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Modeling the effects of thinning on growth response of oak forests

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Contents

Acronyms

BA	Basal area ($m^2.ha^{-1}$)
BAF	Basal area factor
BDH	Diameter at breast height (cm)
CF	Coppice forests
CI	Confidence interval
CP	Clear cut and planting
$\overline{D_i}$	Mean difference between predictions and observations
f_{SMR}	Form factor
GE	Growth efficiency ($kgC.m^{-2}.yr^{-1}$)
GPP	Gross primary production ($kgC.m^{-2}.yr^{-1}$)
H	Tree height (m)
HF	High forests
LAI	Leaf area index
NPP	Net primary production ($kgC.m^{-2}.yr^{-1}$)
N_{rep}	Represented tree number
NUE	Nitrogen use efficiency (C/N)
$\overline{obs}$	Mean of the observations
PI	Prediction interval
RUE	Radiation use efficiency ($kg\ C.W^{-1}$)
SD	Standard deviation
SOM	Soil organic matter
T	Thinning
V	Volume ($m^3.\ ha^{-1}$)
WUE	Water use efficiency ($kgC.mm^{-1}$)

Abstract

The aim of this study was to evaluate the application of extended BIOME-BGC model to assess the thinning effects on coppiced oak forests in Austria. Furthermore, it also analyzed the growth response, i.e. growth efficiency (GE), nitrogen use efficiency (NUE), water use efficiency (WUE) and radiation use efficiency (RUE), of forests to thinning. The results were simulated for coppice and high forests, and then compared to know the response of forests after thinning. In this study, the adapted BIOME-BGC was used to simulate the oak forest ecosystem. It operates and simulates on a daily time basis to assess the cycling of energy, water, carbon and nutrients within oak forest in Hochleithenwald.

The forest field data of the year 2006 and the respective model runs were used to evaluate the models application. The strong positive relationship between the predicted and observed volume with no biased results verifies that the model can be used as a diagnostic tool to assess management effects.

Thinning has increased the GE, NUE and WUE, however it decreased the RUE. While comparing two practices, the coppice forests have higher average values in each parameter of growth responses than high forests after thinning. Although they have higher values, only the increase in NUE was found statistically significant (@ α= 5%) to the management regimes as the study was based on temporal development of stand. But at stand level, the effects of thinning show a significant difference in all growth parameters between the two management regimes. Even if the coppice forest shows better productivity at present, the higher variation in efficiency after thinning in coppice forests ensure that it has a higher risk of management than the high forests. As coppice forests, which have a comparatively higher amount of biomass removed, show the higher growth efficiency, it needs further study to focus on the effects of thinning in nutrient cycling.

Key words: Thinning, growth response, BIOME-BGC, coppice forests, high forests

Zusammenfassung

Das Ziel dieser Studie war es, die Anwendbarkeit des erweiterten BIOME-BGC Modells für die Abschätzung von Durchforstungseffekten in Eichenniederwäldern Österreichs zu evaluieren. Außerdem wird die Wachstumsreaktion der Bestände nach einer Durchforstung anhand von „Growth efficiency“ (GE), „Nitrogen use efficiency“ (NUE), „Water use efficiency“ (WUE) und „Nitrogen use efficiency“ (NUE) analysiert. Simulationen mit dem adaptierten BIOME-BGC Modell wurden für Niederwälder aber auch für Hochwälder durchgeführt, sowie deren Ergebnisse verglichen, um die jeweilige Reaktion auf Durchforstung zu analysieren. Das Modell simuliert auf Tagesbasis die Kreisläufe für Energie, Wasser, Kohlenstoff und Nährstoffen in terrestrischen Waldökosystemen.

Für die Analyse wurden Bestandesdaten aus dem Jahr 2006 und die jeweiligen Simulationsläufe verwendet. Ein starker positiver Zusammenhang zwischen den beobachteten und berechneten Volumina sowie kein erkennbarer Bias bestätigen, dass das Modell als diagnostisches Werkzeug zur Abschätzung von Bewirtschaftungseffekten eingesetzt werden kann.

Durchforstungen hat in beiden Bewirtschaftungsarten GE, NUE und WUE gesteigert, jedoch RUE gesenkt. Im Vergleich der beiden Bewirtschaftungen ergaben Niederwälder höhere Mittelwerte der betrachteten Parameter als Hochwälder. Obwohl der Niederwald höhere Effizienz nach einer Durchforstung aufwies, war nur die höhere NUE signifikant (bei α =5%). Auf Bestandesebene ergaben die Durchforstungseffekte signifikante Unterschiede zwischen den Bewirtschaftungsarten für alle Parameter. Obwohl der Niederwald gegenwärtig eine bessere Produktivität aufweist, deuten die Schwankungen der Effizienz nach einer Durchforstung in Niederwäldern darauf hin, dass diese einem höherem Risiko ausgesetzt sind als Hochwälder. Da Niederwälder mit ihrer vergleichsweise höheren Entnahme von Biomasse eine höhere Wuchsleistung aufweisen, sind weitere Untersuchungen, im Besonderen über die Auswirkung von Durchforstungen auf den Stickstoffkreislauf, notwendig.

Schlüsselwörter: Durchforstung, Wachstumsreaktion, BIOME-BGC, Niederwald, Hochwald

1 Introduction

1.1 Forest ecosystem and its management

A forest ecosystem is a dynamic complex of plant, animal and micro-organism communities and their abiotic environment interacting as a functional unit, where trees are a key component of the system. Humans, with their cultural, economic and environmental needs are an integral part of many forest ecosystems (FAO, 2003). It can also be defined as the assemblage of organisms together with their surrounding environmental substrate, interacting inside a defined boundary. It is a dynamic living system that changes regularly according to the surrounding environment. The temporal development of forests usually stand interpreted as a sequence of several developmental or succession stages (Peterken, 1996). Its development has been greatly influenced by biotic factors. The rapid changes on their structure and function have been experienced as a result of a growing pressure of human demands on natural resources (Kohyama, 1993). The component stands each have their unique developmental pattern determined by a set of conditions, and the most important one is the intervention done by man. Forest management tries to control the way the whole forest develops, both temporally and spatially, so that the pattern of stands over the whole forest is continuously suitable for the purposes of management. To maintain the functions and services of forest resources successfully, management must regulate the development of the stands in that forest. It tends to create the stands at the right stage of development and in sufficient number to yield the desired products and services, in both quantity and quality.

Currently, forest ecosystems receive growing attention due to their importance on mitigating environmental change along with fulfilling the needs of forest products (Tatarinov et al., 2006). Specifically, it provides a number of vital services i.e. timber production, protection of water resources, carbon sequestration, biodiversity, recreation and so on. The future capability of forest ecosystems to provide such services is determined by changes in socio-economic characteristics, forest management, atmospheric composition and climate. Forest management aims to optimize forest use for a given demand of society, while ensuring long-term sustainability of the resources by maintaining their productivity. As a result of global change, forest management has to adapt to new conditions, and has to account for ongoing changes in site conditions. The continuous discussion and actions to develop environmentally and socially desirable forest management practices have been employed to maintain the forest ecosystem's productivity.

Forest management is referred to the application of biological, physical, quantitative, social and policy principle to the regeneration, tending, utilization, and conservation of forest to meet specified goals (Sampson and Scholes, 2000). It changes according to the needs of society and time. For example, the management practices have been changed regularly in central Europe as a result of human interest. Central Europe has long history of forest management, and the dramatic changes taken place as the industrialization substantially increased the demand on forest products. In the past forest management was only responsible for litter raking, fuel wood extraction, and timber production at local level. This has been replaced by intensive forest management like tending, thinning and shelter wood cutting to ensure the sustainable timber production (Assmann, 1970). Forest management is concerned with regulating the structure of the forest as that is expressed in the proportion of the stands in the forest that are at each stage of development for each stand type. It does not only control the timing of availability for harvest, but also the location of the stands available for harvesting.

The main aim of management is to sustain the amount of harvest through controlling the stand structure but the selection of management strategies depend upon tree species in the forest and management objectives as well as those of the owners. Sustaining products and services is very much concerned to the maintenance of productivity of forest resources, and now a day's management focuses on optimal extraction of forest resources.

1.2 Oak forest in Austria

With 47.2% of Austria's area being forest, it is among the most densely forested countries of Europe (BFW, 2004). According to the Austrian Forest Inventory 2000/02 the forest area has been increased by 270,000 hectares since its first inventory period in 1961/1970. Regarding tree species and mixture, a tendency towards mixed stands with higher share of broad leaved trees and a simultaneous decline of pure spruce stands can be observed independently of the ownership structure.

