Use of process based models to assess the spatio-temporal variability of the effect of climate change on forest development.

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by

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Abstract

Advances in the study of climate change have seen much emphasis placed on the variability and non-static nature of climate. With the projected trends of likely impacts of climate change on forest ecosystems, it has become important to incorporate climate change consideration in forest development. However under these circumstances, forest managers require models that can function across spatial and temporal scales. The study aimed firstly to validate the responses of the physiological principles of predicting growth model (3PG) and the 3PG-Nitrogen (3PGN) in estimating above ground biomass and secondly to evaluate the effect of climate change on Stem biomass production of Sitka spruce across Scotland. The aboveground biomass production was simulated using the 3PG and the 3PGN models. Precipitation, temperature, soil, and solar radiation data were used to run the models. Permanent sample point data provided with observed biomass data that were compared graphically to model outputs. The 3PG model gave better results than 3PGN when observed above ground biomass (AGB) is low in the measured plots. The 3PGN model performance was better in cases where observed above ground biomass was higher. To evaluate the models performance Root Mean Square Error (RMSE) method was used. The 3PGN predictions gave a RMSE of 40.1tDM/ha while 3PG gave RMSE of 44.4tDM/ha. For climate change analysis 3PGN-spatial was used in running the simulations. Stem biomass production results showed that less productive areas are situated to the north and north-west parts of Scotland producing between 1-30 tDM/ha. Areas to the south and south-east show stem biomass of between 91-105tDM/ha. The model also predicts that baseline stem biomass (1961-1990) will increase mostly in the south and south-east Scotland until the 2050s (2040 – 2069) period. By the 2080s (2070 -2099) period, the prediction indicates both increase and decrease in stem biomass production in parts of south-east Scotland. Predicted temperature had more influence on stem biomass production when compared to predicted precipitation. The study demonstrates that 3PGN and 3PGN-Spatial process based models can provide more accurate and relevant forest productivity estimates at both stand and landscape level.

Keywords: Climate, Forest, Biomass, Scotland, 3PG, 3PGN, 3PGN-Spatial

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List of Acronyms

AGB	Above Ground Biomass
CO_2	Carbon Dioxide
DBH	Diameter at Breast Height
GHG	Green House Gas
IPCC	Inter-Governmental Panel on Climate Change
PSP	Permanent Sample Point
SS	Sitka spruce
SNR	Soil Nutrient Regime
tDM/ha	Tonnes of Dry Mass per hectare
UKCIP02	United Kingdom Climate Impact Programme 2002
UNFCCC	United Nations Framework Convention on Climate Change
Ws	Stem biomass

1. Introduction

Forests form one of the world's most important renewable resources and play an important role in preserving biodiversity, protecting critical watersheds and providing livelihoods. As governments commit themselves to sustainable forest management and climate change initiatives, such as United Nations Framework Convention on Climate Change (UNFCCC) and Kyoto Protocol, there is increasing demand for precise estimates of standing forest biomass and potential productivity at both local to global scales (UNFCCC. 1997).

Methods and models to estimate individual tree volume and growth at stand level were introduced in the 18th and early 19th centuries and together with accurate area information from maps, form the basis of sustainable management of forests (Amaro et al. 2003). Traditionally, forest growth and yield models assume that environmental factors such as climate are constant. With increasing evidence in the changing climate and environment due to increased global surface temperatures, extreme weather events as well as change in precipitation patterns are expected (IPCC. 2007b). The projected trends of likely impacts of climate change on forest ecosystems, (IPCC. 2007b), mean that it is important to incorporate climate change when considering forest development. Under these circumstances, forest managers require models that can function across spatial and temporal scales.

The Inter-Governmental Panel on Climate Change (IPCC) defines climate change as "statistically significant variation in either the mean state of the climate or in its variability persisting for a longer period and may be attributed to natural and human induced activities that alter the composition of the global atmosphere" (IPCC. 2007b). IPCC reports indicate that in future Europe will experience warmer and wetter winters, dry and warm summers with substantial impacts on forest conditions and growth (IPCC. 2007b).

This research described in this thesis has been formulated within the project dealing with *Transnational Forestry Management Strategies in Response to Regional Climate Change Impacts* (ForeSTClim). ForeSTClim is a European Union funded project, which brings together 21 partners from United Kingdom, Germany, France, The Netherlands and Luxemburg who have a wide range of expertise in forest management (ForeStClim. 2008a). This trans-national co-operation was established to develop proactive regional forestry management strategies in response to expected regional climate change (ForeStClim. 2008a).The strategies are expected to show regional climate change impacts on forest site characteristics (ForeStClim. 2008a). The project also aims to secure sustainable timber production and efficient forest protections among other objectives.

1.1. Conceptual framework of the interactions between forest and climate change

Models are simplifications of reality and may not consider the complexity of the forest. The conceptual diagram, figure 1, show the interactions between forest, climate and the anthropogenic drivers, their impact and the response to the climate change as well as their linkages. Gases such as methane or carbon dioxide that are emitted to the atmosphere cause greenhouse effect. The green house effect is reflected by increase in temperature and precipitation change. These changes affect the way forests grow as well as the functions that they offer. For this reason process based models try to simulate the way forests grow under the changing climatic conditions.

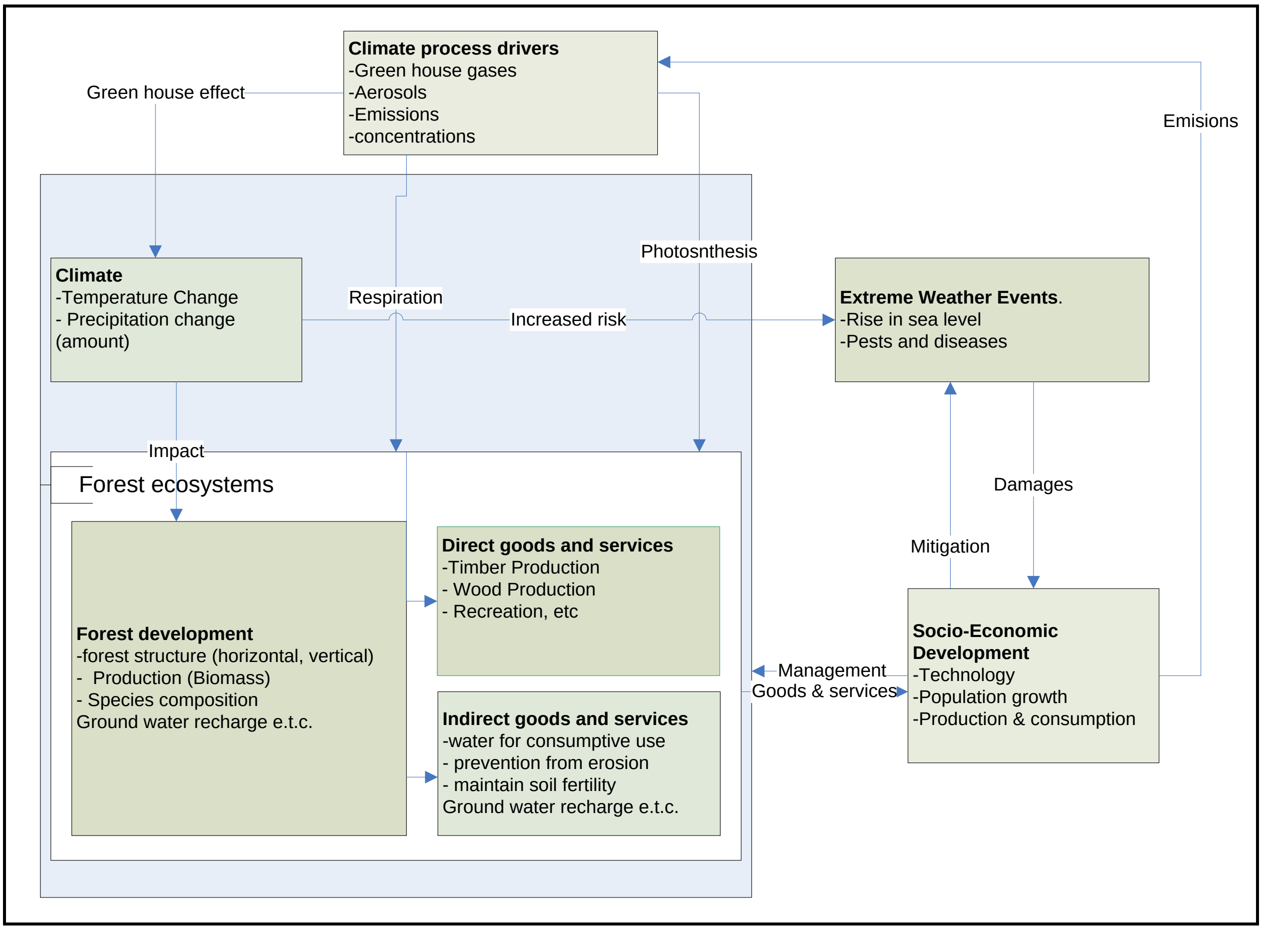


Figure 1: A conceptual framework of the interactions between forest ecosystems and climate change. (Adopted with omissions from IPCC, (2007b).

1.2. Research Problem and Justification

Today's information needs require models that can function across spatial and temporal, scales. Forest management agencies require more accurate yield estimates for planning and to make good decision for sustainable forest management as climate change effects in forests continue to show. The tools available for this have limited capabilities to them hence there is therefore a need to develop process based models that can take into account spatial temporal variability.

The use of empirical yield models has described growth adequately for average environmental conditions, but they may perform poorly during dry and wet years. Despite their usefulness, yield models are considered to have limitations for long-term modelling because they are insensitive to inter annual climatic variations as well as changes in management practices (Stape et al. 2004). Most existing yield models focus on wood production and are not concerned with other aspects of forest development (Vanclay. 1999). Empirical growth models do not allow forest production to be integrated into broader ecosystem framework of resource use (Landsberg and Waring 1997). The issues of changes in soil condition and timber production have increasing social and economical relevance(Brown et al. 1997). Hence there is need to shift and focus more on process based models that are capable to assess risks of climatic variation on forest development and a framework for management programs (Stape et al. 2004). Forests provide us with important functions such as carbon sequestration and services such as timber production. With the current trend in climate change, these forests will develop under different precipitation patterns, warmer temperature and higher carbon dioxide (CO_2) concentrations as compared to what they are currently (IPCC. 2007b). This affect the way forests develop, resulting in changes in biomass production and consequently in the services they offer.

Forest growth models are employed in order to study and understand climate change and to evaluate possible future climate developments. Models provide an efficient way to prepare resource forecast but a more important role is their ability to explore the outcome of different management practices (Vanclay. 1999). Forest growth models are divided into process based and empirical based models (Amaro et al. 2003). Empirical growth models are based on statistical analysis of sample plot data whereas process- based model are designed to predict forest productivity at large scales (Vanclay. 1999) and they use knowledge of how plants function and will be useful under climate change.

The development of forest process based models to predict forest growth has rapidly progressed in the last 10-15 years (Landsberg and Waring 1997). However their operational application in forest management is still being researched. This is because these models still need to be simplified so that they may be of interest to forest managers (Landsberg and Waring 1997). Despite this, process-based models have been shown to provide good estimates of growth and biomass productivity (Landsberg et al. 2001) and can be adapted to incorporate variations in current climates. An example of such model is Physiological Principles of Predicting Growth (3-PG), which is a generalized model of forest productivity that use simplified concepts of radiation-use efficiency, carbon balance and partitioning. Its variant 3-PG Nitrogen (3PGN) includes the soil nitrogen pools.

Studies that have been done so far are mostly on application of 3-PG and not 3-PGN. The 3PG model has been tested as a practical tool against forestry data from Australian tropical rainforests in New South Wales, Brazil, South Africa and also in Great Britain. Test results show excellent correspondence between stand growth measurements and simulated stem growth over 30 years (Landsberg et al. 2001). 3-PG is capable to convert biomass values into variables of interests to forest managers (Sands and Landsberg 2002) and has been used and tested as research tool in different parts of the world with data from a wide range of environments (Amaro et al. 2003). 3-PGN has been parameterized in Scotland's Scots pine to assess sensitivity and uncertainty of the model in predicting forest production. The models successfully predicted stem biomass and volume for some plots that were being studied. (Xenakis et al. 2008). 3-PGN has also been parameterized for Sitka spruce (SS) in Scotland (Minunno 2009). The parameter values that were developed by Minunno (2009) are the ones that are used in this research.

In order to investigate this problem, this research addresses the case for Sitka spruce (SS) (*Picea sitchesis* (Bong.) Carr.) in Scotland. Scotland's forests are managed by the Forestry Commission (FC) of Great Britain for the purposes of recreation and timber production. To date Great Britain timber production supplies 20% of the national demand. The timber production is mainly based on growing of Sitka spruce that represent the 29% of Britain's forestland and 47% in Scotland (Forestry Statistics. 2006).

Under projected changes in climate, Scotland is expected to have warmer summers and milder winters (Ray et al. 2008). The rainfall distribution will change leading to drier summers (Hulme. 2009). Scotland is already experiencing the effects of climate change as increasing global temperatures bring changes in weather patterns and more frequent severe storms. The implications of climate change for Scotland are uncertain due to its geographical location. It is located in the path North Atlantic drift and the Scottish climate is known to have been highly variable from the ice age to present day (Lowe 1993). The challenge is to predict these changes and their implication for forest development. To achieve this, the research will consider the effect of the United Kingdom Climate Impact Programme 2002 (UKCIP02) high emission scenario for current period (1961-1990) and projected for the years 2050s (2040 -2069) and 2080s (2070-2099) and their consequence for the biomass production of SS.

1.3. Research Objectives and Questions

Objectives

1. To validate the responses of 3PG and 3PGN in estimating above ground biomass for Sitka spruce (SS) using Scotland's permanent forest sample plot data, available soil data and spatial layers of temperature, precipitation and solar radiation.
2. To evaluate the effect of climate change on Stem biomass production of Sitka spruce across Scotland.

Research Questions

To achieve the objectives, the following research questions were asked:

1. Will there be any difference in amount of above ground biomass predicted between 3PG output and 3PGN output when compared to actual tree growth data?
2. How is the stem biomass distributed under current, 2050s and 2080s period?
3. What is the effect of predicted changes in temperature and precipitation on the production of stem biomass of Sitka spruce?

The first research questions will be addressed using Arc-GIS, 3PG and 3PGN Excel versions. The second and third research questions will be addressed using Arc-GIS and 3PGN-Spatial versions. Climate data was obtained from Northern Research Station, Scotland, It consisted of United Kingdom Climate Change Impact of 2002 (UKCIP02) dataset based on AIFI Special Report on Emissions Scenarios (SRES) developed for Great Britain. The baseline climate data covers the period 1961 to 1990.

1.4. Organization of the thesis

Following the discussion of the background of the study, statement of the problem, objectives of the study and research questions in this chapter, the thesis is organized in five chapters. Chapter 2 presents a review of literature relevant to the research. Chapter 3 discusses and compares forest process based models (3-PG and 3-PGN) in predicting above ground biomass (AGB). Chapter 4 is on the effect of climate change on stem biomass (Ws) assessment and chapter 5 looks at the general conclusion and recommendations of the study.

2. Literature Review

This chapter gives background on the IPCC and the United Kingdom Climate Impact Programme 2002 (UKCIP02) scenarios in climate change and their relationship with forest development. It is necessary to understand the nature of climate change in order to estimate the nature and gravity of the possible effects on forests. Forests act as sink and storage of carbon dioxide (CO_2) hence helping to mitigate climate change. Also temperature and rainfall also play a major role in plant growth so any changes in climate will have effect on the forest development in terms of structure and composition. Process based models are thought to be able to model the changes brought by climate change and its effects on tree growth. With such changes occurring, the following two questions are asked to attempt and to try to predict these changes. First, how is the stem biomass distributed under current, 2050s and 2080s period? And second, what is the effect of predicted changes in temperature and precipitation on stem biomass assessment of Sitka spruce? The chapter also describes Sitka spruce and its importance for forestry in Great Britain.

2.1. IPCC Scenarios in Climate change

Scenarios “are alternative images of how the future might unfold and are an appropriate tool with which to analyse how driving forces may influence future emission outcomes and to assess the associated uncertainties. They assist in climate change analysis, including climate modeling and the assessment of impacts, adaptation, and mitigation” (IPCC. 2000). These scenarios are described in the paragraphs below.

Scenarios have been developed as a tool to analyse potential developments in the long range since it is not possible to predict the future anthropogenic green house gas (GHG) emissions (IPCC. 2000). Scenarios allow the consequence of alternative future GHG emissions on the climate and environment to be evaluated. In ForeStClim project, the following scenarios have been selected, A1B, A2, and B1 (ForeStClim. 2008a). However for this research, A1F1 scenarios are used, instead of the project proposed scenarios since the data available for the study area is for A1F1 scenarios.

