis were:

- **Carbon quantity (stocks)**
  - To compare the effects of clearfell systems - brash removal (WTH), conventional stem-only harvesting (CH) and fertilization (CHF) on soil C quantity in the litter, fragmented and humified organic surface horizons (OSH).
  - To compare the effects of thinning to transform to irregular shelterwood (CCF) with unthinned (UN) on soil C quantity in the OSH.
- **Carbon quality (proximate pools and N dynamics)**
  - To compare the effects of clearfell systems - WTH, CH and CHF on soil C quality in the OSH.

- To compare the effects transitioning practices to CCF silvicultural system - CCF and UN, on soil C quality in the OSH.

- **Fine root biomass and dynamics**

  - To compare the effects of clearfell systems - WTH, CH and CHF on tree fine roots (< 2mm diameter) dynamics.

Table 6.1 summarizes the significant results that are relevant to the aims and objectives of the present thesis. Contextually, table 6.1 is meant to be followed as a visual guide where the treatments are assigned a positive or negative effect on the within-horizon[1] soil C storage, inclusive of the response variable in relation to soil C stock accumulation. Hence, table 6.1 summarizes the main positive and negative effects of all experimental treatments on soil properties and fine root dynamics.

As part of the C quantity objectives highlighted in the present thesis (see chapter 1.4) this study demonstrated that the CHF treatment stores significantly more C in the L soil horizon when compared to WTH and CH treatments ($p < 0.01$). Since needles and twigs contain a substantial amount of nutrients (Clarke et al. 2015), this may have promoted a better development of above-ground biomass for the CHF and CH treatments. This was noticeable from within the plots (refer to figure 2.3) and was also confirmed by previous studies (see chapter 3.3.3). Fertilisation may therefore have the capacity to promote higher litter inputs to soils compared to conventionally managed systems or whole-tree harvested systems, which in turn can promote rotation growth due to higher nutrient input and availability.

The study also demonstrates that the C stock in the WTH treatment was significantly affected in the F horizon (CH-WTH $p = 0.03$; CHF-WTH $p = 0.01$), with 22.8 and 28.9

[1] or soil layer for the 0 to 15 and 15 to 30 cm soil depth.

Table 6.1: Table of within-soil-horizons comparison between forest management practices. The symbology identifies significant differences in the response variable between the treatments. Response variables are assigned positive or negative effects on the treatment in relation to soil C storage (eg. higher N concentration or a lower C:N ratio that exacerbate soil C mineralization are negatives).

		soil horizon				soil layer
attribute	**managem**	**L**	**F**	**H**	**A**	**15to30cm**
C quantity						
C stock	**WTH**	-	-			
	CH	-	+			
	CHF	+	+			
C concentration	**WTH**	++				
	CH	+				
	CHF	-				
Soil depth	**WTH**		-			
	CH		+			
	CHF		+			
C stock	**UN**			-		
	CCF			+		
Bulk density	**UN**		+			
	CCF		-			
C quality						
C:N ratio	**WTH**		+			
	CH		+			
	CHF		-			
Nitrate	**WTH**			+		
	CH			=		
	CHF			-		
N concentration	**UN**	-	-	-		
	CCF	+	+	+		
C:N ratio	**UN**	-		-	-	
	CCF	+		+	+	
Ammonium	**UN**			-		
	CCF			+		
Fine root C						
fine root necromass	**WTH**					-
	CH					=
	CHF					+

Note:
Symbology. ++: The treatment is significantly ($p<0.05$) more positive compared to other treatments; +: significantly more positive compared to -; =: not significantly different from other treatments.

Table 6.2: Forest of Ae. Table of average soil C stock (Mg ha^{-1}) by management practice and horizon.

forest	managem	hor	Cstock
		L	2.48
	WTH	F	27.79
		H	215.48
		L	2.47
	CH	F	50.62
Ae		H	138.22
		L	3.26
	CHF	F	56.68
		H	188.26
	WTH	Total	8.21
	CH	Total	135.09
	CHF	Total	541.96

Table 6.3: Clocaenog forest. Table of average soil C stock (Mg ha^{-1}) by management practice and horizon.

forest	managem	hor	Cstock
		L	2.85
	UN	F	43.70
		H	18.59
Clocaenog		L	2.11
	CCF	F	43.39
		H	87.02
	UN	Total	65.15
	CCF	Total	132.52

Mg C ha^{-1} less C stored in the soil F horizons under the WTH treatment (compared to CH and CHF respectively) more than twenty years after planting (see table 6.2).

Overall the study on C stock confirms the negative effects of WTH to store C in the soil F horizon when compared to CH and CHF, as well as the advantages in terms of litter production within the L horizon for CHF compared to WTH and CH.

Transformation to irregular shelterwood have highly significant ($p < 0.01$, table 3.3) positive effects on the ability of soils to store C within the H horizon. The H horizon in the CCF treatment holds nearly 70 Mg C ha^{-1} more than the UN treatment (table 6.3), representing a 350.46% higher within the H horizon compared to the UN treatment. The contribution of the H horizon in terms of overall C stock within the OSH was 28.53 and 33.31% for UN and

CCF respectively. This is a remarkable difference considering that the L and F horizons C stock was not significantly different between UN and CCF.

Further research is needed to quantify the C storage potential of UN and CCF within the mineral horizon so to complete the full soil profile down to its parent material. This will help to understand if the mineral horizons play a major role in soil C storage, transformation, allocation and long term C sequestration for the UN treatment by way of organo-mineral interactions and aggregate occlusion or if alternatively, the CCF treatment has a higher soil C storage potential throughout the soil profile as a whole.

Results from the present studies suggest that the ability of soil to store C and mitigate the effects of climate change is driven by the presence of N, with N concentration often positively related to C stock. For the Forest of Ae in particular, N concentrations can be used to predict the amounts of soil C stock in each horizon (figure 4.16). Plateauing levels of N concentration suggest SOM and soil N mineralization in the H horizon for the treatments at the Forest of Ae. Particularly, significantly higher levels of nitrate in the H horizon of the CHF treatment when compared to WTH suggest a (non-significant) loss of C in the CHF treatment. H horizon C% increased proportionally with concentrations of soil available N in the form of ammonium (figure 4.19). Ammonium was found significantly higher in the H horizon when it held significantly less C stock (tables 3.3 and 4.2). In this instance similar dynamics were noticed in both of the sites under study. At the Forest of Ae, the H horizon in the CHF treatment had significantly higher available N as nitrate, and less soil C stock on average compared to WTH. This may be promoted by microbial mineralization of SOM, hence the need to investigate the dynamics of microbial activities which could play an important role in soil C stocks and C quality between the treatments.

Forest management practices can significantly affect soil base cation, nutrients and the pH of forest soils in sensitive areas and on sensitive soil types (Vanguelova et al. 2010). The breakdown of SOM can affect pH of forest soils, weathering and uptake of nutrients, therefore further research should concentrate on the analysis of these variables to understand effects on potential soil C storage of the treatments in the experimental sites at the Forest of Ae and Clocaenog forest. Microbial biomass and respiration rates should also be investigated to better understand the dynamics of microbial activities which could be linked to differences in soil C stocks and C quality between the treatments.

With regards to the soil proximate C pools, this research shows that differences between treatments were probably too narrow to be detected with the forage fibre analysis for both sites. Differences are more likely identified when comparing different age or species compositions and soil horizons (Gartzia-Bengoetxea et al. 2009). Nevertheless, significantly lower LCI values within the F horizon for the WTH treatment at the Forest of Ae (table 4.1) suggest that the CHF treatment may be subject to lower decomposition rates within the F horizon. While LCI may exert an effect on decomposition rates, C allocation within the F horizon for the CHF (and CH) treatment is mostly the result of brash left on site, higher above-ground growth and litter production. While comparing horizons was not the purpose of the present research, results presented a substantial difference on average (see table 6.4) and C pools could be used for soil C model calibrations. Further analysis could reveal a C pool-related contribution to soil C storage within the L or F horizons, which could extend to the lower organic and mineral horizons.

While the fine root dynamics only differ in necromass of the lower soil layer (15 to 30 cm), CHF held significantly more fine root necromass than WTH treatment. This is not reflected within the soil H horizon which in contrast held more C on average in WTH compared to CHF. As discussed, the rates of mineralization promoted by the presence of N from both

Table 6.4: Forest of Ae. Table of average soil proximate C pools (%) and LCI by management practice and horizon.

forest	managem	hor	OM	Cell_sol	Hemicel	Cellul	Lignin	LCI
	WTH	L	96.77	29.54	14.89	26.96	28.61	0.41
	CH	L	96.25	31.50	14.37	25.39	28.75	0.42
	CHF	L	95.57	31.93	13.60	26.69	27.78	0.41
	WTH	F	92.34	25.40	18.86	18.62	37.12	0.50
Ae	CH	F	92.79	22.50	17.61	19.83	40.06	0.52
	CHF	F	90.36	25.06	15.85	19.03	40.06	0.53
	WTH	H	85.40	55.08	12.33	8.91	23.68	0.52
	CH	H	74.53	56.71	10.78	8.06	24.45	0.56
	CHF	H	74.52	57.32	9.89	8.98	23.82	0.54

fertilization and brash left on site at the time of harvesting may play a role in limiting the accumulation of further C within the H horizon for the CHF treatment. In addition, significantly higher fine root decomposition within the H horizon of the CHF treatment may exacerbate soil C mineralization and N leaching. On the other hand, higher N availability may promote a more sustained nutrient uptake and higher C allocation aboveground. The results from fine root C dynamics, coupled with those from soil C stock provide evidence of the beneficial effects of Conventional stem-only harvesting and fertilization practices for long term soil C sequestration and ultimately climate change mitigation.