In Austria, oak stands i.e. high forests and coppiced with standards covers about 4% of the total forest area, and such oak-rich mixed forests are commonly associated with beech and hornbeam (Hochbichler, 1993). Half the area of oak stands is managed by coppice, or coppice with standards, and the rest is managed by high forest. Here in Austria, the oak stands are predominant in both large and small private forests. Furthermore, due to economic changes and increasing respect for the ecological interrelations, the management of oak forest in Austria in federal and private forests has been increasing. It emphasized the management systems like increasing planting of oak stands, a more intensive tending and fostering of oaks in the oak-rich high forests and coppice with standards, and an increasing change from coppice systems and/or coppice with standards into over-wood rich coppice with standard (high forest system). The reason behind applying such management intervention is to use the existing capacity of the sites more efficiently and to make more stable oak forest stands. The objective oriented treatment of oak stands, considering the growth potential of the site in the high forests as well as in the coppice with standards forests, has been emphasized to presents the opportunity for forest owners (Hochbichler, 1993).

1.2.1 Coppice with standard

Coppicing is a traditional woodland management system where the new forest was regenerated from cut stump or ‘stool’. Such systems are still continued to manage broad leaved trees in Europe. The coppice system was applied to produce small timber as compared to the forest developed from seedling. Once the forest was established from seeding or planting, it was used to make two to three coppices according to its performance on productivity and the management objective of the forest owners. When the stand get certain age, the forest were cut to produce the new shoots or stools, which finally developed as new forest. There are different kinds of coppice forests, simple coppice to coppice with standards. Here, coppice with standards means certain parts of the forest were left to produce large timber, and rest were periodically cut to produce small size timber. Moreover, the forests were also considered to provide ecological benefits and services. In this situation, the same forest land was served with two rotations, one for standards and the other one for coppice. The rotation of standards should be the multiple of the rotation of coppice.

1.2.2 High forest

High forest can be defined as the forest which is either developed by naturally or by planting/seeding. Unlike the coppice with standard such forest has only one rotation age. The forests are clear cut on its rotation age and the new forest will be developed either by new planting or by naturally. Such forests are generally managed for the production of large size timber along with other ecological benefits and services. The plantation forests could be the nice example

1.2.3 Thinning

Thinning is an important part of practical strategies for increasing the economic outcome of forestry. Thinning does not increase production (Assmann 1970), but shifts the distribution of growth to qualitative and valuable trees. The study of thinning effects on Norway spruce shows that the thinning usually leads to a periodic decrease in volume increment (Braastad and Tveite, 1999, 2001; Slodicak et al., 2005). The intensity of thinning is commonly assessed by the proportion of basal area removed. The remaining basal area of the stand density is used as a measure to predict the growth response after thinning. Light thinning could be a treatment option to increase C storage in forest standing biomass, with little or no economic drawback. Increased density can also increase litter fall (Slodicak et al., 2005). A decrease in soil respiration with increasing stand density could be expected, since soil temperatures often decrease with increasing density. A build up of soil C is therefore expected if reduced thinning activity is chosen, due to both increased litter fall and reduced soil respiration. On the other hand, the disappearance of ground vegetation due to high densities could reduce this effect (Nilsen and Strand, 2008).

The study of thinning the volume increment shows that the volume per unit area does not decrease proportionally with the decreasing basal area. The volume increment immediately after thinning is lower than the un-thinned situation, but converges to the level of un-thinned stand when the diameter of the trees increases. The relationship strongly depends on tree species, site quality, time and intensity of thinning (Hasenauer et al., 1997).

1.2.4 Growth response to thinning

Evaluating the management effects on an ecosystem processes is difficult if the management appears to be a minor component of the system’s total biomass. But if the comparison is made with a different management regime within the same environmental and external conditions, the difference on the growth will show the effect of selected management application. In this study the thinning intervention for each management system i.e. coppice with standards and high forest system, has been applied to the same forest stand. In this situation, the growth response in terms of growth efficiency (GE), nitrogen use efficiency (NUE), water use efficiency (WUE) and radiation use efficiency (RUE) of oak forests managed under the selected systems were analysed to find the effects of thinning on forest growth.

1.2.4.1 *Growth efficiency (GE)*

The Growth efficiency (GE) of a tree is the relationship between growth and occupied resources, and can generally be expressed as stem volume increment per unit leaf area for the individual tree (Waring, 1983). At stand level, it is defined as the ratio of the net primary production (NPP) versus the leaf area index (LAI), and symbolically represented as,

$$GE = \frac{NPP}{LAI} \text{ ……………… ………. (3),}$$

Where, GE is growth efficiency ($kgC.m^{-2}.yr^{-1}$)

NPP is net primary production ($kgC.m^{-2}.yr^{-1}$)

LAI is leaf area index (dimensionless)

1.2.4.2 ***Nitrogen use efficiency (NUE)***

The nitrogen use efficiency (NUE) measures the amount of biomass produced per unit of N taken up from the soil, where the NPP and N_{uptake} are measured in units of dry matter production or it measures the amount of biomass produced per unit of N taken up from the soil per square meter of land surface per unit of time (i.e. g of DM $M^{-2}.yr^{-1}$ or g of N $M^{-2}.yr^{-1}$). In detail, the NUE can be described by two processes i.e. N productivity and mean residence time of N in biomass in years (Finzi et al., 2007).

$$NUE = \frac{NPP}{N_{content}} * \frac{N_{content}}{N_{uptake}} \text{ , ……………… (4)}$$

$$= \frac{NPP}{N_{Uptake}}$$

Where, NUE is nitrogen use efficiency (C/N)

NPP/$N_{content}$ is the $N_{productivity}$, and

$N_{content}/N_{uptake}$ is known as mean residence time of biomass in years.

NPP is net primary production ($kgC.m^{-2}.yr^{-1}$)

N_{uptake} is the nitrogen taken by plants ($kgN.m^{-2}.yr^{-1}$)

1.2.4.3 ***Water use efficiency (WUE)***

The water use efficiency is defined as the ratio of CO_2 assimilation into the photosynthetic biochemistry to water lost, via transpiration through the stomata (Dolman et al., 2003). It generally depends on the environmental and management condition of the forest.

$$WUE = \frac{NPP}{Transpiration} \text{ ……………………… (5)}$$

Where, WUE is water use efficiency ($kgC.mm^{-1}$)

NPP is net primary production ($kgC.m^{-2}.yr^{-1}$)

Transpiration is the water lost ($kgH_2O.m^{-2}.yr^{-1}$)

1.2.4.4 ***Radiation use efficiency (RUE)***

The radiation use efficiency represents the integration of every photosynthetic and respiratory process (Medlyn, 1998) and is a simple yet robust variable describing growth (Sinclair and Muchow 1999). Radiation use efficiency may be affected by site conditions (e.g. fertility, climate, water availability) and by cultural practices like thinning and harvesting. F. J. Muell noticed that thinning increased RUE in Eucalyptus regnans, where he mentioned that it attributed to the extra below-ground resources and irradiance made available by thinning (West and Osler, 1995).

$$RUE = \frac{NPP}{Absorbed\_radiation} \qquad \text{..........................} \; (6)$$

Where, RUE is water use efficiency (kg $C.W^{-1}$)

NPP is net primary production ($kgC.m^{-2}.yr^{-1}$)

Absorb radiation is canopy absorbed shortwave flux ($W.m^{-2}$)

1.2.4.5 ***Net primary production (NPP) and Gross primary production (GPP)***

Net primary productivity (NPP) is a key ecosystem variable that describes the dynamics of forest ecosystems. It explains the process by dealing with carbon pools in the ecosystem. It plays a key role in our understanding of carbon exchange between biota and the atmosphere, both currently and under climate change conditions (Woodward*et al.*, 1995; Melillo *et al.*, 1996). GPP represents the total gain of C to the system by net photosynthesis and is defined as the daily sum of gross photosynthesis and daily foliar respiration. GPP was calculated based on absorbed photosynthetically active radiation, atmospheric CO_2 concentration, air temperature, vapour pressure deficit, precipitation, atmospheric N deposition, LAI, and available N content in the soil. NPP represents the net accumulation of C by the stand and is determined as the difference between GPP and the sum of the maintenance (Rm) and growth (Rg) respiration components.

The practical importance of NPP is in its utility as a measure of crop yield and forest production (Milner *et al.*, 1996), as well as other economically and socially significant products of vegetation growth. NPP gives the mass of carbon that is added to the system by square meter ground per year ($kg.c.m^{-2}.yr^{-1}$). The ecosystem carbon storage results of the carbon balance between NPP and heterotrophic respiration, which is regulated by the microbial activity for decomposition, the seasonal input of vegetation biomass and soil organic matter pools and the annual mortality rate of the corresponding tree species (Pietsch and Hasenauer, 2006).