There is A1 family of scenarios that represents a more integrated world, characterized by rapid economic growth with a global population that reaches 9 billion in 2050 and then later on gradually declines. This scenario shows that there is a quick spread of new technologies as well as extensive social and cultural interactions worldwide. The A1 family has subsets based on their technological emphasis. These are the A1B and A1F1 with balanced emphasis on all energy sources with estimated temperature rise of 2.8^0C and emphasis on all fossil fuels and estimate temperature rise of 4.0^0C respectively.

The A2 family is of a divided world. They are mainly characterized by a world of independently operating and self-reliant nations. Estimated temperature rise for this family is about 3.4^0C. Technological changes and improvements to per capita income are slower and more fragmented to this scenario.

The next family is of B1 scenarios that are of the world more integrated and ecologically friendly. Like A1, B1 scenarios are characterised by rapid economic growth, but with rapid changes towards a service and information economy. The emphasis is on the introduction of clean and resource efficient technologies as well as global solutions to social, economic and environmental stability. Temperature has been estimated to rise to about 1.8^{0}C.

The B2 family portray a world that is more divided but ecologically sound. These are also a continuously increasing population, but the rate is lower than that of the A2 scenarios. The emphasis on this scenario is rather on local than global solutions to economic, social and environmental stability. Figure 2 show the storylines of the emission scenarios.

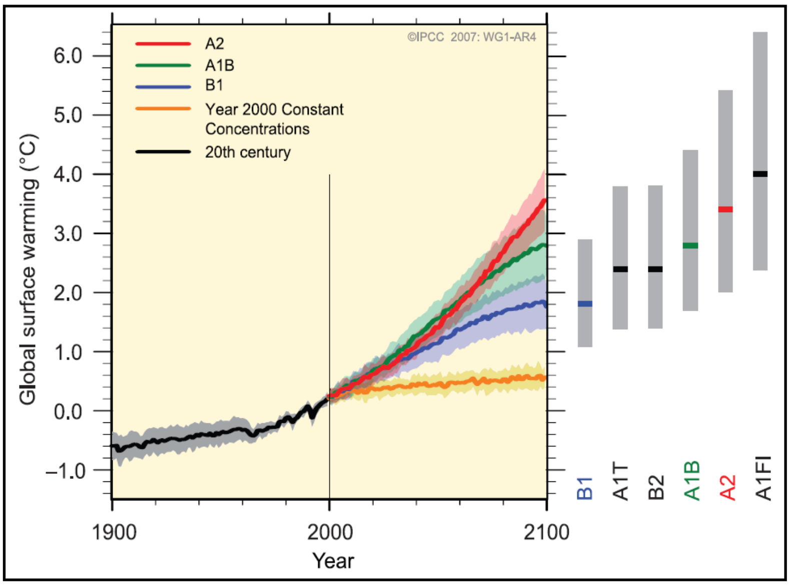


Figure 2: An illustration of the four storylines and Global average surface temperature from the IPCC Special Report on Emission Scenarios. Source (IPCC. 2007b).

2.1.1. UKCIP02 scenarios

The UKCIP02 scenarios represent advanced descriptions of future UK climates. They are based on new global emissions scenarios published in 2000 by the IPCC in their Special Report on Emissions Scenarios. They are based on a series of climate modelling experiments completed by the Hadley Centre using their most recently developed models. The scenarios describe four alternative future climates for the UK, namely: Low Emissions, Medium-Low Emissions, Medium-High Emissions and High Emissions. The scenarios were derived from 5 km resolution monthly climate data set for the UK for the period 1961 to 2000 (Hulme et al. 2002).

As suggested by Hulme et al (2002) by the 2080s, the UKCIP02 scenarios show that atmospheric carbon dioxide concentrations may increase up to about 525 parts per million (Low Emissions scenario) and 810 parts per million (High Emissions). This represents an increase from the average 1961-1990 concentration of about 334 parts per million of between 57 and 143 per cent, and is between almost two and three times the pre-industrial concentration of 280 parts per million.

2.2. Process based models

The past two decades have seen considerable progress in developing process-based models to predict current and potential forest productivity. They range in resolution, complexity, generality and applicability and they have been now around for more than a century (Battaglia et al. 2007). These process based models aim to simulate the growth of stands in terms of underlying physiological processes and the way stands are affected by the physical conditions to which trees are subject and with which they interact (Tickle et al. 2001b)

Espreya (2004) noted that many of the highly parameterised models of tree growth that describe physiological processes in great detail are used purely as research tools, usually to understand the cause and effect of changes in the system. Hence the development of such complex models requires much theoretical and applied research that spans for several years, and the models do not directly address questions of interest to forest managers. Bettaglia et al (2007) noted that recently process based models are increasingly seen as part of forest management decision making process.

2.2.1. Why 3-PGN?

3-PG and 3-PGN and 3PGN spatial were selected as a result of the model review process outlined in (Landsberg and Waring 1997; Xenakis et al. 2008) for their flexibility, relative simplicity and reasonable requirements in terms of parameter values. 3-PG is a stand-level model of forest growth developed by Landsberg and Waring (1997). The model requires readily available site and climate data as inputs and predicts the time-course of stand development on a monthly basis. Since the initial publication of 3-PG, several structural modifications have been made to the model. A full detailed description of this model is provided within several publications by (Landsberg and Waring 1997; Sands and Landsberg 2002; Nightingale et al. 2008; Xenakis et al. 2008).

The model can be run for any number of years, using actual monthly weather data or long-term monthly averages. The normal procedure of running the model is to use historical long-term average data unless for specific events, such as droughts (Landsberg et al. 2001). In such a case 3-PG can account for changing growth patterns as a result of climatic variability. This makes 3-PG a powerful tool that allows the user to set up various scenarios.

3PG model has been applied to both single-species plantations and even-aged or relatively homogeneous forests throughout the world (Landsberg and Waring 1997; Tickle et al. 2001a; Sands and Landsberg 2002; Espreya et al. 2004; Xenakis. 2007; Xenakis et al. 2008). The model is yet to be applied in modeling tropical rainforest stands, which are structurally complex and characterised by a wide range of species with different age and growth distributions (Vanclay. 1991b).

The 3-PGS (S for satellite) model, developed by (Coops et al. 1998) is another version of the original 3-PG model. It is driven primarily by photo synthetically active radiation (PAR) absorption, which determines potential physiological growth rates. It calculates intercepted radiation and LAI from updated monthly satellite estimates of the fraction of photo synthetically active radiation (fPAR). The model then partitions the estimate of Net Primary Production (NPP) into above- and below-ground biomass pools as per the 3-PG model, providing estimates of stand allometry that are updated during the model simulation. The model relies on monthly updated estimates of satellite-derived fPAR, so it cannot be applied to grow a forest stand older than the available archive of satellite data. Both 3-PG and 3-PGS forest growth models were used for the development of a model-based approach for assessing carbon dynamics within the wet tropics bioregion. During this research, both models are implemented using the comparison and integration (Xenakis. 2007; Nightingale et al. 2008) for the purpose of above ground biomass assessment.

3-PG has been applied across several species that include Sitka spruce (*Picea sitchensis* (Bong.) Carr.), Scots pine (*Pinus sylvestris* L.), Eucalypt (*Eucalyptus grandis* Hill ex Maiden), Ponderosa pine (*Pinus ponderosa* Douglas ex C. Lawson), Loblolly pine (*Pinus taeda* L.), Mexican weeping pine

(*Pinus patula* Scheide. ex Schldl. & Cham.) and lodgepole pine (*Pinus contorta* Douglas ex Loudon) (Coops et al. 1998; Tickle et al. 2001a; Tickle et al. 2001b; Sands and Landsberg 2002; Stape et al. 2004; Xenakis. 2007; Xenakis et al. 2008). Many of these studies have already highlighted strengths and weaknesses of the model. Additionally, two studies have explored the internal feedbacks between parameters and outputs (Espreya et al. 2004; Xenakis et al. 2008).

3PGN is a simplified process-based model, composed by two sub-models: 3PG (Landsberg and Waring 1997) and ICBM/2N (Introductory Carbon Balance Model) (Andrén and Kätterer 1997). 3-PG is a model based on eco-physiological principles and works at stand level resolution, ICBM/2N is used to calculate the carbon and nitrogen balances in the soil. The combination (3PGN) therefore allows carrying out complete analyses at ecosystem level. It has a spatial version 3-PGN-Spatial. This is a modified version of 3-PGS developed by (Coops et al. 1998; Tickle et al. 2001a) which includes the ICBM model to calculate the carbon and nitrogen balances. 3-PGN Spatial (Xenakis et al. 2008) was developed modifying the C++ source code allowing to interface the model with ArcInfo, GIS Work Station.

A better understanding of the internal feedbacks of the model was given by the sensitivity analyses of parameters and output variables carried out in a few studies (Espreya et al. 2004; Xenakis et al. 2008). The results of the sensitivity analysis by Xenakis et al ((2008) showed that 3-PGN can reliably represents patterns of stem biomass, stand volume and diameter at breast height.

2.3. Sitka spruce

Sitka spruce (*Picea sitchesis* (Bong.) Carr.) originates from North America, where it takes the name from Sitka Island in Alaska. This species occur along the pacific coast, from Alaska to the North of the California (Forestry Commission. 2009). The height of SS can be 50m or more with a trunk over 2m in diameter at breast height (DBH). The needles, 1 to 2, 5 cm long, are pungent and flat and they have a long life (6-8 years); the cones are small (5 – 10 cm). The root system is superficial; which causes the tree to be prone to wind damage. Sitka spruce is a lowland species, distributed from the sea level to 1,000 m; it is well adapted to sites characterised by high atmospheric humidity and does well in well drained soils that are rich in organic matter. Sitka Spruce grows rapidly with an MAI (Mean Annual Increment) of 12 m^3 ha^{-1} a^{-1}. Figure 3 show typical plantation of Sitka spruce species. The photograph of the Sitka spruce plantation was obtained from Forestry Commission website.

The species was introduced in Great Britain 1831 and it is therefore a non native conifer. It provides with high volumes of timber. Thus, the Sitka spruce plantations in Great Britain are managed mainly for timber production and clear felling is the main silvicultural system applied. In terms of growing period, Sitka spruce needs only 40-60 years to reach its maximum timber potential. Small trees removed from the plantation through thinning are used for paper making. The common rotation length adopted is 50 years. The rotation length of the tree is limited by the stability problems of the higher trees (Forestry Commission. 2009)

Figure 3: Sitka spruce plantation species

2.4. Biomass assessment

Biomass assessment has received considerable attention for quite sometime, especially after pulpwood demand in the 1960s and oil crisis in the 1970s (de Geir. 2003). Biomass estimation is a usual practice to quantify fuel and wood stock and allocate harvestable amounts. Forest biomass assessment is important for national development planning as well as for scientific studies of ecosystem productivity, carbon budgets and many more (Parresol 1999; Zianis and Mencuccini 2004). Biomass is an important element in the carbon cycle, especially for carbon sequestration. It is used to help quantify pools and fluxes of Green House Gases (GHG) from the terrestrial biosphere to the atmosphere associated with land-use and land cover changes (Cairns et al. 2003)

The concentration of atmospheric carbon dioxide (CO_2) is a major constituent of GHG and has increased from 278ppm in the pre-industrial era (1970) to 379ppm in 2005 at an average of 1.9ppm per year (IPCC. 2007b). With the increasing concern for rising CO_2 concentrations, the role of forests as a long-term carbon pull for assimilation of CO_2 is being increasingly realized hence studies are afoot for assessing the use of forest biomass sinks to sequester carbon as part of a global mitigation effort. Changes in forest biomass are influenced by plantations, management practices, natural disturbances as well as climate change. Thus Biomass assessment is important to understand changes in the forest structure. Above ground biomass is done because trees generally account for the greatest function of total living biomass in the forest. In this thesis AGB refers to total amount of above-ground organic matter in living trees >7cm in diameter at breast height (DBH), that is 1.3m from the ground including foliage (FAO. 2006)

The preceding chapter goes on to look at comparison of the two process based models' (3PG and 3PGN) capability of estimating above ground biomass (AGB).

3. Comparison of forest process based models (3PG and 3PGN) in predicting Above Ground Biomass.

3.1. Introduction

The chapter compare the two process based models' (3PG and 3PGN) capability of estimating AGB. The importance of AGB has already been elaborated in detail in section 2.4. Newly developed or improved ecosystem process models need to be continuously tested to allow for improvement in their development.

The chapter also presents the results of the comparison of the two models' estimation of AGB for Scotland in Great Britain. The objective of this modelling exercise was to validate the responses of 3PG and 3PGN in estimating above ground biomass for Sitka Spruce (SS) using Scotland's permanent sample plot data, soil and spatial layers of temperature, precipitation and solar radiation. To achieve this objective, the following research question was asked: Will there be any difference in amount of above ground biomass predicted between 3PG output and 3PGN output when compared to actual tree growth data?

The methods and materials used to accomplish this objective are also provided. Finally discussions and conclusions of the chapter were made.

3.2. Study area

The area was selected because it met the following criteria: In Scotland there is series of permanent sample plots for Sitka species that are spread all over the country. PSP are necessary for the validation of 3PG and 3PGN model. Scotland was selected also for it houses Craik forest, a demonstration site for ForeStClim project. Thus changes occurring in Southern Scotland in particular would most likely affect Craik forest.

Scotland is one of the most sensitive areas of the world in relation to climatic instability- the north east Atlantic and the adjacent mainland (Lowe 1993). The weather is unpredictable, as this has been viewed over a geological timescale and evidence points to a long history of major and dramatic climatic changes (Lowe 1993).

Scotland is divided into three main regions; the Highlands, the Central Lowlands and the Southern Uplands. (Met Office. 2009). Its climate is dominated by the combined effects of the warm North Atlantic Drift and the rain-bearing westerly air flow (Lowe 1993). Figure 4 shows the location of Scotland in relation to the rest of Great Britain.

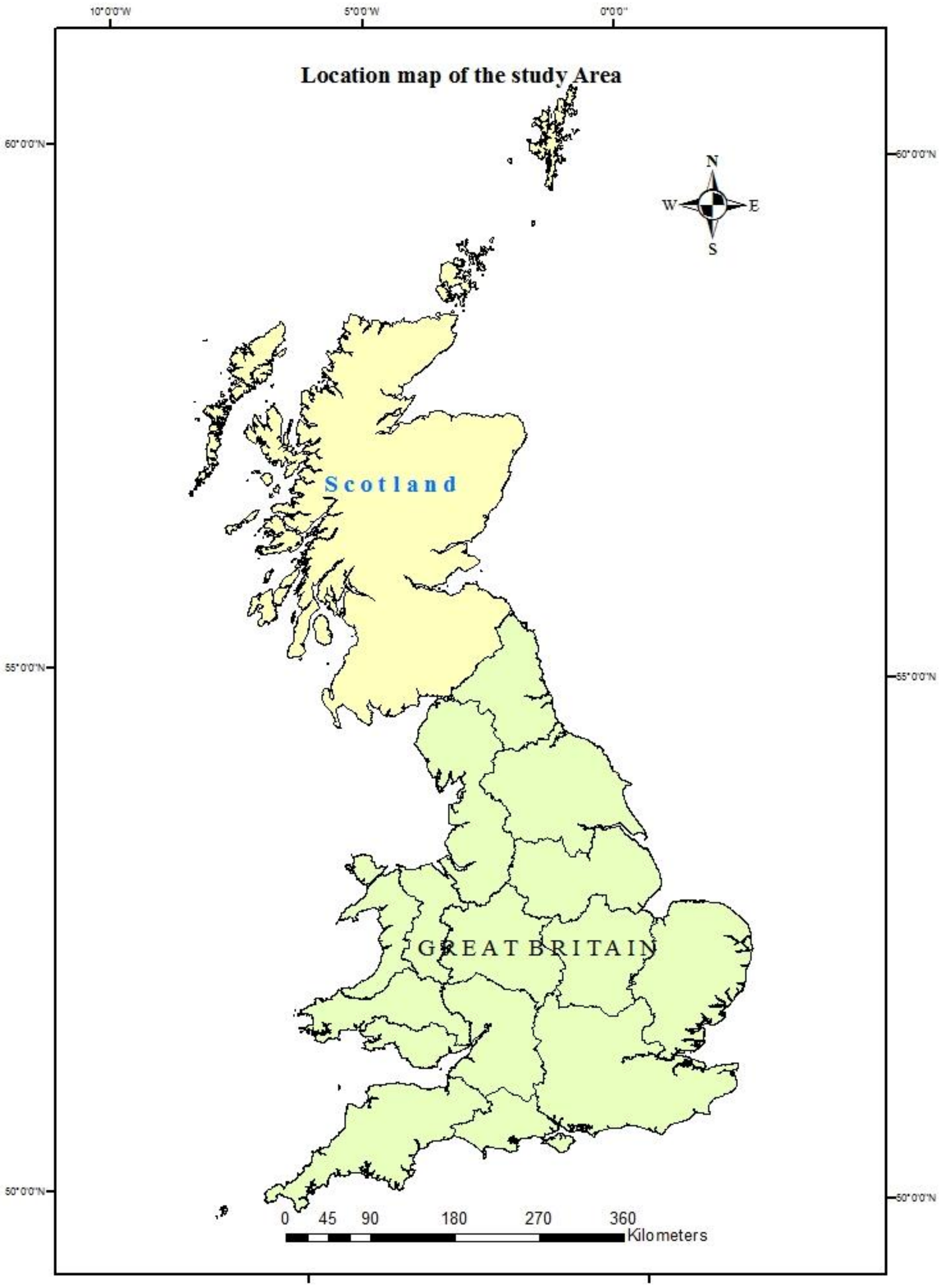


Figure 4: The location map of the study area Scotland, in Great Britain. (Map provided by Northern Research Station, Edinburgh).