References

Achat, D. L., C. Deleuze, G. Landmann, N. Pousse, J. Ranger, and L. Augusto. 2015. Quantifying consequences of removing harvesting residues on forest soils and tree growth - A meta-analysis. *Forest Ecology and Management.* 348:124–141.

Addo-Danso, S. D., C. E. Prescott, and A. R. Smith. 2015. Methods for estimating root biomass and production in forest and woodland ecosystem carbon studies: A review. *Forest Ecology and Management.* 359:332–351 Available online at: http://www.sciencedirect.com/science/article/pii/S0378112715004405.

Andreasson, F., M. Gonzalez, L. Augusto, and M. R. Bakker. 2016. Comparison of ingrowth cores and ingrowth meshes in root studies: 3 years of data on Pinus pinaster and its understory. *Trees-structure and function.* 30(2, SI):555–570.

ANKOM. Forage Fibre Analysis. Available online at: https://www.ankom.com/.

AOAC International. 2007. *Official Methods of Analysis, 18th ed. Association of Official Analytical Chemists, Washington, D.C.*

Arcangeli, C. 2018. Clocaenog CCF trial - CLG1: unthinned treatment.

Arcangeli, C. 2016. Clocaenog CCF trial - CLG2: irregular shelterwood treatment.

Ashwood, F., K. Watts, K. Park, E. Fuentes-Montemayor, S. Benham, and E. Vanguelova.

2019. Woodland restoration on agricultural land: long-term impacts on soil quality. *Restoration Ecology*.

Ball, T., K. A. Smith, M. H. Garnett, J. B. Moncrieff, and A. Zerva. 2011. An assessment of the effect of Sitka Spruce (Picea sitchensis Bong. Carr) plantation forest cover on carbon turnover and storage in a peaty gley soil. *European Journal of Soil Science*. 62(4):560–571.

Bani, A., S. Pioli, M. Ventura, P. Panzacchi, L. Borruso, R. Tognetti, G. Tonon, and L. Brusetti. 2018. The role of microbial community in the decomposition of leaf litter and deadwood. *Applied Soil Ecology*. 126:75–84.

Bates, D., M. Martin, B. Ben, and W. Steve. 2015. Fitting Linear Mixed-Effects Models Using lme4. *Journal of Statistical Software*. 67(1):1–48.

Belanger, N., D. Pare, and S. H. Yamasaki. 2003. The soil acid-base status of boreal black spruce stands after whole-tree and stem-only harvesting. *Canadian Journal of Forest Research*. 33(10):1874–1879.

Benham, S., E. Vanguelova, and R. Pitman. 2012. Short and long term changes in carbon, nitrogen and acidity in the forest soils under oak at the Alice Holt Environmental Change Network site. *The Science of the total environment*. 421-422:82–93 Available online at: http://www.sciencedirect.com/science/article/pii/S0048969712001787.

Bergholm, J., B. A. Olsson, B. Vegerfors-Persson, and T. Persson. 2015. Nitrogen fluxes after clear-cutting. Ground vegetation uptake and stump/root immobilisation reduce N leaching after experimental liming, acidification and N fertilisation. *Forest Ecology and Management*. 342:64–75.

Blasko, R., B. Forsmark, M. J. Gundale, T. Lundmark, and A. Nordin. 2020. Impacts of tree species identity and species mixing on ecosystem carbon and nitrogen stocks in a boreal forest. *FOREST ECOLOGY AND MANAGEMENT*. 458.

Bradford, M. A., W. R. Wieder, G. B. Bonan, N. Fierer, P. A. Raymond, and T. W. Crowther. 2016. Managing uncertainty in soil carbon feedbacks to climate change. *Nature Climate Change*. 6(8):751–758.

Brady, N., and R. Weil. 2008. *The nature and properties of soils*. 14th ed. Vernon, A. (ed.) Pearson.

Brassard, B. W., H. Y. H. Chen, and Y. Bergeron. 2009. Influence of Environmental Variability on Root Dynamics in Northern Forests. *Critical Reviews in Plant Sciences*. 28(3):179–197 Available online at: http://dx.doi.org/10.1080/07352680902776572.

Brunner, I., and D. L. Godbold. 2007. Tree roots in a changing world. *Journal of Forest Research*. 12(2):78–82.

Brunner, I., M. R. Bakker, R. G. Björk, Y. Hirano, M. Lukac, X. Aranda, I. Børja, et al. 2012. Fine-root turnover rates of European forests revisited: an analysis of data from sequential coring and ingrowth cores. *Plant and Soil*. 362(1):357–372 Available online at: http://dx.doi.org/10.1007/s11104-012-1313-5.

Butnor, J. R., L. J. Samuelson, K. H. Johnsen, P. H. Anderson, C. A. G. Benecke, C. M. Boot, M. F. Cotrufo, et al. 2017. Vertical distribution and persistence of soil organic carbon in fire-adapted longleaf pine forests. *Forest Ecology and Management*. 390:15–26.

Castellano, M. J., K. E. Mueller, D. C. Olk, J. E. Sawyer, and J. Six. 2015. Integrating plant litter quality, soil organic matter stabilization, and the carbon saturation concept. *Global Change Biology*. 21(9):3200–3209.

Catoni, M., M. E. D'Amico, E. Zanini, and E. Bonifacio. 2016. Effect of pedogenic processes and formation factors on organic matter stabilization in alpine forest soils. *Geoderma*.

263:151–160.

Cavicchioli, R., W. J. Ripple, K. N. Timmis, F. Azam, L. R. Bakken, M. Baylis, M. J. Behrenfeld, et al. 2019. Scientists' warning to humanity: microorganisms and climate change. *Nature Reviews Microbiology*. Available online at: https://doi.org/10.1038/s41579-019-0222-5.

Cheng, X., M. Yu, and G. G. Wang. 2017. Effects of thinning on soil organic carbon fractions and soil properties in Cunninghamia lanceolata stands in eastern China. *Forests*. 8(6).

Christophel, D., S. Spengler, B. Schmidt, J. Ewald, and J. Prietzel. 2013. Customary selective harvesting has considerably decreased organic carbon and nitrogen stocks in forest soils of the Bavarian Limestone Alps. *Forest Ecology and Management*. 305:167–176.

Clarke, N., P. Gundersen, U. Jönsson-Belyazid, O. J. Kjønaas, T. Persson, B. D. Sigurdsson, I. Stupak, and L. Vesterdal. 2015. Influence of different tree-harvesting intensities on forest soil carbon stocks in boreal and northern temperate forest ecosystems. *Forest Ecology and Management*. 351:9–19 Available online at: http://www.sciencedirect.com/science/article/pii/S037811271500256X.

Cools, N., L. Vesterdal, B. De Vos, E. Vanguelova, and K. Hansen. 2014. Tree species is the major factor explaining C:N ratios in European forest soils. *Forest Ecology and Management*. 311(SI):3–16.

Covington, W. W. 1981. Changes in Forest Floor Organic Matter and Nutrient Content Following Clear Cutting in Northern Hardwoods. *Ecology*. 62(1):41–48 Available online at:

http://doi.wiley.com/10.2307/1936666.

Crawley, M. J. 2013. *The R book.* 2nd ed. John Wiley & Sons, Ltd.

Creutzburg, M. K., R. M. Scheller, M. S. Lucash, L. B. Evers, S. D. Leduc, and M. G. Johnson. 2016. Bioenergy harvest, climate change, and forest carbon in the Oregon Coast Range. *Global Change Biology Bioenergy.* 8(2):357–370.

Crowther, T. W., K. E. O. Todd-Brown, C. W. Rowe, W. R. Wieder, J. C. Carey, M. B. Machmuller, B. L. Snoek, et al. 2016. Quantifying global soil carbon losses in response to warming. *Nature.* 540(7631):104–108.

De Wandeler, H., H. Bruelheide, S. M. Dawud, G. Danila, T. Domisch, L. Finér, M. Hermy, et al. 2018. Tree identity rather than tree diversity drives earthworm communities in European forests. *Pedobiologia.* 67:16–25.

Department for Business Energy and Industrial Strategy. 2019. The Climate Change Act 2008 (2050 Target Amendment) Order 2019. Available online at: https://www.legislation.gov.uk/ukdsi/2019/9780111187654.