1.2.4.6 *Leaf area index (LAI)*

The properties of ecosystems are sensitive to alterations in the availability of resources. Among these, the Leaf area index is identified as the most general structural variable. LAI is the ratio of total upper leaf surface of vegetation divided by the surface area of the land on which the vegetation grows. It has a value, typically ranging from 0 for bare ground to 6 for a dense forest. The increment of LAI differs on the developmental stages of the stands. It increases rapidly in the early stages of stand development and remains relatively stable for some time, particularly when the tree species fill in gaps that develop in the over storey canopy (Waring and Running, 1998). The LAI is used to predict the photosynthetical primary production and is also used as a reference tool for crop growth. In the Biome-BGC model, the LAI is obtained by multiplying carbon allocated to the leaves with the specific leaf area (m^2 leaf per kg leaf carbon) of the particular species (Pietsch and Hasenauer, 2002).

1.3 Modeling

The modelling of forest growth and yield has a long history, therefore yield tables were constructed to address the past issues. The further development in technology and recent advancement on physiological and ecological researches initiated the current complex models. On these days, a model is able to account for species composition, inner stand structure, physiological processes and also the management intervention as well predicting future yields. Finally, it helps to develop a suitable forest management plan by explaining natural dynamics and the ongoing process in forest ecosystems. The estimation of stocks and fluxes of carbon, water and energy between terrestrial ecosystems and the atmosphere is important. Several studies use ecosystem models to assess the potential impacts of climate change and changes in land use or management practices (Pietsch, 2006). Typical models are ORCHIDEE, LPJ, MC1, BIOME-BGC, IBIS or SDGVM, where state and flux variable changes are modelled explicitly (cited in Pietsch, 2006). On the basis of underlying process in the model, its input and out put varies. There are three major groups: namely empirical (management), successional (gap) and mechanistic (biogeochemical) models (Hasenauer et al. 2000). As this study is intended to explore the effects of thinning on the growth of oak forest in Austria, the Bio-geochemical model was considered. It captures effects of a number of abiotic (temperature, vapor pressure deficit, soil water, solar radiation, and CO_2 concentration) and biotic (leaf area index, leaf, and root N contents) controls on production.

1.4 Objectives of the study

In general, the aim of the study is to model the effects of thinning on the growth response of oak forests. Specifically it can be elaborated as;

- Assessing the model output by comparing the predicted versus observed volume in coppiced oak forests measured in the year 2006.
- Assessing and comparing the growth efficiency, the nitrogen use efficiency, the water use efficiency and the radiation use efficiency of coppice and high forests.

1.5 Hypothesis

- There is no significant difference between the predicted and the observed volume of coppiced oak forest.
- There is no significant difference between the growth efficiency, the nitrogen use efficiency, the water use efficiency and the radiation use efficiency of coppice and high forests.

2 Methods

2.1 The BGC-Model

The study was based on the Biome-BGC Version 4.1.1 model (Thornton et al., 2002), which is used to assess the forest ecosystem dynamics. The integration of the main physical, biogeochemical and physiological processes based on our current understanding of key ecophysiological mechanisms is the basic concept of this model. It gives the mechanistic description of the interactions between the living plants and their surrounding environment (Waring and Running, 1998). Models, which operate and simulate on a daily time basis, are explicitly designed to assess the cycling of energy, water, carbon and nutrients within a given ecosystem.

In this study, the BIOME-BGC 4.1.1 was adapted by incorporating extensions on hydrology (Pietsch et al., 2003), species specific parameterisation (Pietsch et al., 2005) and self initialization (Pietsch and Hasenauer, 2006) to simulate the forest ecosystems in Austria. The ecosystem is defined on the basis of the following variables which describe the cycling of energy, water, carbon and nitrogen in a daily time resolution.

- Daily canopy interception, evaporation and transpiration
- Soil evaporation, outflow, water potential and water content
- Leaf area index (LAI)
- Stomatal conductance and assimilation of sun lit and shaded canopy fractions
- Gross primary production (GPP) and net primary production (NPP)
- Allocation of carbon and nitrogen to the different ecosystem compartments (soil, litter, roots, stem leaves)
- Litter-fall and decomposition
- Mineralisation, denitrification, leaching and volatile nitrogen losses

2.1.1 Input data

The climate data, the site descriptive parameters and the ecophysiological characteristics are the essential input for the model. The fundamental environmental driving forces for the ecological processes in the model are daily meteorological data: air minimum and maximum temperature, daily total precipitation, humidity defined as daytime average vapour pressure deficit, daytime average incident solar radiation and day length, and site descriptive characteristics: geographic coordinates, elevation, soil depth, soil texture determined as the properties of sand, silt and clay, atmospheric nitrogen deposition and CO_2 concentration. Furthermore, the prescribed ecophysiological characteristics describing the vegetation at a particular site are also needed as the input data for the model. The given parameters are held constant through out the simulation. The starting values of carbon, nitrogen and water in the ecosystem at the beginning of the simulation process are needed for the self-initialisation procedure. If available, the required parameters are used from direct measurements in the field for the applications at a particular site. Otherwise, the parameters are estimated on the basis of reviewed literatures (White et al. 2000).

2.1.1.1 ***Meteorological and climatic data***

The meteorological input parameters comprise daily air minimum and maximum temperature, incident short wave solar radiation, vapour pressure deficit and precipitation and day length are not always available directly for the whole area of study. The climatic data is to be interpolated to each required plot from the possible surrounding weather stations. Climate data was provided by the Austrian National Weather Centres. The point version of DAYMET (Petritsch, 2002) validated for Austria (Hasenauer et al., 2003) was applied. The program needs the geographic position, the elevation, slope, aspect and the angle to the horizon in the West and in the East to calculate the climate for a location.

Recently, the daily weather records for the 46 years (1960 – 2005) were available. The 46 years series of daily climate data was used repeatedly throughout the whole simulation process, beginning with the self-initialisation up to present day simulations. The beginning of climate data has to be reset in such a way that it can ensure the climate record measured for the specific years were used while processing the simulation.

The CO_2 content in the air in the preindustrial CO_2 concentration of 280ppm (IPCC WG I, 1996) was used in the model for the spin-up. When the industrialisation activities started, the CO_2 concentration has been increasing annually since 1765 to the present levels.

In case of atmospheric nitrogen deposition, a preindustrial level of 0.0001 kg m^{-2} yr^{-1} was assumed (Ulirch and Williot, 1993, Cited in Pietsch, et al., 2002) and has been increasing at the same rate as the CO_2 concentration to an actual value of 0.00172 kg m^{-2} yr^{-1} with reference to the year 1995.

2.1.1.2 *Site descriptive parameters*

The site descriptive parameters are also the essential input for the model. They are the geographic latitude, elevation, albedo, soil texture (given as the relative share of sand, silt and clay), effective soil depth (depth of soil with water storing capacity, calculated as real soil depth reduced by the volume percentage of soil particles bigger than 2 mm) and the nitrogen fixation ($kgNm^{-2}yr^{-1}$). The nitrogen fixation value was chosen as 0.0008 $kgNm^{-2}$ yr^{-1}. The value of albedo differs with the land cover type. So, the assigned value should be compatible with the presence of vegetation. Here, as the study was conducted in the oak forest the value for albedo was assigned to 0.2. For this study, the soil texture having 20% sand, 55% silt and 25% clay. The effective soil depth of 1m was considered.

2.1.1.3 *Eco-physiological parameters - Species specific parameterization*

Other characteristics of input data needed for the model are eco-physiological characteristics of the dominant vegetation type of the studied area. The species specific parameterisation already developed for the major tree species in Central-Europe (Pietsch et al., 2005) was applied to this study. The parameterization reduced maximum stomatal conductance from suggested values for all forest biomes, and also the boundaries for conductance reduction due to leaf water potential, the vapour pressure deficit. Allocation ratios to leaves, to fine roots and to living and dead fractions of the stem and coarse root were changed for the oak species. Fractions of lignin, cellulose and labile material in litter, fine roots and deadwood were also changed. Among the canopy parameters the water and light extinction coefficients, the average specific leaf area, the ratios of all sided to projected LAI and the fraction of leaf nitrogen in ribulose-1,5- bisphosphate carboxylase/oxygenase (RubisCO), to determine the amount of this key carbon fixing enzyme were also parameterised.

Another improvement of the model is the correction of the self-initialization procedure by proposing a dynamic biomass mortality routine (Pietsch and Hasenauer, 2006). It avoids the overestimation in the soil, litter and above ground pools versus the commonly used constant mortality rates.