Mean annual temperatures over the region vary from about 9 °C close to less than 6 °C over the higher ground of the Grampians (mountain range of central Scotland). Elsewhere in the Great Britain, mean annual temperatures reach over 11°C in Cornwall and the Channel Islands. Within the region, significant variations in temperature arise from the combined effects of proximity to the coast, topography and, to a lesser extent, urban development. Rainfall is generally well-distributed throughout the year (Met Office. 2009). The underlying geology, glaciations and climate all influence the formation of different soil types.

3.3. Materials

The section explains briefly the structures of the materials to be used. 3PGN, which is composed of the two sub-models: 3PG and ICBM/2N. 3PG is based on eco-physiological principles and works at stand level resolution. ICBM/2N is used to calculate carbon and nitrogen balances in the soil. This enables 3PGN to carryout complete analyses at ecosystem level. The parameters for Sitka spruce used in this study were developed by Minunno (2009).

3.3.1. 3PG Structure

Landsberg and Waring (1997) together with Sands and Landsberg (2002) gave a complete description of 3PG. The model is composed of two sets of calculations; one provides the biomass production of the stand and the other the carbon partitioning between different organs of the tree (foliage, roots and stem). In additions, three other sub-models are used to calculate the changes in stem number, soil water balance and variables of interest to forest managers such as stand timber volume, diameter at breast height stand basal area and mean annual increment.

Similarly to earlier models such as FOREST-BGC(Running and Gower 1991) and BIOMASS (McMurtrie et al. 1992). 3PG is based on the principle that the growth of a stand is a function of radiation interception. GPP (Gross Primary Production) is calculated by multiplying the fraction of the photo-synthetically active radiation absorbed by the stand ($\varphi p.a.$) with canopy quantum efficiency (αc). The canopy quantum efficiency is calculated by the theoretical maximum canopy quantum efficiency of a stand (αcx) corrected by an array of site and physiological modifiers that vary between 0 and 1 (atmospheric vapour pressure deficit (VPD)), air temperature, frost, water balance, age and nutrition conditions of the site (FR)). Net primary production (NPP) is calculated as a constant fraction of gross primary production (GPP) (Waring et al. 1998; Tickle et al. 2001a)

Figure 5a and 5b show the flow diagram of 3PG model with some of the inputs to be used in this research.

(5a) (5b)

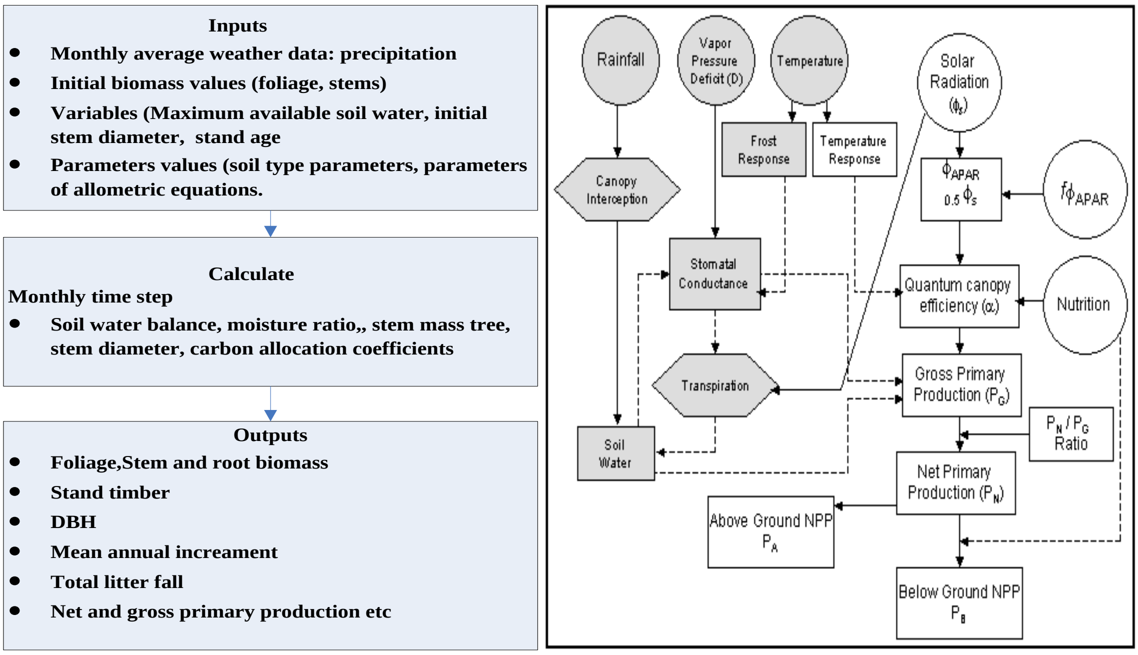


Figure 5: Flow diagram of 3PG. 5(a) shows the sequence calculations in 3-PG and how it process input data. Figure 5(b) left-hand, grey, side show components affecting hydrologic balance and the right hand side (white) show hydrological components affecting carbon balance. Adopted with omissions (Landsberg and Waring 1997)

Once the biomass has been fixed, allometric relations, on a single-tree basis, are used to partition the carbon between the tree organs (Landsberg and Gower 1997; Sands and Landsberg 2002). To begin with, a fraction of NPP is allocated belowground by a root allocation coefficient that is affected by soil fertility. The remaining biomass is partitioned between the aboveground organs by a relationship between diameter at breast height and foliage: stem ratio. Stem population can vary over time due to natural mortality or thinning. Mortality is calculated using the -3/2 thinning law that assumes a maximum value of above ground biomass for a certain stand density. Soil water balance is given by the rainfall inputs and the losses due to canopy interception and transpiration. The latter is calculated using Penman- Monteith equation that is widely used in soil science (Tickle et al. 2001a). The model can also simulate silvicultural events such as thinning, fertilisation and irrigation (Sands. 2001).

3.3.2. ICBM/2N structure

Introductory Carbon Balance Model, (ICBM/2N) is composed of three different pools of carbon (C) and three pools of Nitrogen (N), consisting of different forms of organic matter, with each pool having a different decomposition rate. The rates vary across the year with the environmental conditions (such as temperature and soil water content), but do not change during stand development (Berg and Ekbohm 1993; Titus and Malcolm 1999; Mäkelä and Vanninen 2000). The model has a "young labile"pool, that includes small tree detritus (such as litter-fall and root turnover), a "young refractory" pool, that includes coarse woody detritus (coarse roots and branches). It has also an old pool that represents the humified organic matter. Subsequently, the humication coefficient determines the rate at which the carbon decomposed from the "young labile" and "young refractory" pools turns into the old pool. The fraction from each "young" pool, which is decomposed but not humified, is considered as respiratory loss. Similarly, decomposition losses take place from the "old" pool. The sum of all out-fluxes from the three pools, gives the heterotrophic respiration. The nitrogen balance is based on fixed C:N ratios and the size of the C fluxes and pools.

Finally, two more parameters, representing the microbial efficiency, are used to calculate the fraction of carbon allocated to microbial growth. In 3PGN, the biomass losses of the stand (litter-fall, root turnover, death of trees), calculated by 3PG, are the inputs for ICBM/2N. The latter model is used to calculate the soil nutritional status of a site, expressed by the FR parameter of 3PG.

3.3.3. 3-PGN Structure

3 PGN follows the conventional structure of process based model that include photosynthesis and respiration and major environmental factors affecting tree growth (Xenakis et al. 2008). 3PGN provides with a new way to account for soil nutritious status by introducing a fertility rating that varies over the life of a stand (Xenakis et al. 2008). 3PGN as has already been explained in section 2, it is composed by two sub-models, the 3PG and ICBM. More details of explanations are provided by Andrén et al (1997) and Xenakis et al (2008).

3.3.3.1. 3PGN parameters

Table 1 shows the description of the 3-PGN parameters, symbols and values for *Picea sitchensis* (Bong) Carr (Sitka spruce) that is used in this research.

Table 1: Description of the 3-PGN parameters, symbols and values for *Picea sitchensis* (Bong.) Carr (Sitka spruce).

Parameter Description	**3-PGN Symbol**	**Units**	**Picea sitchensis** (Bong.) Carr.
Allometric relationships & partitioning			
Foliage:stem partitioning ratio @ D=2 cm	pFS2	-	1.4*
Foliage:stem partitioning ratio @ D=20 cm	pFS20	-	0.8*
Constant in the stem mass v. diam. relationship	StemConst	-	0.138*
Power in the stem mass v. diam. relationship	StemPower	-	2.3*
Maximum fraction of NPP to roots	pRx	-	0.45
Minimum fraction of NPP to roots	pRn	-	0.3
Temperature modifier (fT)			
Minimum temperature for growth	Tmin	deg. C	-5
Optimum temperature for growth	Topt	deg. C	12
Maximum temperature for growth	Tmax	deg. C	35
Frost modifier (fFRost)			
Days production lost per frost day	kF	days	1
Soil water modifier (fSW)			
Moisture ratio deficit for f_q = 0.5	SWconst	-	0.55

Power of moisture ratio deficit	SWpower	-	6
Fertitlity effects			
Value of 'm' when FR = 0	m0	-	0
Value of 'fNutr' when FR = 0	fN0	-	0.3
Age modifier (fAge)			
Maximum stand age used in age modifier	MaxAge	years	400
Power of relative age in function for fAge	nAge	-	4
Relative age to give fAge = 0.5	rAge	-	0.95
Litterfall & root turnover			
Maximum litterfall rate	gammaFx	1/month	0.01888
Litterfall rate at t = 0	gammaF0	1/month	0.001
Age at which litterfall rate has median value	tgammaF	month	36
Average monthly root turnover rate	Rttover	1/month	0.017
Conductance			
Maximum canopy conductance	MaxCond	m/s	0.02
LAI for maximum canopy conductance	LAIgcx	-	3.33
Defines stomatal response to VPD	CoeffCond	1/mBar	0.05
Canopy boundary layer conductance	BLcond	m/s	0.2
Stem numbers			
Max. stem mass per tree @ 1000 trees/hectare	wSx1000	kg/tree	500
Power in self-thinning rule	thinPower	-	1.5
Fraction mean single-tree foliage biomass lost per dead tree	mF	-	0.5
Fraction mean single-tree root biomass lost per dead tree	mR	-	0.3
Fraction mean single-tree stem biomass lost per dead tree	mS	-	0.2
Canopy structure and processes			
Specific leaf area at age 0	SLA0	m^2/kg	5
Specific leaf area for mature leaves	SLA1	m^2/kg	3
Age at which specific leaf area = (SLA0+SLA1)/2	tSLA	years	5
Extinction coefficient for absorption of PAR by canopy	k	-	0.5
Age at canopy cover	fullCanAge	years	15
Maximum proportion of rainfall evaporated from	MaxIntcptn	-	0.15

canopy			
LAI for maximum rainfall interception	LAImaxIntcptn	-	5
Canopy quantum efficiency	alpha	molC/molPAR	0.06
Branch and bark fraction (fracBB)			
Branch and bark fraction at age 0	fracBB0	-	0.15
Branch and bark fraction for mature stands	fracBB1	-	0.15
Age at which fracBB = (fracBB0+fracBB1)/2	tBB	years	1.5
Various			
Ratio NPP/GPP	Y	-	0.47
Basic density	Density	t/m3	0.55
Conversion factors			
Intercept of net v. solar radiation relationship	Qa	W/m2	-90
Slope of net v. solar radiation relationship	Qb	-	0.8
Molecular weight of dry matter	gDM_mol	gDM/mol	24
Conversion of solar radiation to PAR	molPAR_MJ	mol/MJ	2.3
ICBM - ICBM/N			
Decomposition rate constant for the "Young and labile" pool per month	klmax	per month	0.01
Decomposition rate constant for the "Young and refractory" pool per month	krmax	per month	0.0042394
Decomposition rate constant for the "Old"pool	komax	per month	0.0004589
Quality, C/N ratio of refractory litter input	qir	-	334.29052
Quality, C/N ratio of labile litter input	qil	-	49.084113
C/N ratio of humification	qh	-	23.634867
C/N ratio of soil organism biomass	qbc	-	2.2142768
Efficiency of labile pool	el	-	0.0246367
Efficiency of refractory pool	er	-	0.5612215
Foliage nitrogen concentration	Ncf	-	1.4835506

Source: (Minunno F. 2009)

From the above parameters in table 1, allometric relationships and partitioning (indicated by *) are important for biomass estimation in the model.

3.4. Data sources

Data sources used include the permanent sample points, models initialisation, climate and soil data. All this data was provided from Forestry Commission, Northern Research station.

3.4.1. Permanent Sample Plots (PSP)

The data for validation of the above ground biomass (AGB) for specific sites came from a data base of 250 Permanent Sample Plots (PSP) spread across Scotland. For this research, 5 plots were used since they provided with complete data set for models validation. Figure 6 shows the location of the Permanent Sample Points for Sitka Spruce across Scotland. In the figure, more plots are shown since they provided with DBH information that was correlated with age for field data checks.

The PSP (see table 3) provided information about, plot number, X and Y locations, year planted, year of establishments of the measurements, stand age, mean diameter, mean height and over bark volume. The minimum number of visits to collect measurements per plot was at least 6 with some plots measured 18 times over a period of different years. This study is limited to 4 measurements since volume was not provided for all the years that were observed.

Table 2 shows the summary of the PSP data that was used. Biomass was calculated by multiplying volume with Biomass expansion factor and wood density. For details of the formula used, see section 3.5.2.

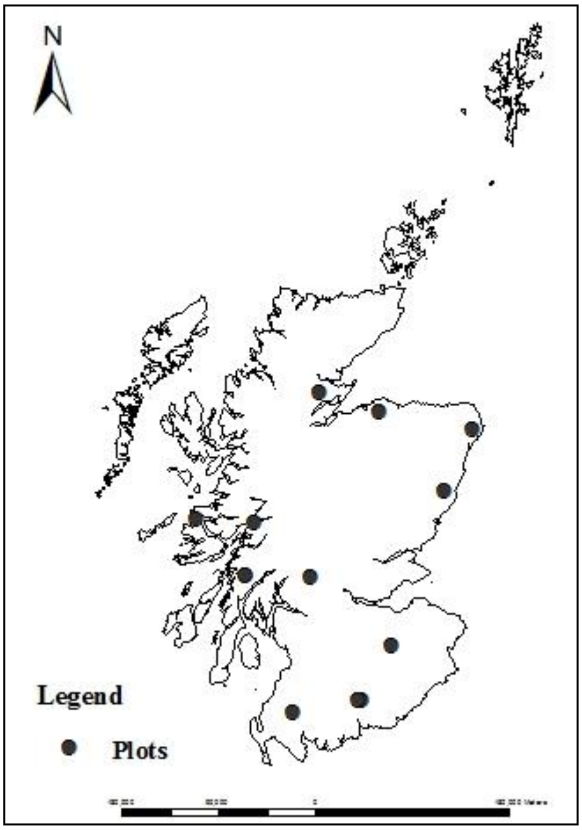


Figure 6: The location of PSP for Sitka Spruce across Scotland that were used for validation of the models. (Data to produce the map was provided by Forestry Commission, Northern Research Station).

Table 2: Summary of field measured variables for the 5 permanent sample plots used in the study.