Dinakaran, J., M. Hanief, A. Meena, and K. S. Rao. 2014. The Chronological Advancement of Soil Organic Carbon Sequestration Research: A Review. *Proceedings of the National Academy of Sciences, India Section B: Biological Sciences.* 84(3):487–504 Available online at: https://link.springer.com/article/10.1007/s40011-014-0320-0.

Donnelly, L., A. M. Jagodziński, O. M. Grant, and C. O'Reilly. 2016. Above- and below-ground biomass partitioning and fine root morphology in juvenile Sitka spruce clones in monoclonal and polyclonal mixtures. *Forest Ecology and Management.* 373:17–25 Available online at: http://www.sciencedirect.com/science/article/pii/S0378112716301980.

EDINA Digimap Ordnance Survey Service. 2016a. Lidar Composite Digital Surface Model

Wales 1m resolution [ASC geospatial data], Scale 1:4000, Tiles: sj0353,sj0453,sj0454.

EDINA Digimap Ordnance Survey Service. 2016b. Lidar Composite Digital Terrain Model Wales 1m resolution [ASC geospatial data], Scale 1:4000, Tiles: sj0353,sj0453,sj0454.

EDINA Digimap Ordnance Survey Service. 2017a. OS Open Rivers [SHAPE geospatial data], Scale 1:25000.

EDINA Digimap Ordnance Survey Service. 2017b. OS Terrain 5 [SHAPE geospatial data], Scale 1:10000, Tiles: sj05se,sj05sw.

Ekschmitt, K., M. Liu, S. Vetter, O. Fox, and V. Wolters. 2005. Strategies used by soil biota to overcome soil organic matter stability - why is dead organic matter left over in the soil? *Geoderma.* 128(1-2):167–176.

Emmett, B. A., P. A. Stevens, and B. Reynolds. 1995. Factors influencing nitrogen saturation in sitka spruce stands in Wales, UK. *Water Air and Soil Pollution.* 85(3):1629–1634.

Endrulat, T., M. Saurer, N. Buchmann, and I. Brunner. 2010. Incorporation and remobilization of C-13 within the fine-root systems of individual Abies alba trees in a temperate coniferous stand. *Tree Physiology.* 30(12):1515–1527.

Finér, L., M. Ohashi, K. Noguchi, and Y. Hirano. 2011. Fine root production and turnover in forest ecosystems in relation to stand and environmental characteristics. *Forest Ecology and Management.* 262(11):2008–2023.

Finn, D., K. Page, K. Catton, M. Kienzle, F. Robertson, R. Armstrong, and R. C. Dalal. 2016. Ecological stoichiometry controls the transformation and retention of plant-derived organic matter to humus in response to nitrogen fertilisation. *Soil Biology and Biochemistry.* 99:117–127 Available online at: http://www.forestryscotland.com/media/322582/confor report on impact of brexit on uk forestry and timber.pdf.

Forest Research. 2020. Ecological Site Classification. Available online at: http://www.forestdss.org.uk/geoforestdss/.

Forestry Commission. 2014. *Carbon in live woodland trees in Britain - National Forest Inventory Report.* Forestry Commission, Edinburgh.

Forestry Commission. 2018. *Forestry Statistics 2018.*

Forestry Commission. 2017. *The UK Forestry Standard - The governments' approach to sustainable forest management.* 4th ed. Forestry Commission, Edinburgh.

Forestry Commission. 2007. *Tyfiant Coed Research Activities at Clocaenog Forest.*

Gartzia-Bengoetxea, N., A. González-Arias, and I. Martínez de Arano. 2009. Effects of tree species and clear-cut forestry on forest-floor characteristics in adjacent temperate forests in northern Spain. *Canadian Journal of Forest Research.* 39(7):1302–1312 Available online at: http://dx.doi.org/10.1139/X09-053.

Godbold, D. L., and M. Lukac. 2011. *Soil Ecology in Northern Forests: A Belowground View of a Changing World.* Cambridge University Press, New York. Available online at: https://www.dawsonera.com:443/abstract/9781139068994.

Goering, H. K., and P. J. Van Soest. 1970. Forage fiber analyses (apparatus, reagents, procedures and some applications). (379).

Gosden, E. 2015. Paris climate change agreement: the deal at a glance - Key elements of the agreement at the UN climate change summit.

Guo, D., R. J. Mitchell, and J. J. Hendricks. 2004. Fine root branch orders respond differentially to carbon source-sink manipulations in a longleaf pine forest. *OECOLOGIA.*

140(3):450–457.

Hassett, J. E., and D. R. Zak. 2005. Aspen harvest intensity decreases microbial biomass, extracellular enzyme activity, and soil nitrogen cycling. *Soil Science Society of America Journal*. 69(1):227–235.

Hazlett, P. W., D. M. Morris, and R. L. Fleming. 2014. Effects of Biomass Removals on Site Carbon and Nutrients and Jack Pine Growth in Boreal Forests. *Soil Science Society of America Journal*. 78(1):S183–S195.

He, Z.-B., L.-F. Chen, J. Du, X. Zhu, P.-F. Lin, J. Li, and Y.-Z. Xiang. 2018. Responses of soil organic carbon, soil respiration, and associated soil properties to long-term thinning in a semiarid spruce plantation in northwestern China. *Land degradation & development*. 29(12):4387–4396.

Helmisaari, H. S., J. Derome, P. Nöjd, and M. Kukkola. 2007. Fine root biomass in relation to site and stand characteristics in Norway spruce and Scots pine stands. *Tree Physiology*. 27(10):1493–1504.

Hobbie, S. E., J. Oleksyn, D. M. Eissenstat, and P. B. Reich. 2010. Fine Root Decomposition Rates Do Not Mirror Those of Leaf Litter among Temperate Tree Species. *Oecologia*. 162(2):505–513 Available online at: http://www.jstor.org/stable/40540187.

Hobbie, S. E., P. B. Reich, J. Oleksyn, M. Ogdahl, R. Zytkowiak, C. Hale, and P. Karolewski. 2006. Tree species effects on decomposition and forest floor dynamics in a common garden. *Ecology*. 87(9):2288–2297 Available online at: http://ejournals.ebsco.com/Article.asp?ContributionID=10690907.

Huang, Z., P. W. Clinton, and M. R. Davis. 2011. Post-harvest residue management effects on recalcitrant carbon pools and plant biomarkers within the soil heavy fraction in Pinus radiata plantations. *Soil Biology and Biochemistry.* 43(2):404–412.

Hume, A. M., H. Y. H. Chen, and A. R. Taylor. 2018. Intensive forest harvesting increases susceptibility of northern forest soils to carbon, nitrogen and phosphorus loss. *Journal of Applied Ecology.* 55(1):246–255.

Ireland, D. 2006. Operational Experience of Continuous Cover Forestry: UK Case Studies.

IUSS Working Group WRB. 2015. *World Reference Base for Soil Resources 2014, update 2015 International soil classification system for naming soils and creating legends for soil maps. World Soil Resources Reports No. 106.* 2015th ed. FAO, Rome.

Jackson, R. B., K. Lajtha, S. E. Crow, G. Hugelius, M. G. Kramer, and G. Pineiro. 2017. The Ecology of Soil Carbon: Pools, Vulnerabilities, and Biotic and Abiotic Controls. Pp. 419–445 in *Annual review of ecology, evolution, and systematics*, Annual review of ecology evolution and systematics. Futuyma, D. (ed.).

Jandl, R., M. Lindner, L. Vesterdal, B. Bauwens, R. Baritz, F. Hagedorn, D. W. Johnson, K. Minkkinen, and K. A. Byrne. 2007. How strongly can forest management influence soil carbon sequestration? *Geoderma.* 137(3-4):253–268.

Jang, W., D. S. Page-Dumroese, and C. R. Keyes. 2016. Long-term soil changes from forest harvesting and residue management in the northern Rocky Mountains. *Soil Science Society of America Journal.* 80(3):727–741.

Jenny, H. H. 1941. *Factors of Soil Formation.* McGraw Hill, New York.

Johnson, D. W., and P. S. Curtis. 2001. Effects of forest management on soil C and N storage: meta analysis. *Forest Ecology and Management.* 140(2):227–238 Available online at: http://www.sciencedirect.com/science/article/pii/S0378112700002826.

Kaarakka, L., P. Tamminen, A. Saarsalmi, M. Kukkola, H. S. Helmisaari, and A. J. Burton. 2014. Effects of repeated whole-tree harvesting on soil properties and tree growth in a Norway spruce (Picea abies (L.) Karst.) stand. *Forest Ecology and Management.* 313:180–187 Available online at: http://www.sciencedirect.com/science/article/pii/S0378112713007445.

Kabacoff, R. 2015. *R in action: data analysis and graphics with R.* 2nd ed. Stout, J. (ed.) Manning Publications, Shelter Island, NY.