2.1.2 The Simulation

The simulation procedure is based on the available input information and the type of ecosystem which has to be modelled. Here, as the initial information about the forest ecosystem is not sufficient, the simulation with the particular stand has been done with a spin-up procedure. As the study was further interested in comparing the results of different forest management, the spin-up is followed by site history simulation and finally by the current stand simulation to develop the desired forest ecosystems.

2.1.2.1 *Spin-up*

The self-initialisation of the model or spin-up run has to be used to obtain the starting values for further simulation, if the initial information is missing. The spin-up starts without soil organic matter (SOM), a very small initial carbon amount in leaves (0.001 kg C m^{-2}) and 50% soil water saturation. Organic matter is accumulated during the ongoing simulation. When the simulation reaches a dynamic equilibrium (i.e. the difference in SOM between two successive climate periods does not exceed the value 0.0005 $kgCm^{-2}Y^{-1}$) of all ecosystem pools, the spin-up process will be stopped. The achieved equilibrium is dynamic with large inter-annual variability caused by variation in weather condition. So, for the simulations, the available climate records, from the year 1960 to 2005, were used. The records are repeated as necessary to create weather records for the model runs for a longer period. At the end of a simulation process the initial values of the following necessary variables are produced:

- Water stored in soil, snowpack and crown
- Carbon and nitrogen amount in particular plant organs (leaf, stem, coarse and fine roots), in coarse woody debris, in four litter pools, in four soil pools
- Amount of mineral nitrogen in soil
- Nitrogen amount for re-translocation
- Maximum amount of carbon in leaves, stem, fine and coarse roots during the year
- Number of days per year without precipitation

The time period this process needs varies between 3000 and 60000 years under different climatic conditions, at different sites and with different vegetation types (Pietsch and Hasenauer, 2006). The typical spin-up run lasts approximately 20000 years depending on the simulated vegetation types (Thornton et al., 2002). For this study the oak is found as the dominating tree species before and also after human intervention. Here, the self-initialisation took 5400 simulation years.

Moreover, a dynamic mortality model is applied for the self-initialisation, as the linear mortality (commonly set to 0.5%) can lead to an overestimation of the ecosystem carbon content by 400% (Pietsch and Hasenauer, 2006). The dynamic mortality setting (vary between 0.6 to 2% of vegetation biomass per year) was used to reach high carbon biomass values. Furthermore, the elliptic mortality length of 150 to 450 years was used.

2.1.2.2 ***Historic land use***

It is well understood that forest management and humans as well as natural disturbances have been affecting the ecosystem. Thus ignoring management site history within the model, simulation leads to systematic overestimations of the carbon amount in litter and soil when compared to the field observations (Pietsch and Hasenauer, 2002). The steady state of the self-initialisation procedure represents the situation without any human interference, and is considered as the starting point for simulating historic land use.

In central Europe, where the intensive forest management began in some areas approximately 600 years ago (Gude 1960, cited in Merganicova, 2004), an exact description of the site history is lacking. The degradation of forest soil due to forest management is caused by the loss of carbon and nutrition, and finally the reduction of site productivity (Pietsch and Hasenauer, 2002). Therefore, based on the available general information, it is suggested to simulate a certain number of successive rotations, assuming clear cutting and the replanting of the forest stand to account for management impact (Pietsch and Hasenauer 2002).

Apart from the direct human impacts, indirect human impacts to nature have been noticed for 250 years through industrialisation and have resulted in an increasing atmospheric CO_2 concentration and higher rates of nitrogen deposition. The designed model can mimic the temporal changes of atmospheric chemistry into account during the simulations, where the changes in CO_2 concentration follow IPCC scenario (IPCC WGI, 1996) and nitrogen deposition changes from the preindustrial levels to current levels at a particular site following the pattern same as of carbon (Thornton et al., 2002).

With a clear-cut all the above ground biomass is removed and the below ground biomass is transferred to the coarse woody debris compartment. Planting means that each plant adds 10 gram of carbon to the leaf pool and 25 gram to the stem pool. To mimic historic land use two complete rotations with 120 years and the current estimated age of stand were simulated, and it finally provides the current situations of forest ecosystems.

2.1.2.3 ***Current stand***

The current forest stands are the functions of the management practices applied and the amount of input information. As the initial information about oak forest is not available, the simulation of the current stands is done only after the first two procedures, i.e. spin-up and the site history for the managed forests. The assumptions of the fully stocks forest is being replaced to address the management issues in forestry. Recently a sub-model of BIOME-BGC has been developed to address the forest growth response to thinning (Petritsch et al., 2007).

The new routines were implemented to permit specification of thinning. Previously, the acceleration of growth following thinning was implicitly included, and now it was designed on the basis of the intensity of the biomass removal (Petritsch et al., 2007). The changing in distribution patterns of assimilates between above and below ground biomass and between wood and leaf biomass observed after a thinning intervention are addressed by a new dynamic carbon allocation regime. With this model the thinning procedure can be explicitly defined, i.e. it is possible to fix the exact amount/percentage of stem carbon removal, leaf carbon removal, stem carbon that is left in the forest and is transferred to the coarse woody debris carbon compartment, root carbon that also goes to the coarse woody debris carbon pool and leaf and fine root carbon that is added to the litter carbon pool.

As the study is conducted in an oak forest, a broad leaved leaf shading tree species, and the thinning is done after the growth seasons, it is assumed that while thinning the whole bole is removed but the leaves remain in the forest and are therefore added to the litter pool. Values are given as the percentage of the total pool size. The same percentage of fine roots as stem carbon removed will therefore be allocated to the litter pool, and bigger roots are assigned to the coarse woody debris carbon pool.

2.1.3 Model output

In BIOME-BGC, the ecosystem is represented by a number of carbon, water, and nitrogen pools, altogether comprising approximately 600 output variables. The output encompasses both state and flux variables. The choice of the output variable along with the time horizons to be written in the output file (day, month, and year) is possible. According to their relation with the pools and the information they have the output variables can be grouped as follows.

- Meteorological variables of site (e.g. daily maximum and minimum temperature, precipitation, vapour pressure deficit, daylight average shortwave flux density, photosynthetically active radiation, day length, daily average temperature)
- Water state and water flux variable in the ecosystem
- Carbon state and carbon fluxes variables in the ecosystem

- Nitrogen state and movement variables in the ecosystem
- Phenological control and daily phonological variables in the ecosystem
- Ecophysiological variables
- Photosynthesis (ratio of leaf nitrogen in rubisco enzyme for sunlit and shade leaves separately)
- Summary variables including NPP, GPP, respiration, amount of carbon fixed in the different vegetative compartments, litter, soil and the whole ecosystem

Among the above mentioned variables, the state variables like live stem and dead stem carbon, sum of transpiration were selected as the state variable for this study. Similarly, NPP, GPP, LAI, absorb solar radiation were selected as the flux variables.

2.2 Site descriptions

The study site located in Hochleithenwald is a flat land with geographic position of 48°23'59'' latitude and 16°34'0'' longitude. The study site lies in lower Austria, the north east direction from Vienna, Austria (Fig. 1 & 2). The lowest and highest elevation among the selected plots in Hochleithenwald was 233m and 283m above see level respectively.