Plot Number	X coordinate	Y coordinate	Year of Establishment	Age in years	Number of Trees	Mean Height (m)	Mean DBH (cm)	Over Bark Volume (m^3/ha)	AGB Biomass (tDM/ha)
3118	19230	70730	1939	15.2	3535	9.2	11.8	141	71.06
			1942	19	1745	12.6	15.1	178	89.71
			1945	22	1229	15.1	18.6	231	116.42
			1952	28.2	746	20.4	24.9	351	176.90
3119	19230	70730	1939	15.8	3337	10	12.3	169	85.17
			1942	19	2503	12.3	13	181	91.22
			1945	22	1976	13.8	15.1	231	116.42
			1952	28.2	1262	17.5	19.6	325	163.8
3125	20100	75540	1943	19.8	3454	10.5	11.9	170	85.68
			1946	22.9	2699	11.9	13.4	216	108.86
			1952	28	2000	14.9	16.4	322	162.28
			1960	37	1115	19.5	23	458	230.83
3155	29640	59040	1947	20.9	1582	9.2	20.5	96	48.384
			1952	26	1017	12.1	23	144	72.57
			1961	34.9	706	16.8	26	272	137.08
			1967	40	480	19.5	35.4	302	152.20
3184	31670	85930	1948	19.6	1901	9.2	20.5	128	64.5
			1954	25	932	12.1	23	215	108.4
			1963	34	580	16.8	26	396	199.6
			1966	38	475	19.5	35.4	461	232.3

3.4.2. Model Initialisation data

The models were initialised using tree density of 1367 ha^{-1} (Green et al. 2005). Initial stem, foliage and root biomass were set at 0.01tC ha^{-1}, 0.1tC ha^{-1} and 0.01tC ha^{-1} respectively. These are the default carbon values for model simulations at age 2 years. Only one rotation period (50 years) was considered hence C_N ratio allocated to all the plots was set at 32.8175 (Wilson. 1998). Fertility was assigned to each soil category. The FR parameter for each soil category was assigned on the basis of the values calculated by Minunno when he calibrated the model (2009). The Yr carbon stock was set to 0 tC ha^{-1}, while the Yl carbon stock was set to 50 tC ha^{-1}, approximately the amount of carbon for grasses, litter and fine roots for the areas covered by pasture. The carbon stock of the old pool was set for each soil type on the basis of data furnished by Dr. Georgios Xenakis (personal communication)

Model outputs taken into consideration were foliage and stem dry mass (tDM ha^{-1}). 3PG and 3PGN models were run using Excel versions.

3.4.3. Climate

UKCIP02 climate data for the whole of Scotland was obtained from Forestry Commission, Northern Research Station. The dataset was provided at 250m resolution. The data set provided values of latitude, mean monthly averages of maximum and minimum temperature (^{0}C), precipitation (mm) and incoming solar radiation (MJ m^{-2} day^{-1}) for the period 1961-1997. Latitude, temperature, precipitation and solar radiation are used as inputs in 3PG and 3PGN.

3.4.4. Soil

The data related to the soil coverage of Scotland were obtained from the Forestry Commission, in Scotland and from the database of permanent sample points as well as from Ecological Site Classification (ESC) bulletin (Pyatt et al. 2001). Each permanent sample point had detailed information of soil type, texture, and fertility. The 27 soil types found in Scotland were reclassified following the method provided by Minunno (2009) and also from the sub-compartment database. The detailed procedure to reclassify soil in this study is therefore as explained below.

From the ESC bulletin available water content (AWC) per meter is given as in table 4 and 5: (Pyatt et al. 2001)

Table 3 : Available soil water content per meter

	AWC per meter	**AWC/mm**
1	Humus layer or peaty soils	400mm
2	Soil Loamy or clayed	170mm
3	Soil sand or loamy sand	100mm
4	Soil extremely stony with sand matrix	50mm

(Pyatt et al. 2001)

From the above description, the following maximum rooting depth per soil was therefore assumed. Respectively the maximum and minimum ASW per soil texture were also empirically defined and results shown below (Xenakis, personal communication).

Table 4 : Minimum and maximum available soil water per soil texture

	Maximum Root Depth	Max ASW	Min ASW
Soil texture 1	1m	400mm	150mm
Soil texture 2	1.5m	255mm	50mm
Soil texture 3	2.5m	150mm	0mm
Soil texture 4	1m	50mm	0mm

Texture was assigned for each soil-type using the information on default Soil Nutrient Regime (SNR) per national soil map type as presented by Pyatt et al (2001) and Wilson (1998). Below is the formula to derive the SNR and Carbon Nitrogen ratio, as presented by Wilson (1998)

If (SNR=1) then

C_N = 32.8175

else if(SNR= 2) then

C_N = 24.83464286

else if(SNR = 3) then

C_N = 20.286

else if(SNR= 4) then

C_N = 21.845

else if(SNR = 5) then

C_N = 17.355

else if(SNR = 6) then

C_N = 21.845 + ((17.355 - 21.845) / (5.0 - 4.0)) * (x - 4.0)

(Wilson. 1998)

Of the data available about soil carbon content and the fertility rating (FR) values of the different soil types were assigned to each soil category as shown in table 4. The soil fertility map produced using ArcGIS software is shown in Appendix I.

Table 5 : Fertility rate values and carbon stocks of the "Old pool" (tC ha^{-1}) at the plantation year assigned to each soil category.

Soil category	**FR**	**Old pool (tC ha-1)**
Peats	0.76	200
Podzols	0.55	150
Gleys	0.55	200
Brown earth	0.7	130
Iron Pan	0.55	175
Regosols	0.425	70
Humic Gleys	0.7	200
Other soils	0.6	150

Source: (Minunno F. 2009)

3.5. Methods

The section gives an overview of the methods used to accomplish the set objective. The section explains and justifies why visual validation method was selected. A conceptual framework of the methods used is also provided. The conceptual framework provided applies to both objectives in this study.

3.5.1. Models validation

The validation of both 3PG and 3PGN models was done to establish the accuracy of the models in predicting AGB of the 5 PSP (see table 3 for the PSP). The models were initialised using climate, soil and parameters derived for Sitka Spruce in Scotland. 5 PSP were used for validation since they provided with a complete dataset necessary for the calculation of above ground biomass. The plots fall in different soil types with two fertility rates (0.4 and 0.7). Fertility is one of the input parameter in the models.

To compare the models predicted and observed above ground biomass, data from PSP was used that provided with the biometric data for the validation sites for many years. Section 3.4.1 provides detailed information of the PSP data that was used to validate the models. Modelled estimates of AGB could be directly validated using data collected at each of the 5 PSP sites. Each plot provides tree measurement data such as mean DBH, mean height, age, volume and soil fertility and soil type. Soil parameters were derived as explained in section 3.4. 4.

IPCC grades highest locally developed biomass equations, as research indicate that equations developed elsewhere may result in very high errors (De Gier, personal communication). Allometric equations used in this thesis were developed in 2004 for Great Britain and no attempt was made to develop new equations specifically for Scotland as this was beyond the scope and resources of this thesis.

Over bark volume was converted to above ground dry biomass using the formula adopted from Lowe et al and Levy et al (2000) and (2004) respectively, for Great Britain Coniferous species.

B_{stand} = V X D X BEF…………………………………………….. (1)

B_{stand} = above ground biomass (AGB) in tones per hectare (tDM/ha)

V = Volume

D = Wood Density (WD)

BEF = Biomass Expansion Factor

WD = 0.35 t/m^3, BEF = 1.44. Volume is in m^3/ha.

This gave the observed plot biomass which was then compared to models predictions of above ground biomass. The calculated above ground biomass is as shown in table 2. AGB was compared to 3PG and 3PGN model predictions. The model errors were obtained using the following formula that has been adapted from Nightingale et al (2007)

Error = (((observed value – simulated value)/observed value)*100)………………. (2)

For each set of simulated and observed above ground biomass produced, the following formula was used to evaluate the two models. The RMSE formula used is from Moore et al (Moore et al. 2007).

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(Pi - Oi)^2}{n}} \quad \text{…………………………………………… …(3)}$$

Where RMSE = Root mean square error, Pi = predicted, Oi = Observed, n = number of years times the number of plots.

All the twenty measurements from five plots were considered. To further verify the results, another formula that averages all the errors so as to measure how close the predictions are to the observed. (Mean Absolute Error formula) was also used. It involves squaring and summing up each of the models errors and divide by n. (n = number of years times the number of plots), Formula not shown.

The runs for validation of the models were made with the implementation of 3PG and 3PGN as a that use Excel spreadsheet as interface (Sands. 2001; Xenakis. 2007).

3.5.2. Visual or graphical validity.

Graphical validity is used to compare the models predictions against observed results. Amaro et al (2003) states that, growth models often consist of sub models composed of functions that describe different components; it is therefore difficult to validate these models in an efficient manner. The most difficulty is on making the judgment of the overall goodness of the prediction of such models. However visual or graphical inspection of model predictions has found to be extremely powerful when compared to other validation methods (Vanclay. 1999). Properly laid graphs can reveal quickly the goodness of prediction of a growth model on either single or several graphs (Amaro et al. 2003).

3.5.2.1. Field Data check for Validation

Scatter plots show the relationship, strength, form, direction and overall pattern of two or more quantitative variables (Moore et al. 2007). Since observed volume had only 4 measurements recorded per plot and this could not clearly show the linear relationship, DBH was then used to show the relationship. Volume is in principle derived from DBH and height measurements.

Collected field data was plotted on the scatter plot as shown in figures 7 and 8.

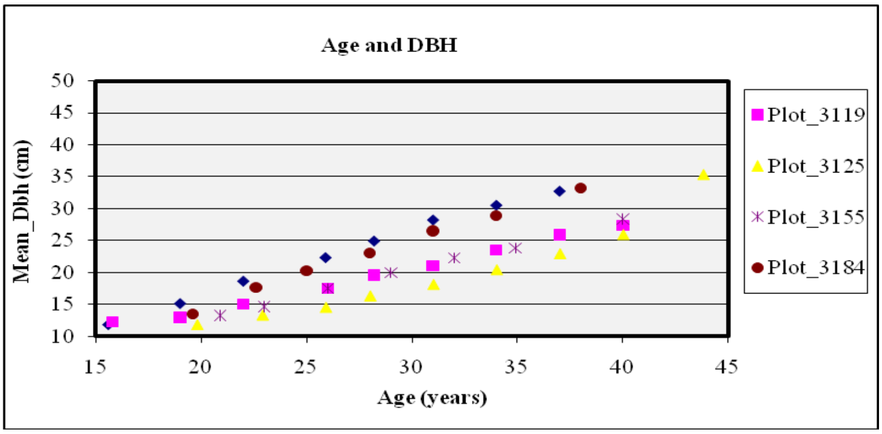


Figure 7: The relationship between Age and DBH.

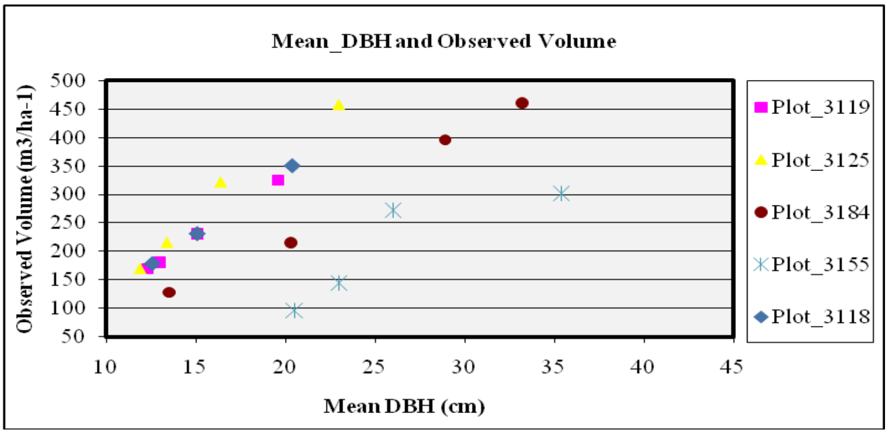


Figure 8: The Relationship between Mean DBH and observed volume

3.5.3. Research Approach

The approach comprises the steps illustrated in the flow chart figure 9, below. Firstly, various studies that utilized the 3PG model as their methodology were reviewed. Secondly, the two models, 3PG and 3PGN were validated for their capability to assess above ground biomass, using Scotland PSP observed data. It was then followed by, chapter four with modelling of forest growth under the influence of changes in temperature and precipitation using the UKCIP02, baseline and 2080s high emission scenarios at a large scale using 3PGN-Spatial.

Thirdly, the results from the models will be discussed and analyzed to determine the models' competence in predicting above ground biomass.

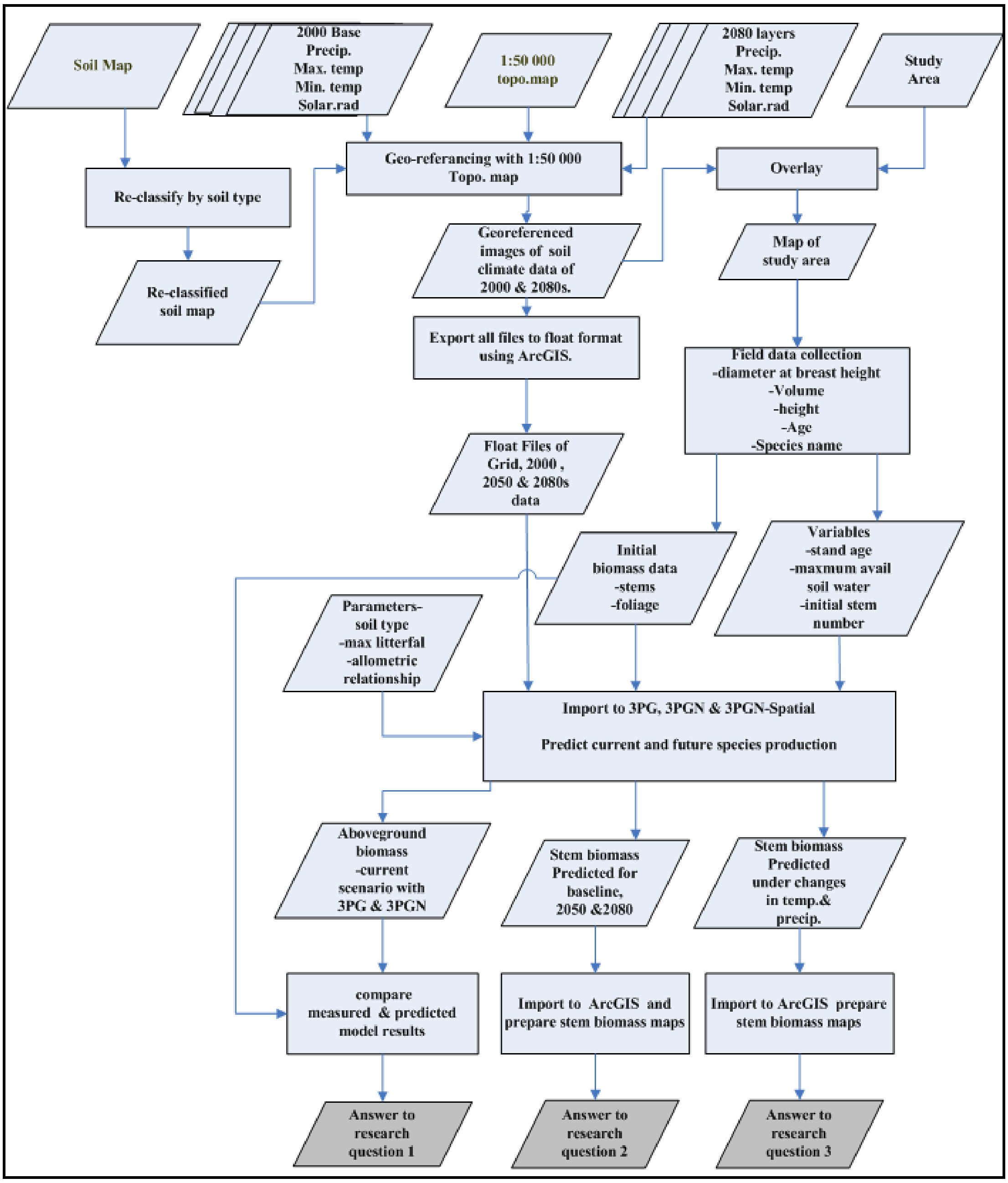


Figure 9 : Flow diagram of the research methodology

3.6. Results

The section shows the results of simulated AGB by 3PG and 3PGN models. The models predictions are compared to observed AGB. Microsoft Excel spread sheet is used to graphically show the relationship between 3PG, 3PGN and predicted AGB for the 5 validation plots. AGB of the 5 plots varied from one plot to the other but portrayed the linear relationship pattern. The relationship between models predicted AGB for the five validation plots is shown in figures 10-14. Appendix II shows Model errors expressed as a percentage per each measurement in a plot. The variation in model predictions could be due to different climatic conditions, different locations, soil types, varying fertility rates, varying ages of the measured plots as well as variations in available soil water.