Kätterer, T., A. Fabião, M. Madeira, C. Ribeiro, and E. Steen. 1995. Fine-root dynamics, soil moisture and soil carbon content in a Eucalyptus globulus plantation under different irrigation and fertilisation regimes. *Forest Ecology and Management.* 74(1-3):1–12 Available online at: http://www.sciencedirect.com/science/article/pii/037811279503529J.

Keeling, C., S. Piper, R. Bacastow, M. Wahlen, T. Whorf, M. H. Eimann, and H. Meijer. 2001. *Exchanges of atmospheric CO2 and 13CO2 with the terrestrial biosphere and oceans from 1978 to 2000.* San Diego.

Keeling, C., S. Piper, R. Bacastow, M. Wahlen, T. Whorf, M. H. Eimann, and H. Meijer. 2020. Scripps CO2 program, primary Mauna Loa CO2 record. Available online at: https://scrippsco2.ucsd.edu/.

Keenan, T. F., and C. A. Williams. 2018. The Terrestrial Carbon Sink. Pp. 219–243 in *Annual review of environment and resources*, Annual review of environment and resources. Gadgil, A and Tomich, T. (ed.).

Kennedy, F. 2002. *The identification of soils for forest management. Field Guide.* Forestry

Commission, Edinburgh, Scotland.

Kerr, G., M. Snellgrove, S. Hale, and V. Stokes. 2017. The Bradford–Hutt system for transforming young even-aged stands to continuous cover management. *Forestry: An International Journal of Forest Research.* (1-13).

Keuskamp, J. A., B. J. J. Dingemans, T. Lehtinen, J. M. Sarneel, and M. M. Hefting. 2013. Tea Bag Index: a novel approach to collect uniform decomposition data across ecosystems. *Methods in Ecology and Evolution.* 4(11):1070–1075 Available online at: http://dx.doi.org/10.1111/2041-210X.12097.

Kleber, M. 2010. What is recalcitrant soil organic matter? *Environmental Chemistry.* 7(4):320–332 Available online at: https://doi.org/10.1071/EN10006.

Klinka, K., R. Greene, R. Towbridge, and L. Lowe. 1981. *Taxonomic classification of humus forms in ecosystems of British Colombia.* Ministry of Forests, Province of B.C. Available online at: https://www.for.gov.bc.ca/hfd/pubs/Docs/Mr/Lmr/Lmr008.pdf.

Kogel-Knabner, I., K. Ekschmitt, H. Flessa, G. Guggenberger, E. Matzner, B. Marschner, and M. von Lützow. 2008. An integrative approach of organic matter stabilization in temperate soils: Linking chemistry, physics, and biology. *Journal of Plant Nutrition and Soil Science.* 171(1):5–13.

Kuznetsova, A., P. B. Brockhoff, and R. H. B. Christensen. 2017. {lmerTest} Package: Tests in Linear Mixed Effects Models. *Journal of Statistical Software.* 82(13):1–26.

Lal, R. 2005. Forest soils and carbon sequestration. *Forest Ecology and Management.* 220(1-3):242–258.

LeBauer, D. S., and K. K. Treseder. 2008. Nitrogen limitation of net primary productivity in terrestrial ecosystems is globally distributed. *Ecology.* 89(2):371–379.

Lefèvre, C., F. Rekik, V. Alcantara, and L. Wiese. 2017. *Soil Organic Carbon: the hidden potential.* FAO, Rome. Available online at: http://www.fao.org/publications/card/en/c/ed16dbf7-b777-4d07-8790-798604fd490a/.

Lehmann, J., and M. Kleber. 2015. The contentious nature of soil organic matter. *Nature.* 528(7580):60–68.

Lenth, R. 2018. *emmeans: Estimated Marginal Means, aka Least-Squares Means.* Available online at: https://cran.r-project.org/package=emmeans.

Lewis, T., T. E. Smith, B. Hogg, S. Swift, L. Verstraten, P. Bryant, B. J. Wehr, N. Tindale, N. W. Menzies, and R. C. Dalal. 2016. Conversion of sub-tropical native vegetation to introduced conifer forest: Impacts on below-ground and above-ground carbon pools. *Forest Ecology and Management.* 370:65–75.

Lozanova, L., M. Zhiyanski, E. Vanguelova, S. Doncheva, M. P. Marinov, and S. Lazarova. 2019. Dynamics and Vertical Distribution of Roots in European Beech Forests and Douglas Fir Plantations in Bulgaria. *Forests.* 10(12) Available online at: https://www.mdpi.com/1999-4907/10/12/1123.

Lukac, M., and D. L. Godbold. 2010. Fine root biomass and turnover in southern taiga estimated by root inclusion nets. *Plant and Soil.* 331(1-2):505–513.

Lundmark, T., J. Bergh, A. Nordin, N. Fahlvik, and B. C. Poudel. 2016. Comparison of carbon balances between continuous-cover and clear-cut forestry in Sweden. *Ambio.* 45(2, SI):S203–S213.

Luo, D., R. Cheng, Z. Shi, and W. Wang. 2017. Decomposition of Leaves and Fine Roots in Three Subtropical Plantations in China Affected by Litter Substrate Quality and Soil

Microbial Community. *Forests*. 8(11).

Luo, Y. 2003. Uncertainties in interpretation of isotope signals for estimation of fine root longevity: theoretical considerations. *Global Change Biology*. 9(7):1118–1129 Available online at: http://doi.wiley.com/10.1046/j.1365-2486.2003.00642.x.

Lützow, M. von, I. Kögel-Knabner, K. Ekschmitt, H. Flessa, G. Guggenberger, E. Matzner, and B. Marschner. 2007. SOM fractionation methods: Relevance to functional pools and to stabilization mechanisms. *Soil Biology and Biochemistry*. 39(9):2183–2207 Available online at: http://www.sciencedirect.com/science/article/pii/S0038071707001125.

Maes, S. L., H. Blondeel, M. P. Perring, L. Depauw, G. Brumelis, J. Brunet, G. Decocq, et al. 2019. Litter quality, land-use history, and nitrogen deposition effects on topsoil conditions across European temperate deciduous forests. *Forest Ecology and Management*. 433:405–418.

Manning, P., F. T. de Vries, J. R. B. Tallowin, R. Smith, S. R. Mortimer, E. S. Pilgrim, K. A. Harrison, et al. 2015. Simple measures of climate, soil properties and plant traits predict national-scale grassland soil carbon stocks Wilsey, B. (ed.). *Journal of Applied Ecology*. 52(5):1188–1196 Available online at: http://doi.wiley.com/10.1111/1365-2664.12478.

Marichal, M. de J., A. Trujillo, M. Cadenazzi, and G. Arias. 2011. Fiber analysis: Evaluation of screen printing fabric filters bags by three statistical approaches. *Animal Feed Science and Technology*. 169(1):79–85 Available online at: http://www.sciencedirect.com/science/article/pii/S0377840111002823.

Marschner, B., S. Brodowski, A. Dreves, G. Gleixner, A. Gude, P. M. Grootes, U. Hamer, et al. 2008. How relevant is recalcitrance for the stabilization of organic matter in soils? *Journal of Plant Nutrition and Soil Science*. 171(1):91–110 Available online at: http://doi.

wiley.com/10.1002/jpln.200700049.

Mason, W. L., H. M. Mckay, A. Weatherall, T. Connolly, and A. J. Harrison. 2012. The effects of whole-tree harvesting on three sites in upland Britain on the growth of Sitka spruce over ten years. *Forestry: An International Journal of Forest Research*. 85(1):111–123 Available online at: http://forestry.oxfordjournals.org/cgi/content/long/85/1/111.

Melillo, J., J. D. Aber, and J. F. Muratore. 1982. Nitrogen and Lignin Control of Hardwood Leaf Litter Decomposition Dynamics. *Ecology*. 63(3):621–626 Available online at: http: https://doi.org/10.2307/1936780.

Merilä, P., K. Mustajärvi, H. S. Helmisaari, S. Hilli, A.-J. Lindroos, T. M. Nieminen, P. Nöjd, P. Rautio, M. Salemaa, and L. Ukonmaanaho. 2014. Above- and below-ground N stocks in coniferous boreal forests in Finland: Implications for sustainability of more intensive biomass utilization. *Forest Ecology and Management*. 311:17–28 Available online at: http://www.sciencedirect.com/science/article/pii/S0378112713003976.

Moinet, G. Y. K., E. Cieraad, J. E. Hunt, A. Fraser, M. H. Turnbull, and D. Whitehead. 2016. Soil heterotrophic respiration is insensitive to changes in soil water content but related to microbial access to organic matter. *Geoderma*. 274:68–78.

Montagnoli, A., A. Di Iorio, M. Terzaghi, D. Trupiano, G. S. Scippa, and D. Chiatante. 2014. Influence of soil temperature and water content on fine-root seasonal growth of European beech natural forest in Southern Alps, Italy. *European Journal of Forest Research*. 133(5):957–968 Available online at: http://dx.doi.org/10.1007/s10342-014-0814-6.