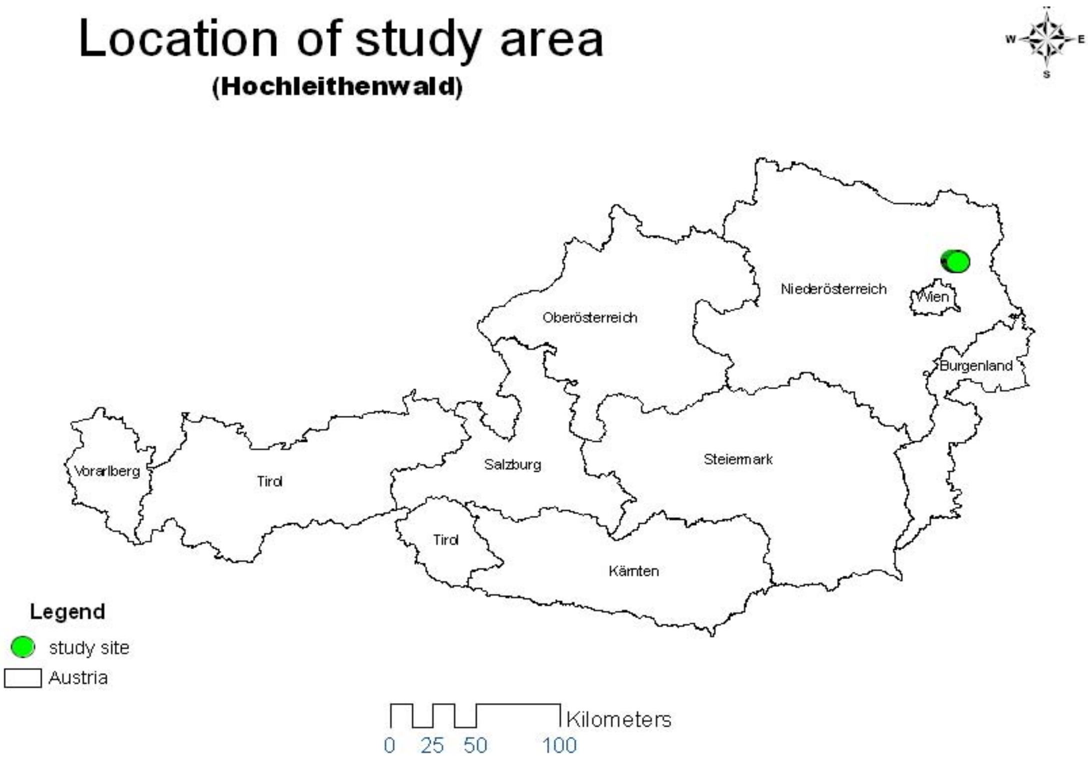

Figure 1: Location of study area in the map of Austria

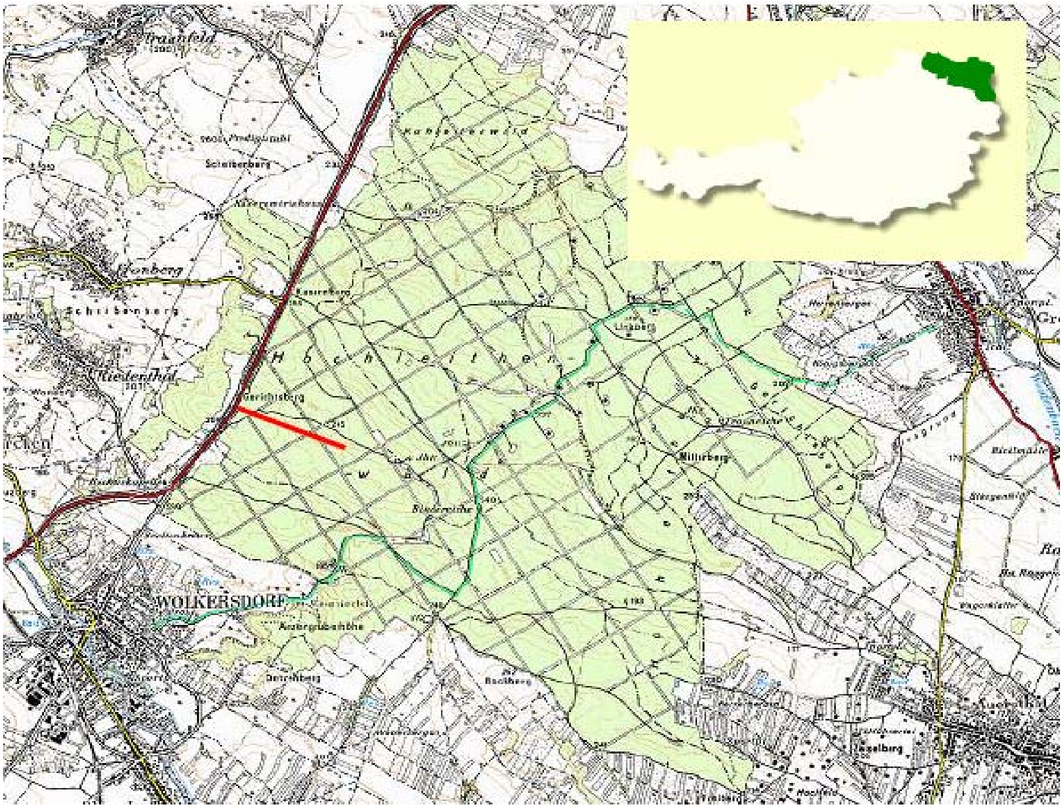

Figure 2: Map of Hochleithenwald (copied from Pietsch et al., 2007)

2.3 Data descriptions

Data used in this study come from different sources. One forest field work was conducted in the end of the year 2006 to collect forest related information. Climatic and secondary data were collected from the concerned organisations. On the basis of received site information and meteorological data the required climatic data were generated by using climate generator.

2.3.1 Forest related field data

The forest related data were collected by applying angle count sampling methods in the year 2006. Fifteen stands were randomly selected in the study area, Hochleithenwald. Three plots in each direction (i.e.15 m, 30m and 45 m far form the center point) within one stand were fixed as the point for angle count sampling. If points lies outside of the area nothing has been done on that point. In this design, one stand may have maximum 12 sampling plots. All together 151 plots were measured during field survey because some stand has less than 12 as the sampling plot falls outside the forest boundary. By using angle count sampling method, the diameter and mean height of tallied trees in the selected plots were measured. The missing heights of the trees were calculated by using the following formula. After getting the height of all trees, volume (V), basal area (BA) and number of trees (N_{rep}) per hectare were also calculated by using corresponding formulae described below.

Formula used in calculations

The 'a' factor was calculated using the known tree height and DBH. The remaining tree height was calculated using the following formula, which is based on the standard height curve formula.

$$\text{Intercept } a = 1/(\sqrt{h - 1.3}) + b / DBH$$

Height Calculated $\hat{H}_{shc} = 1/(a + b / DBH)^2 + 1.3$ (Here value of b is 1.23)

$$Volume(V) = BDH^2 * h * \mathrm{f}_{SMR}$$

BA/ha = BAF * No. of trees per species or (DBH + 0.5/100)2 * л/4

N_{rep}= BAF/BA

Form factor $(f_{SMR}) = b_1 + b_2 In^2 d + b_3 \frac{1}{h} + b_4 \frac{1}{d} + b_5 \frac{1}{d^2} + b_6 \frac{1}{dh} + b_7 \frac{1}{d^2 h}$

Where, BDH is diameter at breast height, and h is the height of tree. Both BDH and height are measured in decimeter. The values for constants are b_1 = 0.1156, b_2 = 0.0000, b_3 = 65.996, b_4 = 1.2032, b_5= -0.9304, b_6= -215.76, b_7 = 168.477, and BAF is 4.

2.3.2 Climate

In this study, the point version of DAYMET (Petritsch, 2002) validated for Austria (Hasenauer et al., 2003) was applied to generate the detail climatic information. For the site descriptions 9 sites were randomly chosen. The information on elevation, aspect, slope and soil information were collected for the selected 9 sites. Then 135 model runs (each stand treated with all sites) were conducted to generate climatic data. On the basis of the available geographic position, the elevation, the slope, the aspect and the angle to the horizon in the West and in the East of the 15 stands, the details of necessary data were received (Annex 1). The summary of the meteorological data has been presented in Table 1. The majority of the precipitation falls in the summer half-year. However, the increased precipitation is compensated in the warm seasons by higher evapotranspiration rates. Spring and autumn are shaped by rain poverty (Schöfberger, 2006). The winters are cold and snow-poor. The summers could be very hot. Further the area has constant wind influence.

Table 1: Meteorological data (averages of maximum and minimum temperature, vapour pressure deficit, solar radiation of study area) calculated by using DAYMET climate model for the year 1960-2005

	Daily Tmax (°C)	Daily Tmin (°C)	Tday (°C)	Annual precipitation ($mm.yr^{-1}$)	Vapor pressure density (Pa)	Solar radiation ($W.m^{-2}$)	Average day length (hours)
Average	12.96	4.71	10.69	536.82	545.88	232.85	11.20
Minimum	-15.09	-23.02	-17.08	343.28	16.78	18.76	7.56
Maximum	35.01	21.16	30.36	745.89	2376.24	487.63	14.84
std. dev.	9.04	6.85	8.32	81.97	416.19	117.05	2.51
Mode	18.09	4.61	16.79	352.84	160.65	174.57	14.84

2.3.3 Geology

The Hochleithenwald is situated in the river basin of Danube, Thaya and March. The basin was developed in Miocene period (20 million years ago) and it is still active. The basement of basin is composed of sand stone (greywacke), flysch, limestone and crystalline. The basin is filled with fluvial sediments of ancient Danube developed in the periglacial region through the action of erosion, discharge, relocation and deposits of soil. Wind blown and deposited the loess to the hochleithenwald basin, and ranges between decimetre to few meters. Loess is carbonated, yellowish coloured and exhibits very high silt contents of 65-80%, clay 10-25% and sand 10 -15 % (Schffer 2002. cited in Pietsch et al, 2007).