3.6.1. Comparison of 3PG and 3PGN predictions of AGB.

Plot 3118

3PG and 3PGN models over-estimated AGB of plot 3118 when compared to measured plot biomass. 3PG over predicted on all the 4 measurements that were done by between -17tDM/ha (-23.9%) to -58.9tDM/ha (-33.3%). See appendix II for all the over-estimated values. 3PGN over predictions of AGB for the plot measurements was between -21tDM/ha (-30.2%) and -71tDM/ha (-40.1%). Figure 10 show the models results and observed measurements.

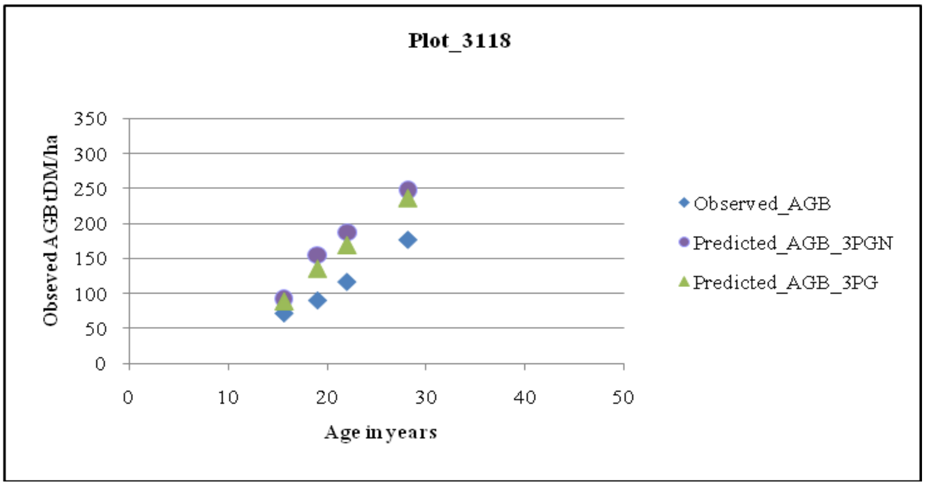


Figure 10: The relationship between observed, 3PG and 3PGN predicted AGB for plot 3118 (tDM/ha)

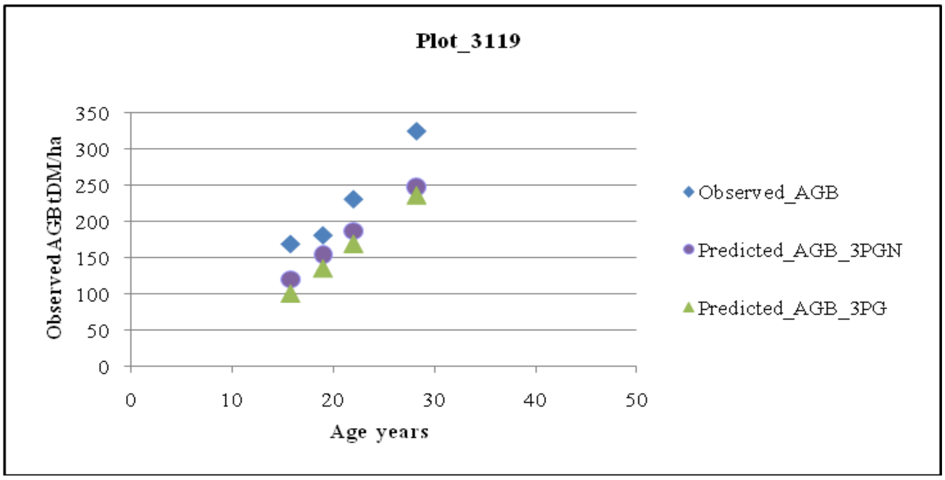


Figure 11: The relationship between observed, 3PG and 3PGN predicted AGB for plot 3119 (tDM/ha)

Models predictions of plot 3119 gave values that are consistently lower than observed values. The lowest predictions made by 3PG fell short by between 46.2tDM/ha and 89.2t/DM/ha to observed plot AGB. This gave an error of 25.5% and 27.4% respectively. 3PGN's predictions for the plot were lower by between 26.1tDM/ha and 77.1tDM/ha and this gave model errors of 14.4% and 27.7% respectively. See appendix II for the rest of the plot errors. The models predictions and observed AGB for plot 3119 is as presented in figure 11.

Plot 3125

In this plot 3PGN predictions were lower than of plot 3118 and 3119. The simulated outputs by 3PGN remained constantly low as indicted by the model errors of -11.1%, -14.9%, -20.7% and -21.6%. 3PG underestimated AGB for this plot but also with low model errors. See appendix II for all the resultant errors and model predictions. Figure 12 show the relationship between the observed and the simulated results of the plot.

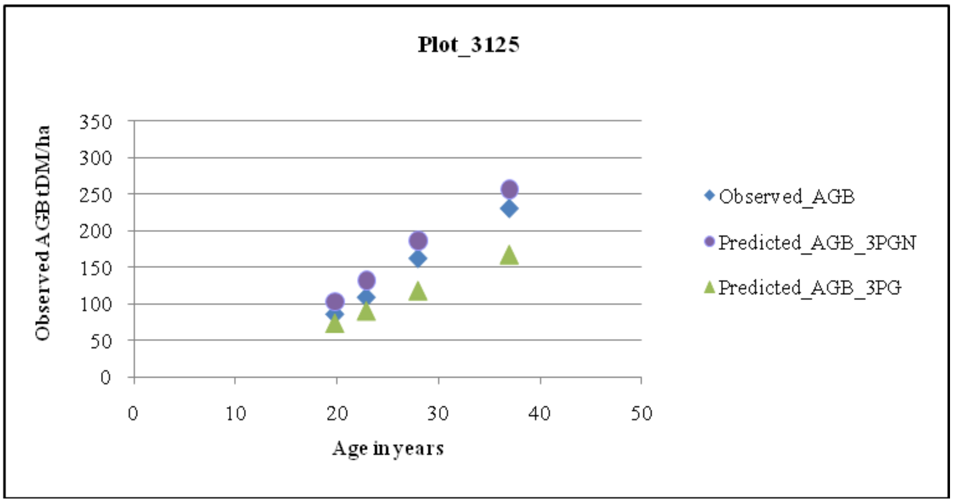


Figure 12: The relationship between observed, 3PG and 3PGN predicted AGB for plot 3125 (tDM/ha)

Plot 3155

This plot has the best agreement between 3PG simulated estimates and observed AGB. Although 3PG over predicted AGB of 3 out of the 4 plot measurements, the error margins are low. The lowest percentage error of 3PG under prediction is 0.5% and whilst the highest percentage error of over prediction being -36.4%. This is shown in appendix II. 3PGN model over predicted on all measurements made on this plot. 3PGN's over predictions are between -0.7 t DM/ha (-5.5%) and -34.1tDM/ha (-47%). Figure 13 graphically present this comparison.

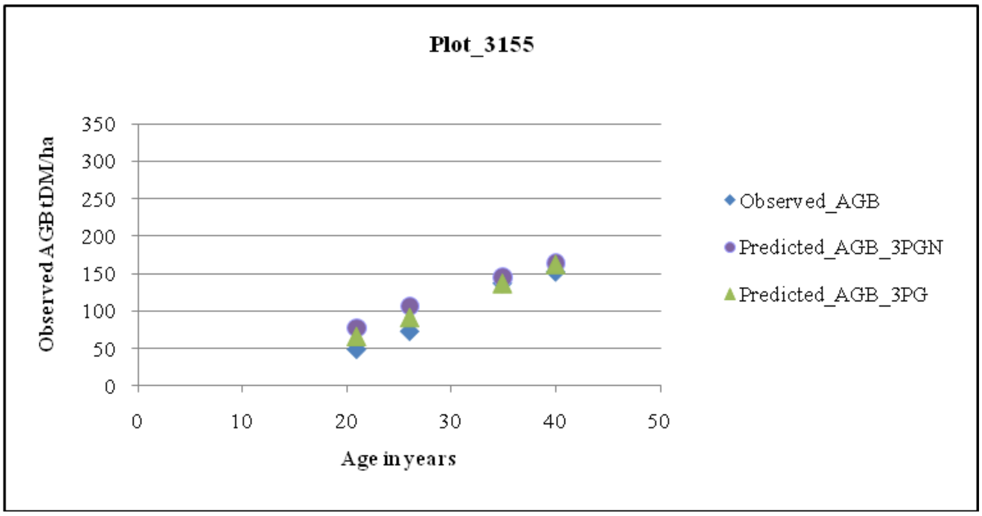


Figure 13: The relationship between observed, 3PG and 3PGN predicted AGB for plot 3155 (tDM/ha)

Plot 3184

3PGN model over estimated AGB of this plot when compared to measured AGB. The highest Over-estimation value by 3PGN was -37.7tDM/ha (-34.6%). 3PG underestimated AGB of 3 out of 4 measurements made on this plot. The highest underestimation value for this plot by 3PG is 54.5tDM/ha (23.5%). Figure 14 show the models predictions and observed AGB.

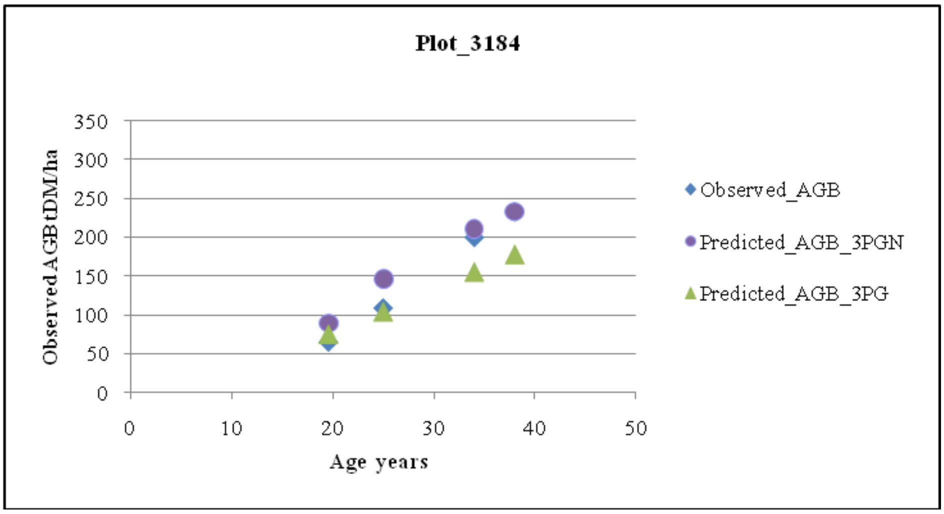


Figure 14: The relationship between observed, 3PG and 3PGN predicted AGB for plot 3184 (tDM/ha)

3.6.2. Model errors analysis

Using the RMSE method, 3PGN produced an error of 40.1tDM/ha, and 3PG an error of 44.4tDM/ha. Using the Mean Absolute error method3PGN predicts on average a value which differs by 33.6 tDM/ha from observed. 3PG predicts on average a value which differs by 36.9 tDM/ha from the observed value. The range of biomass predicted by 3PGN is between 0.37 - 77.1 tDM/ha and for 3PG is between 0.66 - 89.2 tDM/ha. Appendix III provides with all the model calculations.

3.7. Discussion

In any study that predicts forest growth, the key requirement, regardless of the modelling, approach, is to determine how well the predictions mimic the true forest growth in the field. Five model runs are compared, consisting of 5 validation plots for each of the models. Although the models provide a variety of outputs, only AGB estimates are evaluated. AGB accounts for the sum of foliage and stem production. This limited analysis was selected for the following reasons. The first reason is that forest managers are usually more interested in stem ground growth. Secondly above ground biomass is used in the derivation of forest carbon stocks. The chapter discussed in detail the 2 models results.

3.7.1. Comparison of 3PG and 3PGN predictions of AGB.

3PGN predicted in all cases higher AGB than 3PG. The reasons of the models under and over estimation of AGB could be linked to model calibration that could have not captured important information such as litter fall rates as noted by Nightingale et al (2007). Generally both models form the reliable linear patterns of AGB predictions when compared to observed field measurements. Previous studies show that 3PGN can reliably predict stem biomass with predictions of foliage noted as less successful (Xenakis et al. 2008). AGB is a combination of stem and foliage biomass. Hence if one is not correctly predicted, it affects the overall biomass results. It is important to note that although observed AGB is a direct derivation from volume, the models results could differ as they partition biomass into 3 components which are root, foliage and stem in their outputs.

With plot 3118 and 3119, both models over predicted AGB and this could be attributed to a number of factors. It could be that the assigning of soil fertility rate was not properly done, see the calculations in section 3.4.4. on how the soil parameters are derived. The process of re-classification (from 27 to 8 soil classes) compromise on the data quality. Another possibility is that plot 3119 could have been used as a control plot so no thinning could have been done (Personal Communications with Xenakis).

The results show that in some cases the errors were high (see Appendix II). The detailed explanation for this maybe established by detailed investigations of the data and the models behaviour(Landsberg et al. 2000). There is also a possibility that when calibration and parameterisation of the model was done maybe it did not fully represent the different plot characteristics hence the variations in the models predictions.

The difference in solar radiation from one plot to the other contributes to variations in Sitka spruce's production. Waring (2000) in his study of growth limitations of Sitka spruce in Great Britain, revealed that the differences in solar radiation account for difference in production that ranged from 25 m^3ha^{-1} a^{-1} at one site to 45 m^3ha^{-1} a^{-1} on another site. The sites were modelled with the same fertility rate. Plots 3118 and 3119 are among the highest in rainfall and receive average solar radiation if compared to the other sites. Solar radiation is an important input in tree growth. See appendix IVfor plot climatic conditions. The soil fertility for these sites is 0.7. These plots could be close to each other but on the different side of the slope, causing the differences in growth.

3PG under-predicted AGB of 4 out of the 5 plots measured. The worst under-predictions were for plots 3125 and 3184. The plot measurements were taken between 19.8 years and 40 years. It could be that 3PG cannot depict well AGB of older plots (>34 years). 3PG underestimation of AGB for most of the plots is similar to what was also found by White et al (2000) who noted that this could be associated to plots with varying ages and also due to effects of calibration parameters per each plot. The PSP in Scotland exhibited different plot characteristics that include soil type and fertility. This could also have effects on model results

This study agrees with previous studies on AGB estimation that have been done elsewhere using 3PG model. Nightangle et al (2007) provided with the following statistical model errors in their study of AGB estimation. They subtracted measured AGB from modelled AGB for regrowth forests, the error was between -41.1 (60%) to +19.1tDM ha^{-1} (20%) and for plantations, error was -60 (17%) to +62.2tDM ha^{-1} (15%). This is comparable to the results that were obtained in this study. (see appendix II). It is apparent that this study also failed to predict foliage biomass well and agrees with other studies that have been done before(Xenakis et al. 2008). Results not shown.

As has already been captured in the methodology, 3PG consists of two sets of calculations. Those that lead to biomass values and those that allocate various components of the trees and determine the growth pattern of the stand (Landsberg et al. 2001). On the other hand, 3PGN has incorporated all of the main features of 3PG + ICBM/2N, such that soil nutritional status of site are calculated (Xenakis et al. 2008). The above explanation agrees with model results that seem to favour the predictions made by 3PGN model which are showing signs of improvement in model predictions. The results of model performance are shown in section 3.4.6. However it should be noted that biomass production is determined by other factors such as weather condition of any site(Landsberg et al. 2001). As noted by Waring (2000), the most important limitation factor on wood production by SS in Great Britain was solar radiation which is then followed by soil fertility

Most of these sites during the time of measurement were fertilised hence it resulted in more fertile soils and the model could not depict this variation (Miller et al. 1992) together with information obtained from forest commission's database on SS. Also, Scotland's soils maybe poor in nutrients, but trees can still obtain calcium, magnesium, potassium and sulphate from the atmospheric sources. Aerosols in the atmosphere are rich in nitrogen which is needed by plants to grow (Waring. 2000). Hence the models can fail to depict this change and results in under prediction of some plots.

3.8. Conclusion

3PGN predicted in all cases higher AGB than 3PG. 3PG gave better results when observed AGB is low (plot 3118, 3155 and the first two measurements of 3125 and 3184). 3PGN performance was better than 3PG in the cases where observed AGB is higher (plot 3119 and last two measurements of plots 3125 and 3184). 3PGN predictions gave a RMSE of 40.1tDM/ha while 3PG gave RMSE error of 44.4tDM/ha. Using the mean absolute error method 3PGN predicts on average a value which differs by 33.6 tDM/ha from the observed value. 3PG predicts on average a value which differs by 36.9 tDM/ha from the observed value. The range of biomass predicted by 3PGN is between 0.37 to 77.13 tDM/ha while 3PG is between 0.66 to 89.19tDM/ha. 3PGN in this case performs better than 3PG.