Moorhead, D. L., G. Lashermes, R. L. Sinsabaugh, and M. N. Weintraub. 2013. Calculating co-metabolic costs of lignin decay and their impacts on carbon use efficiency. *Soil Biology and Biochemistry*. 66:17–19 Available online at: http://linkinghub.elsevier.com/retrieve/

pii/S0038071713002265.

Moorhead, D. L., R. L. Sinsabaugh, A. Linkins, and J. F. Reynolds. 1996. Decomposition processes: modelling approaches and applications. *Science of The Total Environment*. 183(1-2):137–149 Available online at: http://linkinghub.elsevier.com/retrieve/pii/0048969795049746.

Morison, J., R. Matthews, G. Miller, M. Perks, T. Randle, E. Vanguelova, M. White, S. Yamulki, and Forestry. 2012. *Understanding the carbon and greenhouse gas balance of forests in Britain*. Copyright, C. (ed.) Forestry Commission, Edinburgh.

Muller, E., and T. Linhares-Juvenal. 2016. *Forestry for a low-carbon future – Integrating forests and wood products in climate change*. FAO. Food And Agriculture Organization Of The United Nations, Rome. Available online at: http://www.fao.org/publications/en/.

Nave, L. E., E. D. Vance, C. W. Swanston, and P. S. Curtis. 2010. Harvest impacts on soil carbon storage in temperate forests. *Forest ecology and management*. 259(5):857–866.

Neumann, M., D. L. Godbold, Y. Hirano, and L. Finer. 2020. Improving models of fine root carbon stocks and fluxes in European forests. *Journal of Ecology*.

Nieminen, M. 2004. Export of dissolved organic carbon, nitrogen and phosphorus following clear-cutting of three Norway spruce forests growing on drained peatlands in southern Finland. *Silva Fennica*. 38(2):123–132.

Nisbet, T. R., J. Dutch, and A. J. Moffat. 1997. *Whole-Tree Harvesting, A Guide to Good Practice*. Forestry Commission, Edinburgh.

Nunery, J. S., and W. S. Keeton. 2010. Forest carbon storage in the northeastern United States: Net effects of harvesting frequency, post-harvest retention, and wood products.

Forest Ecology and Management. 259(8):1363–1375.

Olsson, B. A., H. Staaf, H. Lundkvist, J. Bengtsson, and R. Kaj. 1996. Carbon and nitrogen in coniferous forest soils after clear-felling and harvests of different intensity. *Forest Ecology and Management.* 82(1):19–32 Available online at: http://www.sciencedirect.com/science/article/pii/0378112795036970.

Owen, D. 2013. *Background to the Clocaenog CCF Research Area.* Forestry Commission.

Parker, J. L., I. J. Fernandez, L. E. Rustad, and S. A. Norton. 2001. Effects of nitrogen enrichment, wildfire, and harvesting on forest-soil carbon and nitrogen. *Soil Science Society of America Journal.* 65(4):1248–1255.

Parts, K., L. Tedersoo, A. Schindlbacher, B. D. Sigurdsson, N. I. W. Leblans, E. S. Oddsdottir, W. Borken, and I. Ostonen. 2019. Acclimation of Fine Root Systems to Soil Warming: Comparison of an Experimental Setup and a Natural Soil Temperature Gradient. *Ecosystems.* 22(3):457–472.

Paul, E. A. 2016. The nature and dynamics of soil organic matter: Plant inputs, microbial transformations, and organic matter stabilization. *Soil Biology and Biochemistry.* 98:109–126.

Paustian, K., J. Lehmann, S. Ogle, D. Reay, G. P. Robertson, and P. Smith. 2016. Climate-smart soils. *Nature.* 532(7597).

Peng, Y., S. C. Thomas, and D. Tian. 2008. Forest management and soil respiration: Implications for carbon sequestration. *ENVIRONMENTAL REVIEWS.* 16:93–111.

Pennock, D. J., and C. VanKessel. 1997. Clear-cut forest harvest impacts on soil quality indicators in the mixedwood forest of Saskatchewan, Canada. *Geoderma.* 75(1-2):13–32.

Pinheiro, J., D. Bates, S. DebRoy, and D. Sarkar. 2018. nlme: Linear and Nonlinear Mixed Effects Models. *R Core Team.* Available online at: https://cran.r-project.org/package=nlme.

Pitman, R., E. Vanguelova, and S. Benham. 2011. *Report on pilot study of Continuous Cover Forestry effects on soil properties and ground vegetation at Clocaenog, N. Wales.* Forestry Commission.

Poetzelsberger, E., and H. Hasenauer. 2015. Soil change after 50 years of converting Norway spruce dominated age class forests into single tree selection forests. *Forest Ecology and Management.* 338:176–182.

Powers, M., R. K. Kolka, B. J. Palik, R. McDonald, and M. Jurgensen. 2011. Long-term management impacts on carbon storage in Lake States forests. *Forest Ecology and Management.* 262(3):424–431.

Prescott, C. E. 2010. Litter decomposition: what controls it and how can we alter it to sequester more carbon in forest soils? *Biogeochemistry.* 101(1-3):133–149.

Pries, C. E. H., J. A. Bird, C. Castanha, P.-J. Hatton, and M. S. Torn. 2017. Long term decomposition: the influence of litter type and soil horizon on retention of plant carbon and nitrogen in soils. *Biogeochemistry.* 134(1-2):5–16.

Proe, M. F., J. Griffiths, and H. M. Mckay. 2001. Effect of whole-tree harvesting on microclimate during establishment of second rotation forestry. *Agricultural and Forest Meteorology.* 110(2):141–154 Available online at: http://www.sciencedirect.com/science/article/pii/S0168192301002854.

Puhlick, J. J., A. R. Weiskittel, I. J. Fernandez, S. Fraver, L. S. Kenefic, R. S. Seymour, R.

K. Kolka, L. E. Rustad, and J. C. Brissette. 2016. Long-term influence of alternative forest management treatments on total ecosystem and wood product carbon storage. *Canadian Journal of Forest Research*. 46(11):1404–1412.

R Core Team. 2018. *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing, Vienna, Austria. Available online at: https://www.r-project.org/.

Raymond, P., S. Bedard, V. Roy, C. Larouche, and S. Tremblay. 2009. The Irregular Shelterwood System: Review, Classification, and Potential Application to Forests Affected by Partial Disturbances. *Journal of Forestry*. 107(8):405–413.

RStudio Team. 2016. *RStudio: Integrated Development Environment for R*. RStudio, Inc., Boston, MA. Available online at: http://www.rstudio.com/.

Ryan, M. G., J. Melillo, and A. Ricca. 1990. A comparison of methods for determining proximate carbon fractions of forest litter. *Canadian Journal of Forest Research*. 20(2):166–171 Available online at: http://dx.doi.org/10.1139/x90-023.

Saarsalmi, A., P. Tamminen, M. Kukkola, and R. Hautajärvi. 2010. Whole-tree harvesting at clear-felling: Impact on soil chemistry, needle nutrient concentrations and growth of Scots pine. *Scandinavian Journal of Forest Research*. 25(2):148–156.

Sariyildiz, T. 2015. Effects of tree species and topography on fine and small root decomposition rates of three common tree species (Alnus glutinosa, Picea orientalis and Pinus sylvestris) in Turkey. *Forest Ecology and Management*. 335:71–86 Available online at: https://www.sciencedirect.com/science/article/pii/S0378112714005714?via{\%}3Dihub.

Schmidt, M. W. I., M. S. Torn, S. Abiven, T. Dittmar, G. Guggenberger, I. A. Janssens, M. Kleber, et al. 2011. Persistence of soil organic matter as an ecosystem property. *Nature*.

478(7367):49–56 Available online at: http://dx.doi.org/10.1038/nature10386.

Schrumpf, M., K. Kaiser, G. Guggenberger, T. Persson, I. Kögel-Knabner, and E. D. Schulze. 2013. Storage and stability of organic carbon in soils as related to depth, occlusion within aggregates, and attachment to minerals. *Biogeosciences.* 10(3):1675–1691.

Shen, Y., N. Wang, R. Cheng, W. Xiao, S. Yang, and Y. Guo. 2017. Short-Term Effects of Low Intensity Thinning on the Fine Root Dynamics of Pinus massoniana Plantations in the Three Gorges Reservoir Area, China. *Forests.* 8(11).

Smith, J., P. Gottschalk, J. Bellarby, S. Chapman, A. Lilly, W. Towers, J. Bell, et al. 2010. Estimating changes in Scottish soil carbon stocks using ECOSSE. I. Model description and uncertainties. *Climate Research.* 45(1):179–192 Available online at: https://www.int-res.com/articles/cr{_}oa/c045p179.pdf.

Smolander, A., T. Levula, and V. Kitunen. 2008. Response of litter decomposition and soil C and N transformations in a Norway spruce thinning stand to removal of logging residue. *Forest Ecology and Management.* 256(5):1080–1086.

Solly, E. F., I. Schöning, S. Boch, J. Müller, S. a. Socher, S. Trumbore, and M. Schrumpf. 2013. Mean age of carbon in fine roots from temperate forests and grasslands with different management. *Biogeosciences.* 10(7):4833–4843.