2.3.4 Soil

The raw material for the soil development in the Hochleithenwald was formed from loess, rocks found in basin, eroded particles brought by ancient Danube and primitive soil particles. As the raw materials were from different sources, the area has diverse soil types. The dominating soil types are AC type, brown and parabrown soil, relict of brown loam of former soil and so on. The depth of humus layer horizon varies between 20-30 cm and 150-200 cm (Ulrich, 1987. cited in Pietsch et al, 2007). The soil is found loamy clay to clay loam soil types, with sand portions between 42-55%, Silt 19-23% and clay portions 21-41%. For general overview on soil see Figure 3.

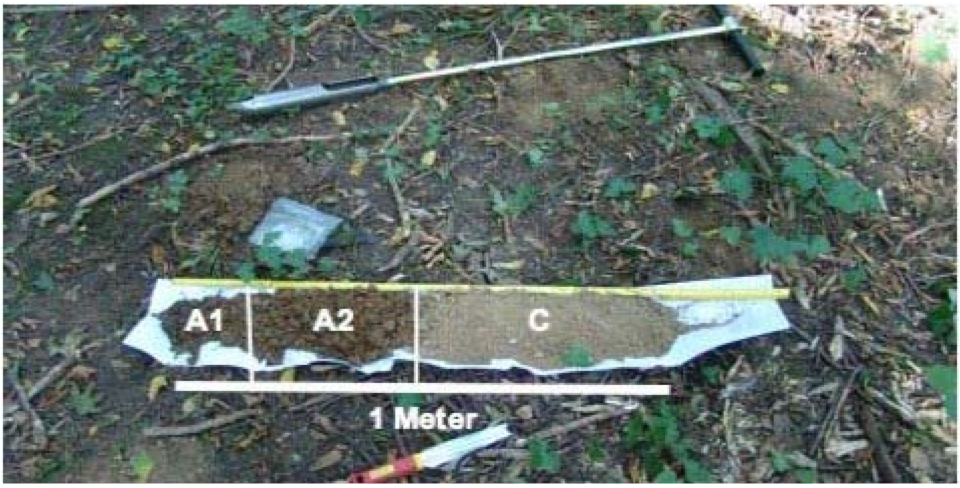

Figure 3: Typical soil of the Hochleithenwald (Photo: S. Pietsch)

2.3.5 Vegetations

2.3.5.1 Age class distribution

The aerial view of forests show that the forest is composed of large size trees as shown in figure 4. The field data of the year 2006 revealed that forest stand is composed different plots having trees with different age. In general, the middle ages trees dominated the study site. The frequency plotted by age class shows that the frequency was highest for the stand with age 30-40 years, followed by 100-110, and then 40-50 and so on. The frequencies for the younger plots were comparatively low (Fig. 5).

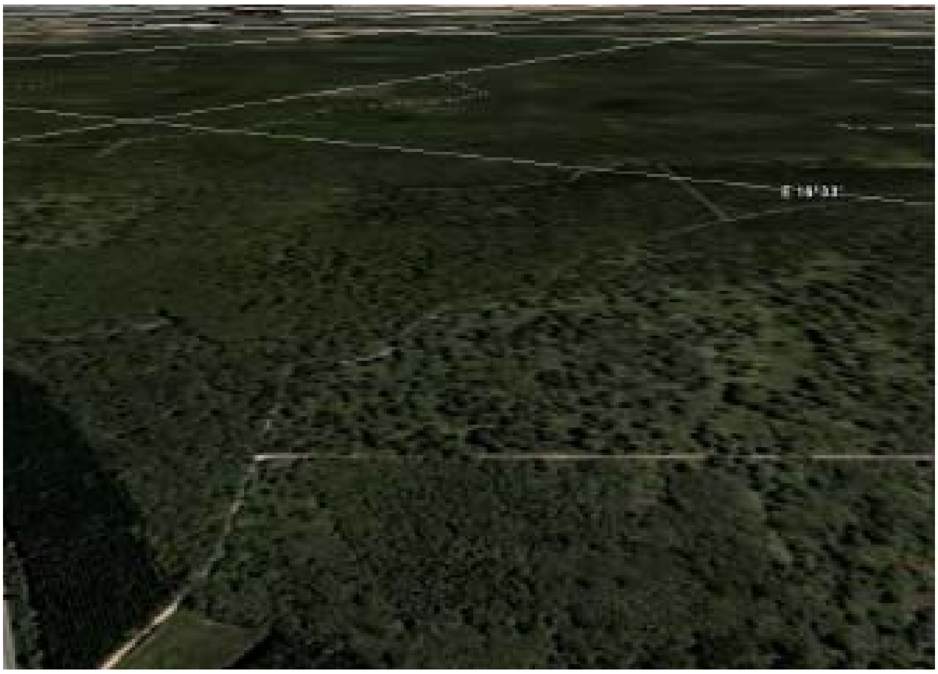

Figure 4: General overview of forest in Hochleithenwald

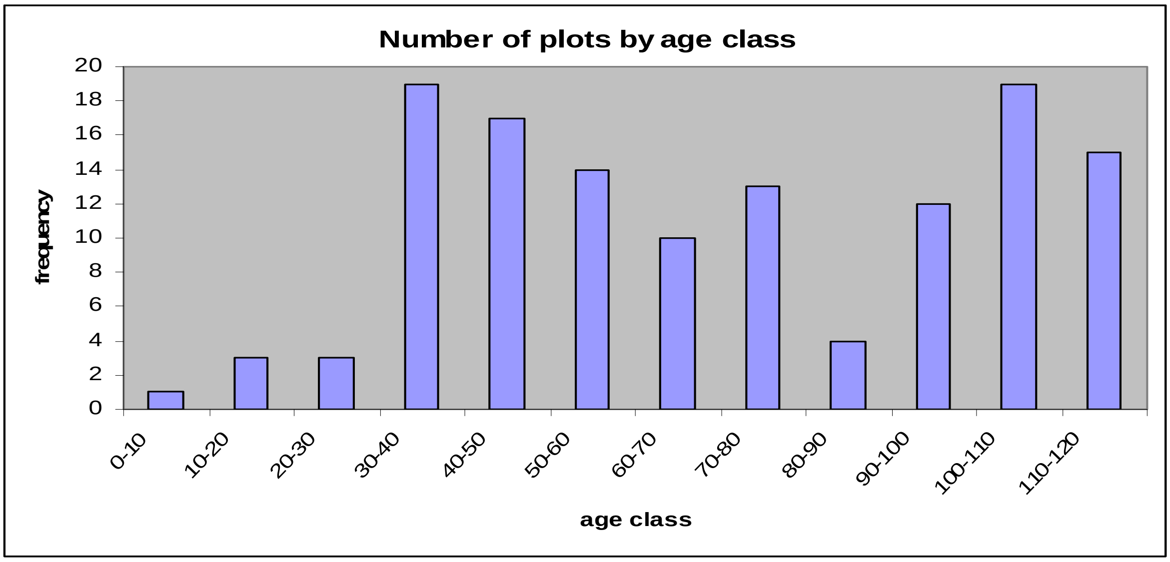

Figure 5: Number of plots by age class in the study area in year 2006

2.3.5.2 Growing stock

The overall average for the predicted and observed volume per hectare of the forest was 136.90 $m^3.ha^{-1}$ (maximum 222.24 and minimum 10.71$m^3.ha^{-1}$) and 137.96 $m^3.ha^{-1}$ (maximum 293.93 and minimum 9.36 $m^3.ha^{-1}$). The large variation between minimum and maximum value within predicted and observed volume per hectare was noticed due to significant variation in stand age, i.e. from 10 to 120 years. The mean volume with different stand ages was found as shown in Figure 6.