The next chapter looks on the effects of climate change on stem biomass assessment using the 3-PGN Spatial model. Most interesting is to note are the effects of predicted changes in temperature and precipitation on the production of stem biomass.

4. Effect of Climate change on stem biomass assessment

Sitka spruce represents 29% of Great Britain's forest land and Scotland alone has 47% forest land covered by Sitka spruce (Forestry Statistics. 2006). The value attached to Sitka spruce by the Scottish people has been briefly explained in chapter 1. Above all forests take longer time to grow; hence any changes that maybe caused to them by changes in climate need to be detected early for better forest management.

The main objective of this chapter is to evaluate the effect of climate change on stem biomass assessment of the SS across Scotland. To assist in answering this research objective the following research questions were therefore asked:

1. How is the stem biomass distributed under current, 2050s and 2080s period?
2. What is the effect of predicted changes in temperature and precipitation on the production of stem biomass of Sitka spruce?

3PGN Spatial and ArcGIS were the tools used in this analysis. 3PGN Spatial was used to demonstrate its usefulness in assessing stem biomass under climate change. For climate change analysis temperature data concerned average monthly maximum and minimum temperature as well as average monthly precipitation. This was done to show the predicted effect of these environmental conditions on stem biomass assessment of Sitka plantations.

4.1. Materials and Method

The section explains the materials (3PGN spatial and ArcGIS), the data sources and the methods employed to answer the set objective.

4.1.1. Materials

3PGN-Spatial

The spatial version of 3-PGN is driven by weather and soil inputs data and has a possibility of incorporating remotely sensed Normalised Difference Vegetation Index (NDVI) data. The input data can be unique values or spatially interpolated grids of mean monthly minimum and maximum temperature, precipitation, vapour pressure deficit, incoming solar radiation, frost days and soil class. To initialise the model it needs also state variables of tree density, stem, foliage and root biomass, labile, refractory and old carbon and nitrogen pools, available soil water, plantation year and latitude. Spatially interpolated grids can be used also for the initialisation of 3-PGN SPATIAL.

The model outputs are spatially and temporally resolved predictions of variables such DBH (mean breast height diameter), stem, foliage and root biomass, carbon and nitrogen stocks for the different soil pools, heterotrophic respiration for the young, refractory and old pools.

4.1.2. Data sources

The data sources used include the climatic and topographic data. Other data sources necessary to run the model have also been provided in this section.

4.1.2.1. Climatic data

Climate data for the whole of Scotland were obtained from the dataset interpolated from the UKCIP02 dataset from forestry Commission Northern Research Station. See chapter 3, section 3.4.3 for the complete set of climate data.

For this analysis latitude, mean monthly maximum and minimum temperature (°C), precipitation (mm) and incoming solar radiation (MJ m-2 day-1) data were used as input for 3PGN-Spatial. Figure 14 show the baseline input data set for the month of April for 3PGN-Spatial.

4.1.2.2. Other Data

Sitka spruce parameters and soil data are all derived as explained in chapter 3. In this work, one rotation (50 years) was taken into consideration.

Figure 16 show the distribution of public Sitka spruce across Scotland. It was necessary to show the distribution of Sitka spruce since the analysis was to look at stem biomass produced by Sitka spruce across Scotland. Map showing all SS forests was not available during the time of this analysis, hence only the map with public forests are shown. This at least shows how SS forests are distributed across Scotland.

A mask grid was generated to remove the areas where SS is not grown. It is important to note that not only the area with current forests was taken into consideration but also potential suitable areas. Appendix V, show the map used in creating the mask grid.

Figure 15 show April input spatial data for the model, which are rainfall, solar radiation and temperature.

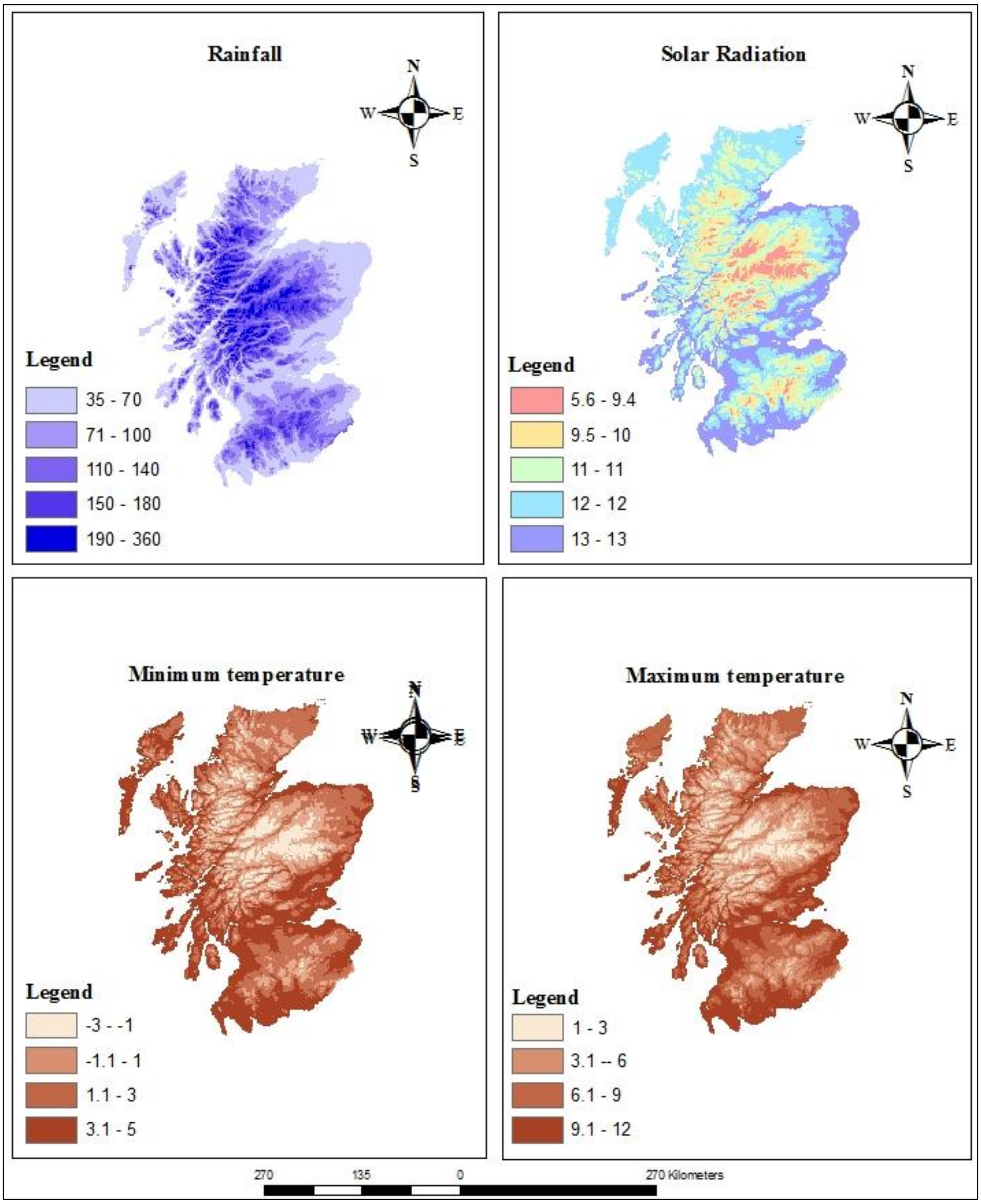


Figure 15: 3PGN-Spatial input climate data for the month of April. (Average monthly rainfall (mm), average monthly incoming solar radiation, (MJ m-2 day-1), Average monthly minimum and maximum temperature (°C). Produced from UKCIP02 baseline data from Forestry commission Northern Research Station).

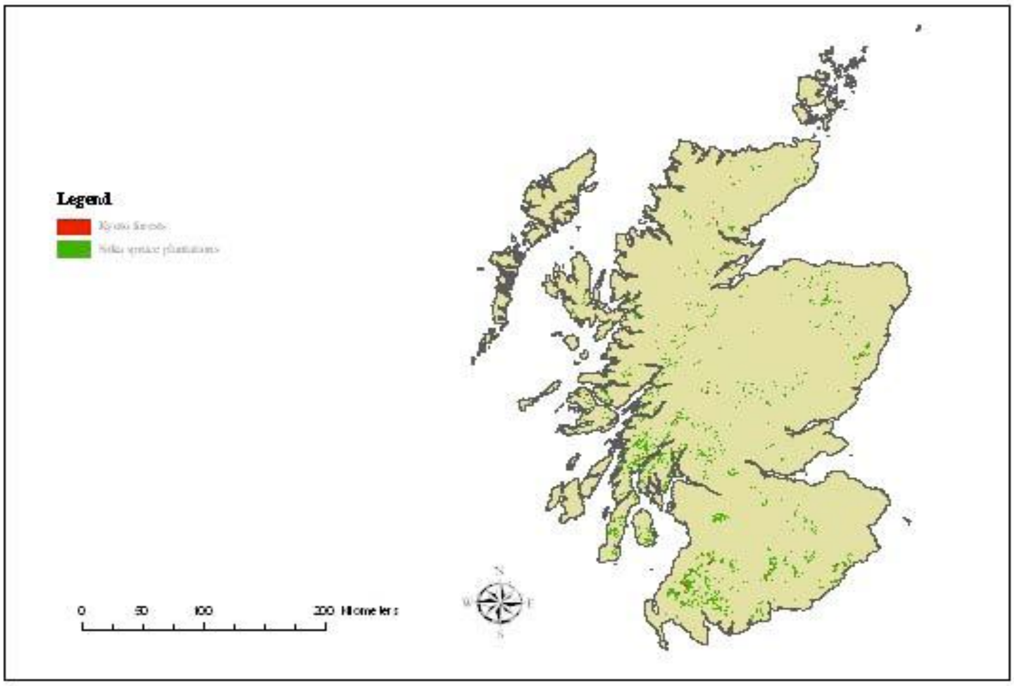


Figure 16: Distribution of public Sitka spruce across Scotland. (Minunno 2009)

4.1.3. Model initialisation

The model was initialised as explained in section 3.4.2

4.1.4. Analysis on climate change

The analysis on the impact of climate change on Ws biomass assessment was carried out taking into consideration the likely changes occurring to temperature and precipitation. Only the high emission scenario predicted by the UKCIP02 for 2050s and 2080s was considered, since it provides with extreme conditions and it was thought to represent well effects of changes in temperature and precipitation. The first analysis was to show how the Ws biomass is distributed among the different time periods using the baseline and high emission scenarios data of 2050s and 2080s period.

The influence of temperature and precipitation changes was then analysed by running the model first with baseline data and 2080s high emission scenarios. Firstly, the model was run with baseline and predicted 2080s high emission scenario temperature. Secondly the model was run with baseline and predicted 2080s high emission scenario precipitation. This analysis was done to demonstrate how well the model predicts Ws biomass under changes in climate and how useful it maybe for forest management.

3PGN-Spatial that uses Windows DOS command and ArcGIS (Sands. 2001; Xenakis. 2007) was used to do the analysis. The 3PGN output considered in this analysis was Ws biomass (tDM/ha).

4.2. Results

The chapter show the results of the Ws biomass produced by 3PGN-Spatial for the baseline data, 2050s and 2080s UKCIP02 high emission scenario. The section also shows the direct influence of predicted temperature and precipitation on Ws biomass assessment for the 2080s period.

4.2.1. Ws produced by Baseline, 2050s and 2080s high emission scenario

Figure 16 shows that less productive areas of Ws biomass in Scotland resulted in some parts to the north and north-west areas producing between 1-30tDM/ha.

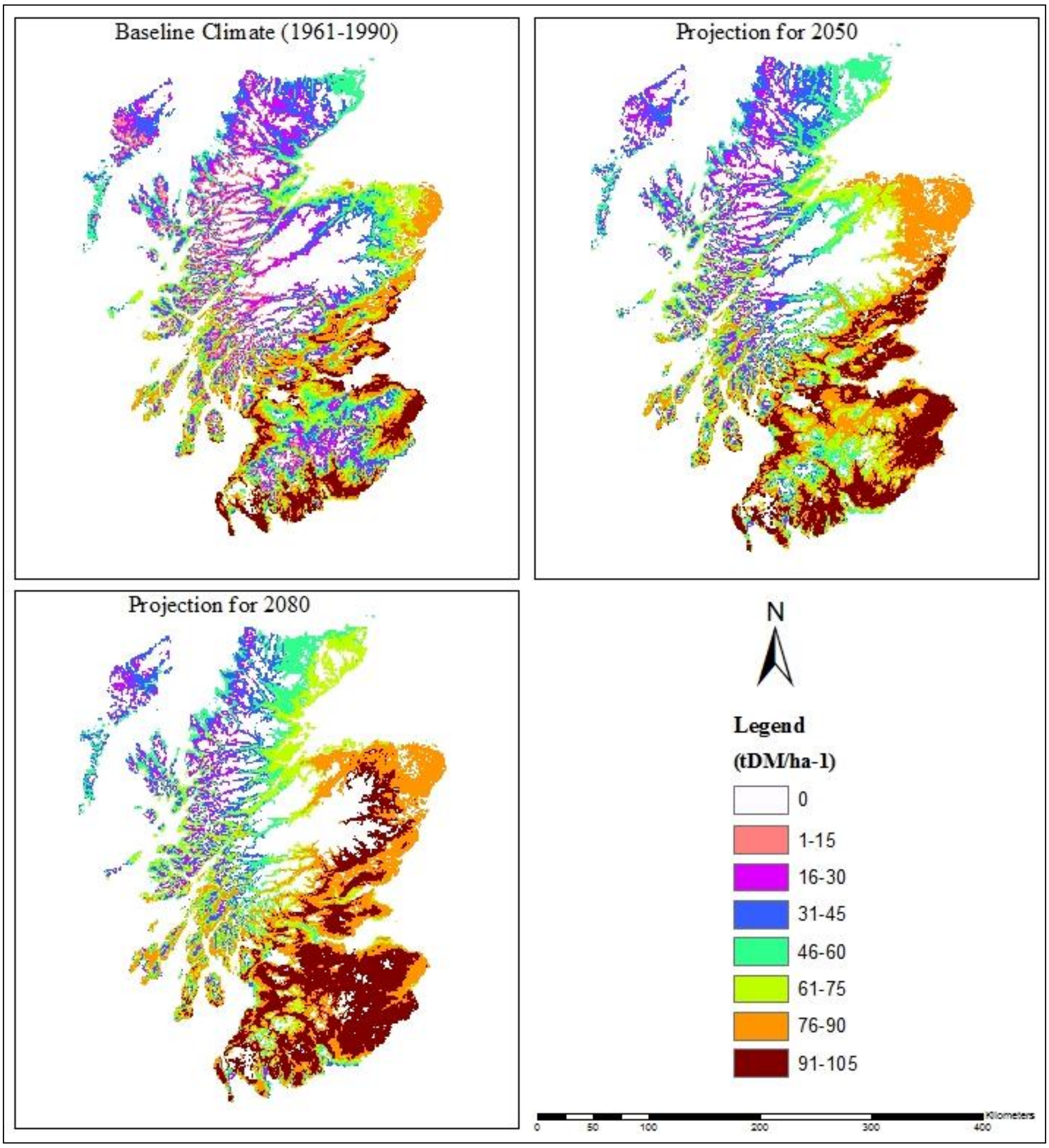


Figure 17: Stem biomass (Ws, tDM /ha) produced by 3PGN- Spatial.

SS is not grown in the areas that are indicated as producing 0 tDM/ha. The more productive areas resulted to the South of the region. This also includes areas situated to the north of Edinburgh and also to the north eastern corner of Scotland. The baseline data shows fewer areas producing between 91-105 tDM/ha. The projection for 2050s period show increased areas with Ws biomass between 91-105 tDM/ha in southern and towards the south east coast of Scotland. By the 2080s period more Ws biomass will be produced in most areas to the south of Scotland. There is also reduction of Ws biomass to areas in the south east. See figure 17 for the differences of Ws biomass as predicted by 3PGN-Spatial model for the different time periods.

4.2.2. Effect of predicted temperature and precipitation on Ws production.

The second analysis is on the predicted influence of temperature and precipitation changes on Ws production of Sitka spruce across Scotland. Here the model is again tested to see if it is sensitive to changes in climate variables. The results were obtained after running the model with baseline data and temperature predicted by UKCIP02 for 2080s period. The second run was with the baseline data and precipitation predicted by the UKCIP02 for 2080s period. Figure 17 shows the model results.