SSSA. Glossary of soil science terms. Available online at: https://www.soils.org/publications/soils-glossary/science-policy.

Stokes, V., and G. Kerr. 2009. *The evidence supporting the use of CCF in adapting Scotland's forests to the risks of climate change.* Forestry Commission.

Strand, A. E., S. G. Pritchard, M. L. McCormack, M. A. Davis, and R. Oren. 2008. Irreconcilable differences: Fine-root life spans and soil carbon persistence. *Science.*

319(5862):456–458.

Swain, E. Y., M. P. Perks, E. Vanguelova, and G. D. Abbott. 2010. Carbon stocks and phenolic distributions in peaty gley soils afforested with Sitka spruce (Picea sitchensis). *Organic Geochemistry*. 41(9):1022–1025.

Tamminen, P., A. Saarsalmi, A. Smolander, M. Kukkola, and H. S. Helmisaari. 2012. Effects of logging residue harvest in thinnings on amounts of soil carbon and nutrients in Scots pine and Norway spruce stands. *Forest Ecology and Management*. 263:31–38.

Thiffault, E., K. Hannam, D. Paré, B. D. Titus, P. W. Hazlett, D. Maynard, and S. Brais. 2011. Effects of forest biomass harvesting on soil productivity in boreal and temperate forests — A review. *Environmental Reviews*. 19(NA):278–309 Available online at: http://dx.doi.org/10.1139/a11-009.

Todd-Brown, K. E. O., J. T. Randerson, W. M. Post, F. M. Hoffman, C. Tarnocai, E. A. G. Schuur, and S. D. Allison. 2013. Causes of variation in soil carbon simulations from CMIP5 Earth system models and comparison with observations. *Biogeosciences*. 10(3):1717–1736 Available online at: https://www.biogeosciences.net/10/1717/2013/.

UKWAS Certification Standard. 2018. *United Kingdom Woodland Assurance Standard*. 4th ed. Edinburgh. Available online at: http://ukwas.org.uk/wp-content/uploads/2018/05/UKWAS-standard-digital-V4.0-FINAL.pdf.

UNFCCC. Background on the UNFCCC: The international response to climate change. Available online at: https://unfccc.int/process/the-convention/history-of-the-convention.

United Nations. 2015. Transforming our world: the 2030 Agenda for Sustainable Development - Resolution adopted by the General Assembly on 25 September 2015.

Available online at: https://sustainabledevelopment.un.org/post2015/transformingourworld.

USDA. 2014. *Keys to Soil Taxonomy.* 12th ed. United States Department of Agriculture, Washington, DC.

Van Breemen, N., and P. Buurman. 2002. *Soil formation.* 2nd ed. Kluwer Academic Publishers, New York.

Van Soest, P. J., J. B. Robertson, and B. A. Lewis. 1991a. Methods for dietary fiber, neutral detergent fiber, and nonstarch polysaccharides in relation to animal nutrition. *Journal of dairy science.* 74(10):3583–97 Available online at: http://www.sciencedirect.com/science/article/pii/S0022030291785512.

Van Soest, P. J., J. B. Robertson, and B. A. Lewis. 1991b. Symposium: Carbohydrate methodology, metabolism and nutritional implications in dairy cattle: methods for dietary fiber, neutral detergent fiber and nonstarch polysaccharides in relation to animal nutrition. *Journal of Dairy Science.* 74(10):3583–3597.

Vanguelova, E., and R. Pitman. 2019. Nutrient and carbon cycling along nitrogen deposition gradients in broadleaf and conifer forest stands in the east of England. *Forest Ecology and Management.* 447:180–194.

Vanguelova, E., E. Bonifacio, B. De Vos, M. R. Hoosbeek, T. W. Berger, L. Vesterdal, K. Armolaitis, et al. 2016. Sources of errors and uncertainties in the assessment of forest soil carbon stocks at different scales - review and recommendations. 188.

Vanguelova, E., S. Chapman, M. Perks, S. Yamulki, T. Randle, F. Ashwood, and J. Morison. 2018. *Afforestation and restocking on peaty soils: new evidence assessment. Report to CXC.* Forest Research.

Vanguelova, E., P. Crow, S. Benham, R. Pitman, J. Forster, E. L. Eaton, and J. Morison.

2019. Impact of Sitka spruce (Picea sitchensis (Bong.) Carr.) afforestation on the carbon stocks of peaty gley soils – a chronosequence study in the north of England. *Forestry: An International Journal of Forest Research*. 92(3):242–252 Available online at: https://doi.org/10.1093/forestry/cpz013.

Vanguelova, E., T. R. Nisbet, A. J. Moffat, S. Broadmeadow, T. G. M. Sanders, and J. Morison. 2013. A new evaluation of carbon stocks in British forest soils. *Soil Use and Management*. 29(2):169–181 Available online at: https://onlinelibrary.wiley.com/doi/abs/10.1111/sum.12025.

Vanguelova, E., S. Nortcliff, A. J. Moffat, and F. Kennedy. 2007. Short-term effects of manipulated increase in acid deposition on soil, soil solution chemistry and fine roots in Scots pine (Pinus sylvestris) stand on a podzol. *Plant and Soil*. 294(1):41–54 Available online at: http://dx.doi.org/10.1007/s11104-007-9225-5.

Vanguelova, E., R. Pitman, J. Luiro, and H. S. Helmisaari. 2010. Long term effects of whole tree harvesting on soil carbon and nutrient sustainability in the UK. *Biogeochemistry*. 101(1/3):43–59 Available online at: http://www.jstor.org/stable/40980874.

Walmsley, J. D., D. L. Jones, B. Reynolds, M. H. Price, and J. R. Healey. 2009. Whole tree harvesting can reduce second rotation forest productivity. *Forest Ecology and Management*. 257(3):1104–1111 Available online at: http://www.sciencedirect.com/science/article/pii/S0378112708008402.

Wan, X., L. Xiao, M. A. Vadeboncoeur, C. E. Johnson, and Z. Huang. 2018. Response of mineral soil carbon storage to harvest residue retention depends on soil texture: A meta-analysis. *Forest Ecology and Management*. 408:9–15.

Wang, C., I. Brunner, S. Zong, and M.-H. Li. 2019. The Dynamics of Living and Dead Fine

Roots of Forest Biomes across the Northern Hemisphere. *Forests.* 10(11).

Wang, X., L. Ma, Z. Jia, and L. Jia. 2014. Root inclusion net method: novel approach to determine fine root production and turnover in Larix principis-rupprechtii Mayr plantation in North China. *Turkish Journal of Agriculture and Forestry.* 38(3):388–398 Available online at: http://tubitak.dergipark.gov.tr/tbtkagriculture/137933.

Ward, S. 2020. Forestry Statistics 2020. in Research, F. (ed.).

Wickham, H. 2016. *ggplot2: Elegant Graphics for Data Analysis.* Springer-Verlag New York. Available online at: http://ggplot2.org.

Wilkinson, M., P. Crow, E. L. Eaton, and J. Morison. 2016. Effects of management thinning on CO2 exchange by a plantation oak woodland in south-eastern England. *Biogeosciences.* 13(8):2367–2378 Available online at: http://www.biogeosciences.net/13/2367/2016/.

Zanella, A., B. Jabiol, J. F. Ponge, G. Sartori, R. De Waal, B. Van Delft, U. Graefe, et al. 2011. A European morpho-functional classification of humus forms. *Geoderma.* 164(3-4):138–145.

Appendix

Table 6.5: Table of acronyms and symbols utilised throughout the thesis.

Acronym	Meaning
Ø	Diameter
Bd	Bulk density
block	Block replication - experimental design
C	Carbon
CCF	Continuous Cover Forestry
CEC	Cation Exchange Capacity
CH	Conventional Harvesting (stem-only harvesting)
CHF	CH and fertilization
CO2	Carbon dioxide
CO2eq	CO2 equivalents
COP21	UNFCCC twenty-first Conference of the Parties in Paris
DOC	Dissolved organic carbon
DOM	Dissolved organic matter
EMM	Estimated marginal means (EMMs), a.k.a. least-squares means
F (Oe)	Fragmented horizon of the soil organic surface horizons
GHG	Greenhouse gas
H (Oa)	Humified organic matter horizon of the organic surface horizons
hor	Soil horizon
HWP	Harvested Wood Products
IPCC	Intergovernmental Panel on Climate Change
L (Oi)	Litter horizon of the organic surface horizons
LCI	Lignocellulose index
managem	Forest management practice - treatment
Mitigation	Climate change mitigation
N	Nitrogen
NPP	Net Primary Productivity
OM	Organic matter
OSH	Organic surface horizon(s)
POC	Particulate organic carbon
POM	Particulate organic matter
REDD+	Reducing Emissions from Deforestation and forest Degradation
RIN	Root Inclusion Net
SOC	Soil organic carbon
SOM	Soil organic matter
SRL	Specific Root Length
UNFCCC	United Nations Framework Convention on Climate Change
WTH	Whole-Tree Harvesting

Table 6.6: Forest of Ae. Results from field and laboratory analysis averaged by block replication: soil field moisture, bulk density, available nitrogen and depth.