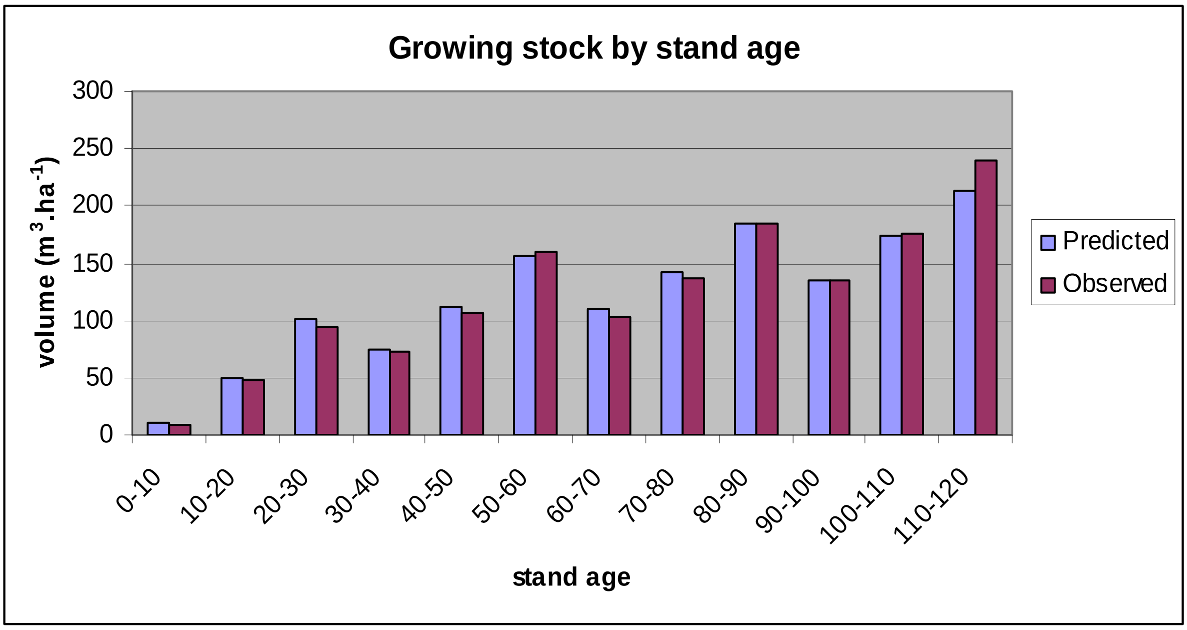

Figure 6: Growing stock by stand age in year 2006

2.4 Ecosystem simulations

The general simulation process of the BIOME-BGC model has already been described in the chapter 2.1.2. In this section, the specific description of the simulation steps applied to simulate the forest ecosystem under the assumed forest management of Hochleithenwald is presented. A different intervention has been applied to simulate forest ecosystems under the coppice with standards and high forest system for the locations used in this study.

As described in chapter 2.1.2.1, the spin up run was used to obtain the starting values of the missing information to carry out further simulation. For this study, the SOM starts with 0.001 kg C M^{-2} and 50 % soil water saturation. The system was first brought to steady state with the preindustrial carbon dioxide concentration (280 ppm, as described by WGI 1996) and nitrogen deposition level (0.0001 $kgN.m^{-2}.year^{-1}$ Holland et al., 1999). As the study was planned to assess the growth responses of forest to forest management in two management regimes, coppice with standards and high forest system, the simulations were performed at each management practices. The accelerated simulation reaches the dynamic equilibrium of all ecosystems within 5400 years. The available climate records for 46 years, from 1960-2005, were used to generate the weather record for the corresponding year and used the same year's record to receive the required climatic parameters. The records are repeated when necessary to create weather records. The dynamic mortality setting was used on this study. The development stage of the stand was determined on the basis of information received on the inventory work done in the year 2006. The individual plots were assigned a particular development stage.

The development stage was estimated by comparing the inventoried data with the corresponding data in the yield table. The basis in estimating the development stage was the volume per hectare of the stand. The volume of the inventoried trees in the year 2006 was calculated by using following formula as mentioned in section 2.3.1.

The calculated volume is compared to the volume in the yield table to find the development stages of each plot. As the study is focused on two different management systems, the development stage of the current stand differ one another. Here, it was assumed that the management intervention only differs in the current stand, and the rotation age of a high forest oak tree and the standards of oak are the same as 120 years. So, the planting year for the coppice with standards and the high forest system were considered the same. But the rotation age for coppice was only 30 years. That is why while managing the forest with the system coppice with standard 3 coppices were produced in one full rotation of the standards, and final cutting of the products of 3rd coppices and standard were done in the same year. Then the planting of new trees on the clear cut areas were conducted.

For the simulations of the current stand the species specific model for oak tree parameterized in Austria was used. Along with the above mentioned information, the following intervention scenario (Table 2) was developed to simulate the forest ecosystem within each management system.

Table 2: Developed intervention scenario

Type	Stand before 3 rotations & more	Stand before 2 rotations	Stand before 1 rotation	Age of current stand						
				0	30	50	60	80	90	120
CF	**No intervention**	CP	CP	CP	T	-	T	-	T	CP
HF	**No intervention**	CP	CP	CP	-	T	-	T	-	CP

Note: CP is clear cut & planting, and T is thinning.

2.5 Assumptions

- Rotation age of trees in high forests was 120 years
- Rotation age of standards and coppice was 120 and 30 years respectively
- Fixed mortality has been assumed
- Added carbon to stand while clear cut and planting was assumed 0.01 $kgC.m^{-2}$ per plant
- Three thinning interventions, when the stand was 30, 60 and 90 years old, were applied in coppice with standards. Such interventions were based on the literature to mimic the current practice of this system in Austria. The amount of carbon remaining in the forest after thinning was 1.6, 3.0 and 3.9 $kgC.m^{-2}.yr^{-1}$ on the successive thinning, 1st, 2nd and 3rd respectively
- Also, two thinning intervention, when the stand was 50 and 80 years old, was applied in high forest system. Such an intervention was also based on the literature to mimic the current practice of this system in Austria. The removal amount of biomass in thinning was 30 and 35% of the growing stock on the first and second thinning respectively

2.6 Statistics

The comparison between the mean volume of the BIOME-BGC model and the observed one, as well as the comparison between the mean of growth efficiency, nitrogen use efficiency, water use efficiency and radiation use efficiency of high forest and coppice forest systems, were subjected to pair-wise t test using SPSS 15. Also the box plot, trend line and scatter plot were used to study the correlation and regression analysis for the concerned variables. Furthermore, the descriptive statistics were used to describe the forest ecosystem properties of the study area.

3 Results

The information received from the forest field data in the year 2006 and the respective model runs were available to assess the applicability of the model and to describe the effects of management on the growth efficiency (GE), water use efficiency (WUE), nitrogen use efficiency (NUE) and radiation use efficiency (RUE) of oak forest managed under different systems i.e. coppice with standard and high forest. The main goal of this chapter is to examine if the model reactions of different management system scenarios correspond with the responses observed in the field and thus, to document that the biogeochemical models can be used as efficient diagnostic tools in the management studies to assess the complex issue of ecosystem sustainability encompassing a balance between plant community, air and soil.

3.1 Model's predictability and applicability

3.1.1 Coppice forest system

In this study, the observed volume and model prediction for the year 2006 was used to ensure no bias or systematic shift in the relationship between the modelled and observed results. As the parameter volume per hectare is not provided directly by the BGC-model, the carbon content in different compartments of the trees was used. The carbon parameter was converted to stand volume units i.e. to cubic meter per hectare, which is directly comparable with the observations. The model's outputs providing the information on live- and dead-stem-carbon were used. The carbon in the above ground woody biomass (live and dead stem C) was divided by the carbon fraction of woody dry mass to obtain the dry mass, and then it further divided by the dry matter fraction of the fresh weight in order to find the fresh weight. A division by the timber density gives the whole volume of above ground woody biomass. According to Pietsch et al., 2005, since only the merchantable timber volume is measured with common forest inventory techniques, e.g. angle count sampling in our case, the above ground woody biomass needs to be multiplied with the merchantable timber fraction to receive the timber volume. The value used in this study is given in Table 3. This step-wise transformation of above ground woody biomass carbon to the merchantable timber volume can be summarized by a specific conversion factor. In this study, the conversion factor 30.3148 is used to convert the carbon content per hectare to the volume (m^3) per hectare of oak forest in Austria (Hochbichler, 1993, cited in Pietsch et al. 2005).

Table 3: The parameter used to convert stem carbon (kgCm^{-2}) into the volume (m^3.ha^{-1})

Species	Merchantable timber fraction	Dry matter carbon fraction	Fresh weight dry matter fraction	Timber density (kg.m^{-3})
Q. robur/petraea *(Austria)*	0.760	0.504	0.500	1000

Note: Values for Q. robur/petraea from Hochbichler 1993 (cited in Pietsch et al. 2005)

If we compared the volume predicted by the model with the observed one in the year 2006, it would show that the model underestimated the growing stock by one percent. The correlation analysis shows the strong positive relationship between the predicted and observed values (Fig. 7). Figure 8 shows the standardized volume residual versus stand age, height, diameter at breast height (BDH) and the predicted volume.