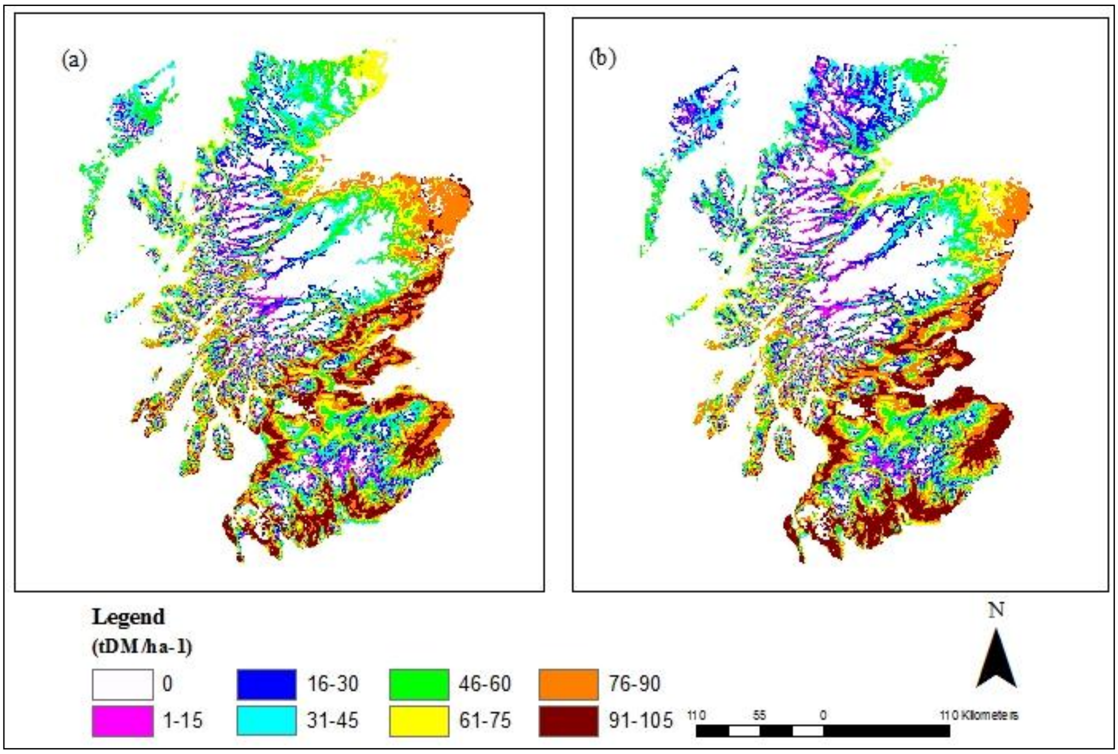


Figure 18: Effect of temperature and precipitation on stem biomass production for Sitka spruce in Scotland. (a) Baseline precipitation plus maximum and minimum temperature for 2080. (b) Baseline maximum and minimum temperature plus precipitation for 2080.

Temperature caused larger changes as compared to precipitation changes during the 50 years of Ws production. Figure 17, (map a) show predicted effect of most changes to the north east of Scotland where Ws biomass production increased from between 46 - 60tDM/ha to between 61-75tDM/ha. Another noticeable change is to east coast where areas of Ws biomass of 76 - 90tDM/ha have increased. Precipitation changes are hardly noticeable in figure 18 (map b) if compared to baseline map, figure 17. The results indicate that predicted temperature changes have greater influence on Ws biomass production when compared to precipitation.

4.3. Discussion

A key application of 3PGN spatial is to provide reliable estimate of forest productivity in terms of biomass assessment. However this is possible if model predictions are enhanced if detailed knowledge of the particular species being investigated is known. This knowledge can be through literature or through key informants, who have detailed information of the growth patterns, distribution and the environment in which it is growing. Hence the map showing distribution of public SS gave an overview of some of the areas where Sitka spruce is grown in Scotland. Changes in precipitation are assumed to have positive or negative effects in Ws production depending on the area.

4.3.1. Ws produced by Baseline, 2050s and 2080s high emission scenario

Figure 17 show maps of predicted stem biomass under different time periods, the baseline which represents current scenario, the high emission scenario of 2050s and the 2080s period. Stem biomass is predicted to increase from baseline into 2050s and 2080s period. Studies that have been done so far reveal that Scotland's summers will become warmer and winters will become milder. Drought periods have been predicted and these may affect mostly south-eastern and eastern Scotland areas. Ws production may reduce with time in these areas. The model has predicted increases as well decreases in stem biomass of the south-east and the eastern Scotland. Cannell (2002) also noted that milder climate improve forest productivity of many species, including Sitka spruce. Although the model predicts the probable changes in Ws biomass production of Sitka spruce, The modelling results suggests that Ws will increase and some areas despite the drought threats. In some areas, the model predicts reduction in Ws biomass.

4.3.2. Effect of predicted temperature and precipitation on stem biomass assessment

Temperature and rainfall are particularly important for species productivity as well as forest management (Ray et al. 2008). To demonstrate the effect of predicted temperature and precipitation on Ws production, the model was first run with the baseline scenario data and temperature for the 2080 UKCIP02 scenario and secondly with the baseline data and precipitation predicted for 2080s. See figure 18 for the outputs. For the baseline data and 2080s high emission scenario see figure 17. Precipitation changes were hardly noticeable thus it seemed to have little or no influence on Ws production. Current researches reveal that there is seasonal rainfall shift that will affect growth of SS in especially along the east coast where soils are susceptible to water logging (Ray et al. 2008). Hence the model underplays the influence of precipitation in this case.

Temperature has influenced some areas to the north-west coast of Scotland to increase Ws biomass from 31 – 45 tDM/ha to between 46 - 60 tDM/ha. Changes are also noticeable to the north eastern corner of Scotland where stem biomass predicted to increase from 46 - 60tDM/ha to between 61-75tDM/ha. Changes in stem biomass are (Ws) distribution was influenced mainly by temperature. Increased temperatures are believed to increase forest productivity. Cannell (2002) in his study revealed that over the past 40 years increase in forest growth has been observed already. The results also agree with studies by Ray et al (2008) who noted that increased temperatures will stimulate higher yields for biomass production in better quality land and in areas of lowland. However Magnani et al (2007) in his research suggested that the increase in forest growth could also be attributed to higher nitrogen availability through deposition.

4.4. Conclusion

The model reveals that less productive areas of Ws biomass in Scotland resulted in parts to the north and north-west parts producing between 1-30tDM/ha.The areas to the south are predicted to have increased Ws biomass from current (baseline) period to the 2050s period. The south-east region shows areas which had increased Ws by 2050s period but decreasing by 2080s period. The model also demonstrated that temperature has larger influence in Ws production when compared to precipitation.

5. Conclusion & Recommendations

The chapter outlines the conclusions and recommendations of this study. The conclusions summarized the acquired results while recommendations addressed what need to be done to improve the results and conclusions.

5.1. Answers to Research Questions

Research Question 1: *Will there be any difference in amount of above ground biomass predicted between 3PG output and 3PGN output when compared to actual tree growth data?*

3PGN predicted in all cases higher AGB than 3PG. 3PG gave better results than 3PGN when observed AGB is low (plot 3118, 3155 and the first two measurements of 3125 and 3184). 3PGN performance was better in cases where observed AGB is higher (plot 3119 and last two measurements of plots 3125 and 3184). To evaluate the models performance Root Mean Square Error (RMSE) method was used. The 3PGN predictions gave a RMSE of 40.1tDM/ha while 3PG gave RMSE of 44.4tDM/ha. Using the mean absolute error method, 3PGN predicts on average a value which differs by 33.6 tDM/ha from the observed value. 3PG predicts on average a value which differs by 36.9 tDM/ha from the observed value. The validation results showed that 3PGN performs better than 3PG.

Research Question 2: *How is the stem biomass distributed under current, 2050s and 2080s period?*

Stem biomass production results showed that less productive areas are situated to the north and north-west parts of Scotland producing between 1-30 tDM/ha. Areas to the south and south-east show stem biomass of between 91-105tDM/ha. The model also predicts that baseline stem biomass (1961-1990) will increase mostly in the south and south-east Scotland until the 2050s (2040 – 2069) period. By the 2080s (2070 -2099) period, the prediction indicates both increase and decrease in stem biomass production in parts of south-east Scotland.

Research Question 3: *What is the effect of predicted changes in temperature and precipitation on the production of stem biomass of Sitka spruce?*

The analysis showed that predicted temperature had more influence on stem biomass production when compared to predicted precipitation. The increase in temperature resulted in increased Ws biomass. Visible changes are to the north-east of Scotland where Ws biomass increased from 46 - 60tDM/ha to between 61-75tDM/ha. For tree species, increases in temperatures results in higher species, productivity of course if water and nutrients are not limited. The effect of precipitation on Ws biomass production showed very little effect.

5.2. Overall Conclusion

The study showed that 3PGN predictions of AGB were better than 3PG in the cases where observed AGB is higher. When predicted AGB is low, 3PG gave better results. The model prediction errors were validated using RMSE that showed 3PGN giving an error of 40.1tDM/ha while 3PG gave RMSE error of 44.4tDM/ha. The validation results showed that 3PGN performs better than 3PG. This claim may be true if same number of sites (5) is used elsewhere within Scotland and if more sites are used this may change. This is so because the model parameters used in this study have been developed for

Sitka spruce in Scotland. Hence the results can only apply to areas with similar climatic (temperature, solar radiation, precipitation) and soil conditions as the plots in this study.

For the analysis of climate change, the model reveals that in the 2050s period stem biomass will increase in some areas in Scotland (mostly the southern and south east areas). By the period, 2080s, there is both increase and decrease in stem biomass production. The decrease is again mainly to the south-east of Scotland. The study also revealed that predicted temperature has more influence on Ws biomass production when compared to predicted precipitation. The study demonstrates that 3PGN and 3PGN-Spatial process based models can provide more accurate and relevant forest productivity estimates at both stand and landscape level.

5.3. Recommendations

The most limiting factor of this research was data needs for process based modelling. The model requires so many data sets that take too much time to prepare and in many cases the data are not available in many study areas. Regardless of this, the following recommendations can be considered if similar studies are to be carried out in future.

5.3.1. Recommendation for future research development

The study underlined the advantages that 3PGN and 3PGN Spatial process based models can have over 3PG in forest management. Some weaknesses of process based models have also been revealed. The following is therefore recommended:

- The number of sampling plots could be increased or should be representative enough to allow one to make solid conclusions of which model performs better. Hence there is need for further research to establish which model performs better. Although in this study a preliminary conclusion of the models performance was done.
- The analysis of the effect of temperature and precipitation on stem biomass assessment can be redone utilising other climatic variables such as $C0_2$ and nitrogen deposition if data is available.

6. References

Amaro, A., D. Reed and P. Soares, Eds. (2003). Modelling Forest Systems CABI Publishing: 416.

Andrén, O. and T. Kätterer. (1997). ICBM: The introductory carbon balance model for exploration of soil carbon balance. Ecological. Applications. 7: 1226 - 1236.

Battaglia, M., O. Grady and D. Mendham. (2007). Process-based Model in Eucalyptus Plantation Management:Reality and Perspectives. **3**: 189 - 205.

Berg, B. and G. Ekbohm. (1993). Decomposing needle litter in Pinus contorta (lodgepole Pine) and *Pinus sylvestris* (Scots pine) monocultural systems - is there a maximum mass loss Scand. J. Forest Research **8**: 457- 465.

Brown, A. G., E. K. S. Nambiar and C. Cossalter (1997). Plantations for the tropics- their role , extent and nature. In: Nammbiar, E. K. S, Brown. A (Eds), Management of soil, Water and Nutrients in Tropical Plantation Forests. ACIAR Monograph N0. 43, Camberra. 24.

Cairns, M. A., I. Olmstead, J. Granados and J. Argaez. (2003). Composition and above tree biomass of dry semi-evergreen forest of Mexico's Yucatan Peninsula. Forest Ecology and Management **186 (1-3)**: 125-132.

Cannell, M. (2002). In Climate Change: Impacts on UK Forests. Bulletin 125, ed. Broadmeadow, M. S. J,. Forestry Commission, Edinburgh.

Coops, N. C., R. H. Waring and J. J. Landsberg. (1998). "Assessing forest productivity in Australia and New Zealand using a physiologically-based model driven with averaged monthly weather data and satellite-derived estimates of canopy photosynthetic capacity." Forest Ecology and Management **104** (1-3): 113-127.

de Geir., A. (2003). A new approach to woody biomass assessment in woodlands and shrublands. In: P. Roy (Ed), Geoinformatics for Tropical ecosystems, Bishen singh Mahendra Pal Sing, Dehra Dun, India : 161-198.

Espreya, L. J., P. J. Sandsb and C. W. Smitha. (2004). Understanding 3-PG using a sensitivity analysis. Forest Ecology and Management. **193**: 235 - 250.

FAO. (2006). Global forest resources assessment 2005. Progress towards sustainable forest management. Publishing Management Service. Rome, Information Division. FAO.

ForeStClim. (2008a). INTERREG IVB North West Europe - Proposal document. In.

Forestry Commission. (2009). Sitka spruce - picea sitchensis. Retrieved 11-12, 2009, from http://www.forestry.gov.uk/forestry/INFD-5NLEJ6.

Forestry Statistics. (2006). "ForestStats2006.nsf/byunique/indexmain.html." Retrieved 15-01, 2010, from http://www.forestry.gov.uk/.

Green, C., B. Tobin, M. O'Shea, E. P. farrell and K. A. Bryne (2005). Above- and belowground biomass measurements in an unthinned stand of Sitka spruce (*Picea sitchensis* (Bong) carr.). Springer: 8.

Hulme, M., G. J. Jenkins, X. Lu, J. R. Turnpenny, T. D. Mitchell, R. G. Jones, J. Lowe, J. M. Murphy, D. Hassell, P. Boorman, R. McDonald and S. Hill. (2002). Climate Change Scenarios for the United Kingdom: The UKCIP02 Scientific Report, School of Environmental Sciences, University of East Anglia. Norwich,UK: 120.

Hulme, M. (2009). The changing climate of the UK: now and in the future, Forestry Commission. Bulletin 125**:** 198.

IPCC. (2000). IPCC SPECIAL REPORT for working group III: EMISSIONS SCENARIOS, Summary for policy makers**:** 1-27.

IPCC. (2000). Special report on Emissions Scenarios. In: (eds. Nakicenovic N & Swart R), 570 pp.

IPCC. (2007b). Summary for Policymakers. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)] Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Landsberg, J. J., T. J. Albaugh, H. I. Allen and S. E. Mckeand. (2001). Applying 3-PG a simple process based model designed to produce practical results, to data from Loblolly Pine experiments. Forest Science. **41**: 43-51.

Landsberg, J. J. and S.T. Gower. (1997). Application of Physiological Ecology to forest management. Academic Press, San Diago, Califonia. 344.

Landsberg, J. J. and R. H. Waring (1997). A generalised model of forest productivity using simplified concepts of radiation-use efficiency, carbon balance and partitioning. Forest Ecology and Management **95**: 209-228.

Landsberg, J. J., R. H. Waring and N. C. Coops. (2001). Performance of the forest productivity model 3-PG applied to a wide range of forest types. Forest Ecology and Management **172**: 199-214.

Levy P.E., S.E. Hale and B.C. Nicoll. (2004). Biomass expansion factors and root:shoot ratios for coniferous tree species in Great Britain. Forestry Commission **77**: 421-430.

Lowe H., G. Seufat and F. Raes. (2000). Comparison of methods used within member states for estimating CO_2 emmisions and sinks according to UNFCCCC and EU monitoring mechanisms: forest and other wood land. . Biotechnol Agron Soc Environ **9**: 315-31.

Lowe, J. J. (1993). Setting the scene: An Overview of Climatic Change. In Smout, T.C. (ed.) Scotland Since prehistory: Natural Change and Human Impact. Aberdeen, Scottish Cultural Press.

Magnani Federico., Mencuccini Maurizio., Borghetti Marco., Berbigier Paul., Berninger Frank., Delzon Sylvain., Grelle Achim., Hari Pertti., Jarvis Paul G., Kolari Pasi., Kowalski Andrew.S., Lankreijer Harry., Law Beverly E., A. Lindroth, Loustau Denis., Manca Giovanni., Moncrieff John B., Rayment Mark., Tedeschi Vanessa., Valentini Riccardo. and Grace John. (2007). The human footprint in the carbon cycle of temperate and boreal forests. Nature Publishing Group Volume 447: 5.

Mäkelä, A. and P. Vanninen. (2000). Estimation of fine root mortality and growth from simple measurements: a method based on system dynamics Trees-Struct.Funct. **14**: 316-323.