			%		g/cm^3		mg/kg		cm	
forest	block	managem	fm0_15	fm15_30	Bd0_15	Bd15_30	Ammonium	Nitrate	depth_F	depth_H
Ae	1	WTH	82.37	73.89	0.10	0.18	10.34	2.55	8.33	18.33
Ae	2	WTH	82.43	78.10	0.10	0.17	13.35	3.09	7.50	21.33
Ae	3	WTH	84.21	79.62	0.09	0.16	8.98	3.08	3.83	26.67
Ae	1	CH	76.34	68.33	0.14	0.22	10.85	2.30	11.00	7.17
Ae	2	CH	80.33	71.68	0.11	0.19	8.05	4.55	11.67	15.50
Ae	3	CH	82.72	84.19	0.07	0.11	11.46	4.31	12.17	24.67
Ae	1	CHF	81.76	74.20	0.09	0.21	10.58	4.98	11.83	11.33
Ae	2	CHF	83.35	82.55	0.08	0.13	12.11	7.30	14.00	24.50
Ae	3	CHF	82.36	79.26	0.07	0.15	13.06	4.60	14.67	27.50

Note:
Data were averaged by block replication before statistical analysis (n=3).
[1] fm015 / fm13_30: soil field moisture % in the 0-15 and 15-30 cm depth.
[2] Bd0_15 / Bd_1530: bulk density in the 0-15 and 15-30 cm soil depth.
[3] Ammonium / Nitrate: Soil available N (H horizon)
[4] depth_F, depth_H: depth of the F and H soil horizons

Table 6.7: Forest of Ae. L horizon water content and dry mass. H horizon water content and Bd averaged by block replication (n=3).

			g	g/cm^3	%	
forest	managem	block	L_drymass	H_Bd	L_Wcont	H_Wcont
Ae	WTH	1	26.98	0.24	69.70	76.77
Ae	WTH	2	28.04	0.18	66.72	82.19
Ae	WTH	3	28.53	0.16	70.70	83.35
Ae	CH	1	30.32	0.21	68.93	79.57
Ae	CH	2	24.40	0.23	73.15	78.17
Ae	CH	3	29.71	0.14	69.53	86.18
Ae	CHF	1	39.26	0.21	64.44	78.25
Ae	CHF	2	35.00	0.16	74.01	83.70
Ae	CHF	3	38.42	0.20	67.94	80.07

Note:
Litter dry mass (g, from 25cm quadrat) and bulk density of the H horizon. L and H horizon field moisture.

Table 6.8: Forest of Ae. Results (total C and N) from elemental analysis averaged by block replication (n=3). For reference to the table footnote please refer to IUSS Working Group WRB (2015).

			WTH			CH			CHF		
			total %			total %			total %		
forest	block	hor	C	N	CNratio	C	N	CNratio	C	N	CNratio
Ae	1	L	55.58	1.15	48.46	54.77	1.18	46.38	54.09	1.15	47.12
Ae	1	F	51.44	1.57	32.94	49.75	1.47	34.24	51.25	1.70	30.19
Ae	1	H	47.80	2.02	23.62	29.33	1.36	21.41	31.48	1.40	22.32
Ae	1	A	18.06	0.71	25.44	7.04	0.34	20.30	9.20	0.40	22.01
Ae	2	L	55.79	1.10	51.02	54.96	1.04	52.78	54.39	1.10	49.82
Ae	2	F	54.76	1.48	37.18	58.24	1.62	35.93	52.82	1.56	34.06
Ae	2	H	52.26	2.18	23.96	50.87	2.30	22.16	53.11	2.40	22.14
Ae	2	A	31.22	1.26	24.74	25.44	0.99	25.69	22.29	0.88	25.13
Ae	3	L	55.43	1.02	54.14	55.09	1.02	54.13	54.35	1.04	52.62
Ae	3	F	53.29	1.37	38.96	55.40	1.49	37.17	53.56	1.65	32.65
Ae	3	H	53.24	2.18	24.64	55.61	2.21	25.19	49.23	2.26	21.85
Ae	3	A	25.21	0.91	27.75	44.32	1.60	27.59	35.62	1.39	25.63

Note:
Horizons L,F,H (Neiker Tecnalia); horizon A (Forest Research). For the purpose of soil horizon depth measurement, the A horizon as seen in the table was retained as an H horizon (total C content values are in between organic (>20% C) and mineral (<20% C) according to WRB.

Table 6.9: Forest of Ae. Ash and OM content, C pools, LCI and total C mass of the OSH.

				Thermogravimetric analyser		Ankom analyser						
				%			% (proximate C pools)					Mg/ha
forest	managem	block	hor	OM	ash_thermogr	ash_furnace	Cell_sol	Hemicel	Cellul	Lignin	LCI	C_Mgha
Ae	WTH	1	L	96.69	3.31	0.54	32.31	13.01	27.11	27.57	0.41	2.40
Ae	WTH	2	L	96.63	3.37	0.14	30.09	13.27	26.81	29.82	0.43	2.50
Ae	WTH	3	L	97.00	3.00	0.41	26.22	18.40	26.96	28.42	0.39	2.53
Ae	WTH	1	F	88.53	11.47	5.24	27.88	17.79	17.77	36.57	0.51	34.41
Ae	WTH	2	F	96.14	3.86	2.86	20.39	20.57	20.57	38.47	0.48	32.76
Ae	WTH	3	F	92.33	7.67	6.84	27.92	18.23	17.53	36.31	0.50	16.20
Ae	WTH	1	H	81.36	18.64	13.04	61.44	10.79	7.59	20.17	0.52	209.52
Ae	WTH	2	H	87.50	12.50	8.39	50.57	13.21	9.89	26.33	0.53	203.65
Ae	WTH	3	H	87.34	12.66	8.00	53.22	12.99	9.26	24.54	0.52	233.28
Ae	CH	1	L	95.69	4.31	1.31	33.39	14.58	24.88	27.15	0.41	2.66
Ae	CH	2	L	96.61	3.39	0.76	30.10	14.23	25.43	30.24	0.43	2.14
Ae	CH	3	L	96.45	3.55	0.86	31.01	14.30	25.84	28.85	0.42	2.62
Ae	CH	1	F	85.09	14.91	10.32	31.18	16.12	16.98	35.72	0.52	43.34
Ae	CH	2	F	98.49	1.51	3.11	16.08	19.79	21.90	42.23	0.50	54.78
Ae	CH	3	F	94.79	5.21	2.18	20.23	16.91	20.62	42.23	0.53	53.75
Ae	CH	1	H	48.80	51.20	38.64	72.75	8.20	5.39	13.66	0.50	45.15
Ae	CH	2	H	83.72	16.28	13.02	51.30	11.34	7.09	30.27	0.62	177.86
Ae	CH	3	H	91.08	8.92	6.38	46.09	12.80	11.69	29.41	0.55	191.65
Ae	CHF	1	L	94.65	5.35	1.61	32.71	13.25	25.91	28.13	0.42	3.40
Ae	CHF	2	L	96.20	3.80	0.42	31.42	14.58	26.93	27.07	0.39	3.05
Ae	CHF	3	L	95.85	4.15	0.49	31.67	12.97	27.23	28.14	0.41	3.34
Ae	CHF	1	F	85.65	14.35	10.94	29.64	15.16	18.39	36.82	0.52	48.33
Ae	CHF	2	F	91.96	8.04	3.97	22.93	15.44	19.60	42.03	0.55	58.93
Ae	CHF	3	F	93.47	6.53	4.26	22.60	16.96	19.10	41.34	0.53	62.77
Ae	CHF	1	H	52.72	47.28	40.92	68.28	7.30	7.29	17.14	0.52	76.10
Ae	CHF	2	H	87.30	12.70	8.12	47.67	11.67	10.98	29.68	0.56	212.36
Ae	CHF	3	H	83.53	16.47	13.84	56.00	10.70	8.66	24.64	0.55	276.32

Note:
Data were averaged by block replication before statistical analysis (n=3).
[1] ash_furnace: % ash from the samples utilised in C fractionation; ash_thermograv: % ash from the thermogravimetric analyser (from OM); OM: % organic matter; Cell_sol: cell solubles; Hemicell: hemicellulose; Cellul: cellulose; C_Mgha: C mass (Mg/ha); LCI:lignocellulose index;

Table 6.10: Forest of Ae. Biomass and necromass (Mg ha^{-1}) of the 0-15 and 15-30 cm soil depths.

			Mg per ha (dry mass)			
forest	block	managem	Standbiom015Mgha	Necrom015Mgha	Standbiom1530Mgha	Necrom1530Mgha
Ae	1	WTH	4.60	0.48	0.14	0.06
Ae	2	WTH	5.09	0.69	0.63	0.15
Ae	3	WTH	4.75	0.52	0.39	0.13
Ae	1	CH	5.85	0.88	0.88	0.22
Ae	2	CH	5.87	0.35	0.28	0.21
Ae	3	CH	3.44	0.54	0.96	0.34
Ae	1	CHF	5.35	0.83	2.09	0.46
Ae	2	CHF	6.76	0.71	1.11	0.35
Ae	3	CHF	6.52	0.60	1.01	0.25

Note:
Data were averaged by block replication before statistical analysis (n=3).
[1] Standbiom: fine root standing biomass; Necrom: fine root necromass; 015: 0 to 15 cm soil depth; 1530: 15 to 30 cm soil depth.

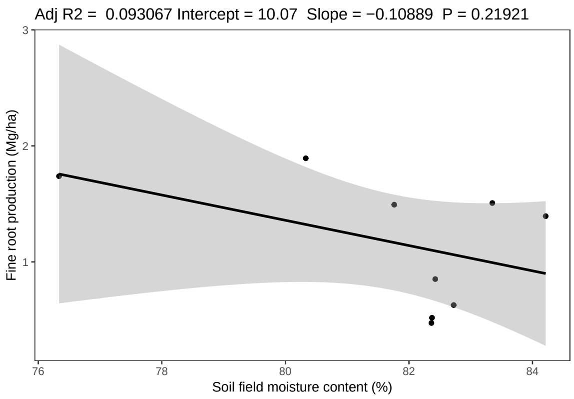

Figure 6.1: Forest of Ae. Linear regression of soil field moisture content and fine root production in the 0 to 15 cm soil depth.

Table 6.11: Forest of Ae. Fine root production (Mg ha^{-1}) from the RIN technique.

			n of roots	Mg per ha (dry mass)	
forest	block	managem	fieldRootsCount	Mgha015	Mgha1530
Ae	1	WTH	18.33	0.85	0.02
Ae	2	WTH	19.50	1.17	0.01
Ae	3	WTH	23.33	1.31	0.00
Ae	1	CH	23.83	1.69	0.02
Ae	2	CH	44.17	1.99	0.09
Ae	3	CH	18.83	0.82	0.03
Ae	1	CHF	22.00	1.48	0.14
Ae	2	CHF	25.83	1.39	0.00
Ae	3	CHF	14.50	0.47	0.04

Note:
Data were averaged by block replication before statistical analysis (n=3).
[1] Mgha015: root production in the 0 to 15 cm layer; Mgha1530: root production in the 15 to 30 cm soil layer; field_root_count: root count in the nets at the time of harvesting

Table 6.12: Clocaenog trial. Litter water content and mass averaged by management (and respacing, CCF only).

			m (CCF)	%	Mg/ha
forest	managem	hor	respace	Wcont	litter_mass
Cloca	UN	L	NA	50.22	5.39
Cloca	CCF	L	1.6	40.46	3.49
Cloca	CCF	L	2	37.22	5.73
Cloca	CCF	L	3.2	47.53	4.29
Cloca	CCF	L	5	29.78	2.44

Note:
Data was averaged to contain the size of the table.
[1] Data within respace/hor is average of five observations (CCF). Data within managem 'UN'/hor is average of fifteen observations. Litter mass refers to the entire litter, not just C.

Table 6.13: Clocaenog Forest. Bd and water content averaged by management (respacing, CCF only) and horizon (F,H,A).

			m (CCF)	H&A	%	g/cm^3
forest	managem	hor	respace	soil_pit	Wcont	Bd
Cloca	UN	F	NA	NA	71.17	0.07
Cloca	UN	H	NA	NA	NA	NA
Cloca	UN	A	NA	1	41.74	0.69
Cloca	UN	A	NA	2	36.77	0.74
Cloca	UN	A	NA	3	38.08	0.76
Cloca	CCF	F	1.6	NA	73.66	0.05
Cloca	CCF	F	2	NA	71.81	0.05
Cloca	CCF	F	3.2	NA	73.38	0.06
Cloca	CCF	F	5	NA	71.88	0.04
Cloca	CCF	H	1.6	2	59.80	0.33
Cloca	CCF	H	3.2	1	50.82	0.58
Cloca	CCF	H	5	3	63.21	0.38
Cloca	CCF	A	1.6	2	38.62	0.79
Cloca	CCF	A	3.2	1	37.66	0.78
Cloca	CCF	A	5	3	29.93	1.15

Note:
Data was averaged to contain the size of the table.
[1] Data within respace/hor is average of five observations (CCF). Data within managem 'UN'/hor is average of five observations (horizon A) and fifteen observations (horizon F). Soil pit only refers to H and A horizons. Due to the shallowness of the H horizon in managem 'UN' this could not be collected.

Table 6.14: Clocaenog Forest. Available N content averaged by management (respacing, CCF only) and horizon (H,A).

			m (CCF)	mg/kg of soil	
forest	managem	hor	respace	ammonium	nitrate
Cloca	UN	H	NA	148.84	0.35
Cloca	UN	A	NA	52.39	0.36
Cloca	CCF	H	1.6	100.71	0.43
Cloca	CCF	H	2	113.10	0.18
Cloca	CCF	H	3.2	96.20	0.52
Cloca	CCF	H	5	145.96	0.89
Cloca	CCF	A	1.6	52.89	0.24
Cloca	CCF	A	2	44.37	0.14
Cloca	CCF	A	3.2	36.58	0.72
Cloca	CCF	A	5	44.78	0.28

Note:
Data was averaged to contain the size of the table.
[1] Data within respace/hor is average of five observations (CCF).
Data within managem 'UN'/hor is average of fifteen observations.

Table 6.15: Clocaenog Forest. Soil depth, total C and N, C mass and proximate C pools averaged by respacing (CCF only) and horizon.

									Ankom analyser					
			m	cm	total %			Mg/ha	%	% (proximate C pools)				
forest	managem	hor	respace	hor_depth	C	N	CNratio	C_Mg_ha	ash	Cell_sol	Hemicel	Cellul	Lignin	LCI
Cloca	UN	L	NA	NaN	52.81	0.94	57.03	2.85	0.40	16.24	14.59	28.49	40.67	0.49
Cloca	UN	F	NA	11.79	51.72	1.81	28.69	43.70	2.09	24.62	10.86	20.96	43.56	0.58
Cloca	UN	H	NA	1.86	24.03	1.13	21.13	18.59	29.92	73.28	8.42	9.57	8.74	0.29
Cloca	UN	A	NA	NaN	6.24	0.41	15.31	NaN	NaN	NaN	NaN	NaN	NaN	NaN
Cloca	CCF	L	1.6	NaN	52.93	0.82	67.72	1.85	0.19	15.61	15.18	28.34	40.87	0.48
Cloca	CCF	L	2	NaN	52.87	0.81	66.45	3.04	0.23	16.81	15.14	28.00	40.05	0.48
Cloca	CCF	L	3.2	NaN	53.02	0.76	71.31	2.28	0.33	16.53	14.53	28.30	40.64	0.49
Cloca	CCF	L	5	NaN	52.95	0.89	62.39	1.29	0.22	16.00	14.85	27.79	41.35	0.49
Cloca	CCF	F	1.6	21.00	50.34	1.73	29.21	46.64	2.84	23.95	12.29	20.27	43.49	0.57
Cloca	CCF	F	2	12.00	51.64	1.75	29.61	27.64	1.73	22.71	11.72	20.12	45.45	0.59
Cloca	CCF	F	3.2	19.40	52.19	1.66	31.44	64.76	1.35	21.47	13.09	20.84	44.59	0.57
Cloca	CCF	F	5	15.00	51.01	1.69	30.33	34.53	1.75	23.61	13.57	20.45	42.37	0.55
Cloca	CCF	H	1.6	9.00	15.66	0.73	21.37	59.18	32.18	80.53	6.75	10.23	2.49	0.12
Cloca	CCF	H	2	10.00	18.83	0.74	25.48	83.83	30.09	79.82	5.70	10.55	3.93	0.20
Cloca	CCF	H	3.2	14.00	22.02	0.90	24.68	136.87	32.27	79.93	5.97	8.33	5.76	0.29
Cloca	CCF	H	5	6.25	23.49	0.94	25.09	68.19	34.60	74.72	8.43	9.71	7.14	0.28
Cloca	CCF	A	1.6	NaN	6.09	0.38	16.42	NaN	NaN	NaN	NaN	NaN	NaN	NaN
Cloca	CCF	A	2	NaN	7.26	0.36	20.38	NaN	NaN	NaN	NaN	NaN	NaN	NaN
Cloca	CCF	A	3.2	NaN	7.38	0.38	20.09	NaN	NaN	NaN	NaN	NaN	NaN	NaN
Cloca	CCF	A	5	NaN	7.10	0.38	18.95	NaN	NaN	NaN	NaN	NaN	NaN	NaN

Note:
Data was averaged to contain the size of the table.
[1] Data within respace/hor is average of five observations (CCF).
[2] Data from managem 'UN'/hor is average of fifteen observations