McMurtrie, R. E., R. Leuning, W. A. Thompson and A. M. Wheeler. (1992). A model of canopy photosynthesis and water-use incorporating a mechanistic formulation of Leaf CO_2 exchange. Forest Ecology and Management **52**: 261-278.

Met Office. (2009). "Climate: Eastern Scotland "Retrieved 12-08, 2009, from http://www.metoffice.gov.uk/climate/uk/es/ .

Miller, J. D., J. M. Cooper and H. G. Miller. (1992). Response of pole satge Sitka spruce to applications of fertilizer nitrogen, phosphorous & potassium in upland Britain. Forestry **65**: 15-33.

Minunno, F. (2009). Parameterisation, validation and application of 3-PGN for Sitka spruce across Scotland: spatial predictions of forest carbon balance using a simplified process based model. Scotland, Edinburgh. Msc Thesis**:** 123.

Moore, D. S., G. P. MaCABE and B. A. Craig. (2007). Introduction to the practice of statistics, W. H. Freeman Company.

Nightingale J.M., M.J. Hill., Phinn S.R., I.D. Davies., A.A .Held. and P.D.Erskine. (2007). Use of 3PG and 3PGS to simulate forest growth dynamics of Australian tropical rainforests. 1. Paramerisation and calibaration for old-growth, regenarating and plantation forests. Forest Ecology and Management **254**: 107-121.

Nightingale, J. M., M. J. Hill, S. R. Phinn, I. D. Davies and A. A. Held. (2008). Use of 3-PG and 3PGS to simulate forest growth dynamics of Australian tropical rainforest: II. An integrated system for modelling forest growth and scenario assessment within the wet tropics bioregion. Forest Ecology and Management **254**: 11

Parresol, B. R. (1999). Assessing tree and stand Biomass: a review with examples and critical comparisons. Forest Science **45**: 573:593.

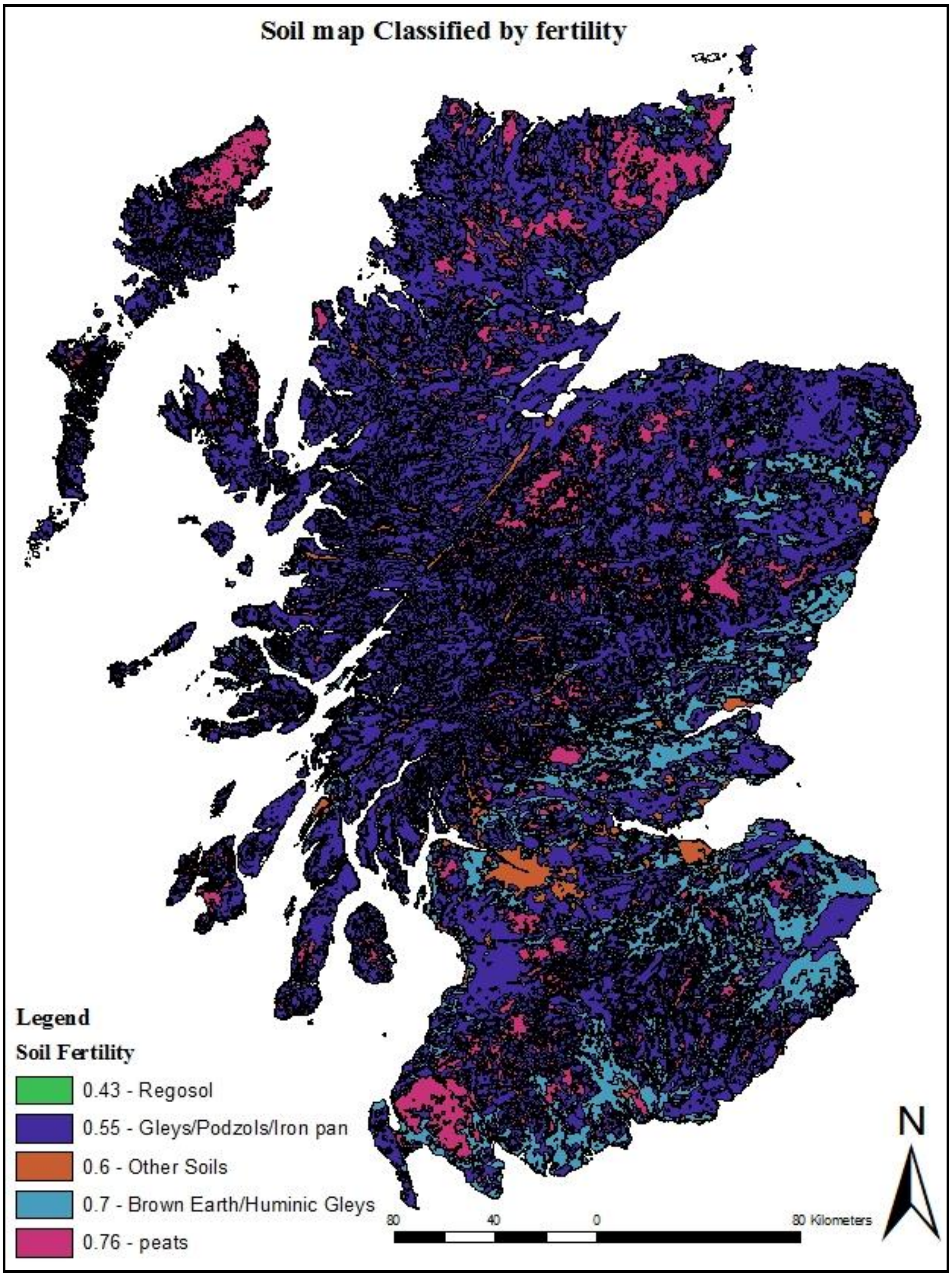
Pyatt, D. G., D. Ray and J. Fletcher. (2001). An Ecological Site Classification for Forestry in Great Britain. Bulletin 124. Forestry Commission, Edinburgh.

Ray, D., D. Wainhouse, Webber and B. Gardiner. (2008). Impacts of climate change on forestry in Scotland - a synopsis of spatial modelling research 101, Forestry Commission, Scotland

Running, S. W. and S. T. Gower. (1991). FOREST-BGC, A general model of forest ecosystem processes for regional applications. 2. Dynamic carbon allocation and nitrogen budgets. Tree Physiolgy. **9:** 147-160.
Sands, P. J. and J. J. Landsberg.(2002). "Parameterisation of 3-PG for plantation grown *Eucalyptus globulus*." Forest Ecology and Management **163**: 273 - 292.
Sands, P. (2001). 3PGpjs – A User-Friendly Interface to 3-PG, The Landsberg and Waring Model of Forest Productivity. Technical Report No. 29, Edition 2.
Stape, J. L., M. G. Ryan and D. Binkley. (2004). Testing the utility of the 3-PG model for growth of *Eucalyptus grandis X urophylla* with natural and manipulated supplies of water and nutrients. Forest Ecology and Management **193**: 219-234.
Tickle, P. K., N. C. Coops and S. D. Hafner. (2001b). Comparison of a forest process model (3-PG) with growth and yield models to predict productivity at Bago State Forest , NSW. Forest Ecology and Management **64**: 111-122.
Tickle, P. K., N. C. Coops, S. D. Hafner and The Bago Science Team. (2001a). Assessing forest productivity at local scales across a native eucalypt forest using a process model, 3PG-SPATIAL." Forest Ecology and Management. **152:** 275-291.
Titus, B. D. and D. C. Malcolm. (1999). The long-term decomposition of Sitka spruce needles in brash. Forestry. **72:** 207- 221.
UNFCCC, (1997). Kyoto protocol to the United Nations Framework convention on climate change. United Nations Office at Geneva. Geneva.
Vanclay, J. K. (1991b). Aggregating tree species to develop diameter increment equations for tropical rainforests. Forest Ecology Management **42**: 143-168.
Vanclay, J. K. (1999). Modelling forest growth and yield: Applications to Mixed Tropical Forest. CAB International, Wallingford. 312.
Waring, R. H., J. J. Landsberg and M. Williams. (1998). Net primary production of forests: a constant fraction of gross primary production? . Tree Physiology. **18**: 129-134.
Waring, R. H. (2000). A process model analysis of environmental limitations on growth of Sitka spruce plantations in Great Britain Institute of Chartered Foresters **73:** 65-79.
White, J.D., N.C. Coops and N.A. Scott. (2000). Estimates of New Zealand forest and scrub biomass from the 3PG model. Ecological Modelling. **131**: 175 -190.
Wilson, S. McG. (1998). The quantification of soil nitrogen regime in British Forests and its field assessment from vegetation and humus type. Ph.D thesis. University of Edinburgh Edinburgh.
Xenakis, G., D. Ray and M. Mencuccini (2008). Sensitivity and uncertainty analysis from a coupled 3-PG and soil organic matter decomposition model. Ecological Modelling. **219**: 1-16.
Xenakis, G. (2007). Assessment of carbon sequestration and timber production of Scots pine across Scotland using the process-based model 3-PGN. Ph.D Thesis. University of Edinburgh. Edinburgh. 307.
Zianis, D. and M. Mencuccini. (2004). On simplifying allometric analyses of forest biomass. Forest Ecology and Management. **187**: 311 - 332.

7. Appendices

Appendix I: Soil map classified by fertility



Appendix II: The observed and predicted AGB (tDM/ha) and models errors. error = (((observed-simulated)/observed value) *100).

Plot N0	**Age (Years)**	**AGB Observed tDM/ha**	**AGB predicted 3PGN tDM/ha**	**AGB Predicted 3PG tDM/ha**	**Observed - 3PGN Prediction**	**Observed - 3PG Prediction**	**3PG Model bias (%)**	**3PGN Model bias (%)**
3118	15.6	71.1	92.5	88.1	-21.4	-17.0	-23.9	-30.2
	19	89.7	154.9	134.8	-65.2	-45.1	-50.3	-72.6
	22	116.4	187.2	168.7	-70.8	-52.3	-44.9	-60.8
	28.2	176.9	247.9	235.8	-71.0	-58.9	-33.3	-40.1
3119	15.8	169.0	120.1	100.0	48.9	69.0	40.8	28.9
	19	181.0	154.9	134.8	26.1	46.2	25.5	14.4
	22	231.0	187.2	168.7	43.8	62.3	27.0	19.0
	28.2	325.0	247.9	235.8	77.1	89.2	27.4	23.7
3125	19.8	85.7	103.4	73.3	-17.7	12.4	14.5	-20.7
	22.9	108.9	132.4	90.3	-23.5	18.6	17.1	-21.6
	28	162.3	186.5	118.0	-24.2	44.3	27.3	-14.9
	37	230.8	256.4	167.7	-25.6	63.2	27.4	-11.1
3155	20.9	48.4	77.8	66.0	-29.4	-17.6	-36.4	-60.8
	26	72.6	106.7	91.2	-34.1	-18.6	-25.6	-47.0
	34.9	137.1	144.8	136.4	-7.7	0.7	0.5	-5.6
	40	152.2	164.2	161.7	-12.0	-9.5	-6.2	-7.9
3184	19.6	64.5	89.4	75.5	-24.8	-11.0	-17.1	-38.5
	25	108.4	145.9	104.3	-37.5	4.0	3.7	-34.6
	34	199.6	211.1	155.1	-11.5	44.4	22.3	-5.8
	38	232.3	232.7	177.8	-0.4	54.5	23.5	-0.2

Appendix III: Evaluation of models performance

AGB Observed tDM/ha	AGB predic. 3PGN tDM/ha	AGB Predic. 3PG tDM/ha	Observed - 3PGN Predict. tDM/ha	Observed - 3PG Pedic. tDM/ha	3PGN observed-predicted^2	3PG observed-predicted^2	3PGN Absolute difference Values	3PG Absolute difference values
71.1	92.5	88.1	-21.4	-17.0	459.38	288.74	21.43	16.99
89.7	154.9	134.8	-65.2	-45.1	4246.06	2033.45	65.16	45.09
116.4	187.2	168.7	-70.8	-52.3	5006.23	2730.69	70.75	52.26
176.9	247.9	235.8	-71.0	-58.9	5036.13	3470.01	70.97	58.91
169.0	120.1	100.0	48.9	69.0	2388.03	4759.85	48.87	68.99
181.0	154.9	134.8	26.1	46.2	682.58	2133.90	26.13	46.19
231.0	187.2	168.7	43.8	62.3	1920.31	3883.78	43.82	62.32
325.0	247.9	235.8	77.1	89.2	5949.09	7954.71	77.13	89.19
85.7	103.4	73.3	-17.7	12.4	313.50	153.29	17.71	12.38
108.9	132.4	90.3	-23.5	18.6	552.10	345.30	23.50	18.58
162.3	186.5	118.0	-24.2	44.3	586.32	1961.71	24.21	44.29
230.8	256.4	167.7	-25.6	63.2	655.17	3991.84	25.60	63.18
48.4	77.8	66.0	-29.4	-17.6	866.69	309.75	29.44	17.60
72.6	106.7	91.2	-34.1	-18.6	1162.88	346.03	34.10	18.60
137.1	144.8	136.4	-7.7	0.7	58.83	0.43	7.67	0.66
152.2	164.2	161.7	-12.0	-9.5	143.60	90.30	11.98	9.50
64.5	89.4	75.5	-24.8	-11.0	617.42	121.69	24.85	11.03
108.4	145.9	104.3	-37.5	4.0	1409.43	16.29	37.54	4.04
199.6	211.1	155.1	-11.5	44.4	132.32	1974.78	11.50	44.44
232.3	232.7	177.8	-0.4	54.5	0.14	2974.55	0.37	54.54
151.2					32186.19	39541.12		
		Sum ((P – O) /n))			1609.31	1977.06	672.73	738.79
							33.64	**36.94**
		N0 of years*Observations (n) =			20			
		RMSE =			**40.1162**	**44.464**	0.37	0.66
							77.13	89.19

3PGN predicts on average a value which differs by 33.6 tDM/ha from the observed value

3PG predicts on average a value which differs by 36.9 tDM/ha from the observed value

The range of biomass predicted by 3PGN is between 0.37 to 77.13 and for 3PG it is between 0.66 to 89.19

* = Predicted

Appendix IV: Climate data for the five plots used in the study

Plot_3118 & 3119

Month	Tmax	Tmin	Rain	Solar rad
Jan	5.8	0.9	154.4	2.2
Feb	6.3	1.2	140.1	4.5
March	7.4	1.2	78.1	8.1
April	9.6	3.0	73.2	11.6
May	12.8	6.1	75.5	75.5
June	15.1	8.2	97.7	15.8
July	15.8	9.9	97.1	14.8
Aug	16.1	9.7	78.0	12.5
Sep	14.2	8.0	109.6	8.7
Oct	10.7	5.5	118.0	5.1
Nov	7.9	2.8	89.7	2.7
Dec	6.2	1.4	146.6	1.6

Plot_3125

Month	Tmax	Tmin	Rain	Solar rad
Jan	5.5	0.7	150.5	2.0
Feb	6.1	0.6	137.1	4.2
March	6.5	1.0	145.3	7.3
April	9.4	2.8	96.2	11.5
May	11.6	5.6	95.0	14.3
June	13.9	7.7	97.1	14.6
July	15.6	9.4	97.4	14.1
Aug	15.3	9.1	102.1	11.8
Sep	13.4	6.9	137.4	8.2
Oct	9.8	4.9	149.0	4.8
Nov	70.2	2.2	167.4	2.5
Dec	5.9	1.3	142.7	1.5

Plot_3155

Month	Tmax	Tmin	Rain	Solar rad
Jan	5.7	0.7	133.9	2.3
Feb	6.2	0.6	121.9	4.5
March	7.5	1.1	101.7	7.9
April	9.7	2.9	95.0	11.4
May	12.7	5.8	93.9	14.5
June	15.1	8.4	91.5	15.8
July	16.5	9.8	85.4	15.3
Aug	16.4	9.5	85.2	13.1
Sep	14.3	7.8	90.6	9.4
Oct	11.0	5.1	103.2	5.5
Nov	7.9	2.8	117.1	2.8
Dec	6.1	1.3	131.1	1.7

Plot_3184

Month	Tmax	Tmin	Rain	Solar rad
Jan	6.0	0.9	50.1	2.1
Feb	6.7	0.7	52.3	4.5
March	7.8	1.2	48.4	8.0
April	10.1	3.1	56.7	12.0
May	12.8	5.8	61.9	15.1
June	14.9	8.5	65.4	16.2
July	16.3	9.9	65.7	15.1
Aug	16.1	9.6	64.3	12.7
Sep	14.0	7.9	59.4	9.1
Oct	11.1	5.2	56.4	5.2
Nov	8.1	3.0	55.0	2.5
Dec	6.3	1.5	53.4	1.5

Appendix V: Sitka spruce suitability map