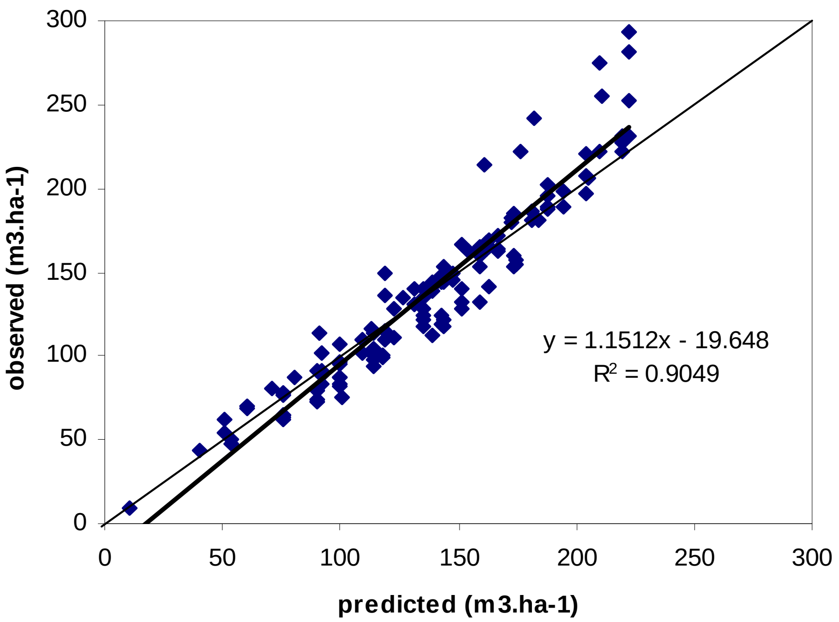

Figure 7: Predicted Vs. observed volume in 2006

3.1.1.1 Correlation and residual analysis

The correlation analysis between the predicted and the observed volume shows a strong positive relationship and is found to be statistically significant having r^2 value with 0.90 (Fig. 7). The model predictions are consistent with the corresponding observations, except for extreme cases - plots having the lowest and highest volume. The model underestimates and is found inconsistent on its results only when the observed plots have the highest growing stock. This is also evident in the trends of the standardized volume residuals versus the stand and site characteristics for the year 2006. Here, the standardized volume residual is calculated as the difference between predicted and observed value divided by standard deviation of the observed value. The standardized residual variability is high when the tree has a stand age of more than 110 years, the diameter lies between 70 and 80 cm, and the height between 17 and 20 m. Furthermore, it also varies greatly when the predicted volume is higher than 200 $m^3.ha^{-1}$.

Although there is variation during some stages of the rotation age, the over all variation in volume prediction and observation variation is only 1% (i.e. average volume for prediction and observation is 136.90 and 137.96 $m^3.ha^{-1}$ respectively). The model underestimated the volume by only 1 percent.

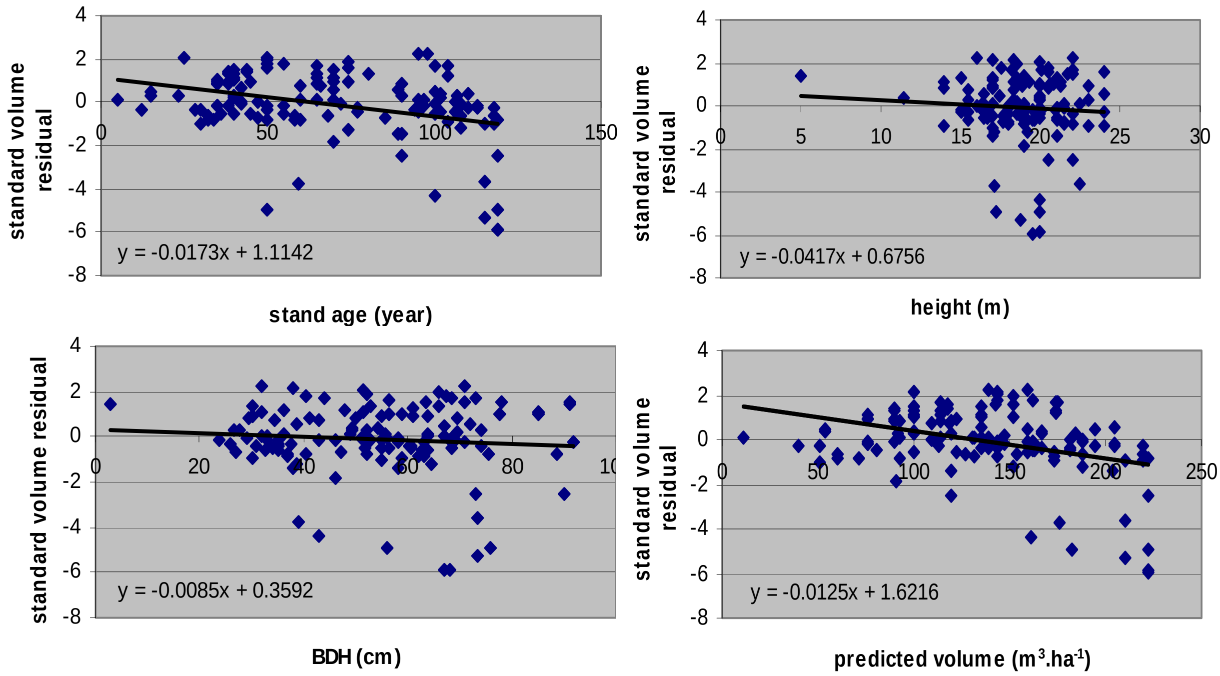

Figure 8: Trend analysis of standardised volume residual (i.e. predicted minus observed divided by standard deviation) vs. stand age, height, BDH and predicted volume.

It can be said that there is no systematic trend noticed while plotting volume residual with different stand and site characteristics. Furthermore, the mean value of volume residual close to zero shows the prediction is unbiased (Table 4).

Table 4: Summary statistics of volume residual in 2006

	Minimum	Maximum	Mean	Std. Deviation
Volume - residuals	-5.9170	2.2546	-0.0872	1.5572

3.1.1.2 **Consistency analysis**

Neither correlation statistics (Fig. 7) nor analysis of residuals (Fig. 8) provides any information about the consistency of future model prediction. Thus, pair t-test was conducted to test whether there is a significant difference between the prediction and observation. The possible option to determine the limits and range of errors in future predictions is to calculate the confidence, prediction and tolerance intervals (Reynolds, 1984). The confidence interval (CI), for the mean of the differences (D) between predicted and observed values, is used to evaluate discrepancies between the expected difference and the estimator $\overline{D}$ (Reynolds, 1984).

$$CI = \overline{D} \pm \frac{SD}{\sqrt{n}} \cdot t_{1-(\alpha/2),(n-1)} \quad \ldots\ldots\ldots\ldots (1)$$

$\overline{D}$ is the mean of differences between predicted and observed volume, SD the standard deviation of the differences $\overline{D}_i$, n is the sample size and t is the 1-α/2 quantile of the *t*-distribution with n-1 degrees of freedom.

The range of the differences of D_i among prediction versus observations is given by the prediction interval (PI) and can be denoted as:

$$PI = \overline{D} \pm \sqrt{1+\frac{1}{n}} \cdot SD \cdot t_{1-(\alpha/2),(n-1)} \quad \ldots (2)$$

The mean averages, mean of differences, standard deviation, t-value (@ α= 5%), confidence interval and prediction interval of field data were calculated (Table 5)

Table 5: Result of error analysis in volume prediction

Parameters	$\overline{obs}$	$\overline{D}$**i**	**SD**	***t***	**CI**	**PI**
Volume	137.96	-1.057	18.868	0.5254	-4.90 to 2.70	-44.01 to 41.90
(m^3ha^{-1})		(-0.77%)	(13.67%)		(-3.55 to 1.96%)	(-31.90 to 30.37%)

$\overline{obs}$ is the mean of observations, $\overline{D}_i$ the mean of the differences between predicted and observed values, SD the standard deviation of the differences and t the value from paired t-statistics. CI and PI are the confidence and prediction intervals of the error (Reynolds, 1984, in Pietsch et al., 2005).

Statistically, the pair t-test shows no significant difference between the model prediction and the observation volume in the year 2006 (@α= 5%). That is why the BGC-model describes the current volume of the study site situated in Hochleithenwald. No trends were observed. The CI shows that 90% of the values of current predicted values have an error range from -3.55 to 1.96% on their prediction, and that in the future such models can predict 90% values with an error range from -31.90 to 30.37%.

3.1.2 High forest system

The application of the model to the high forests in oak forests has already been tested in one study conducted in Austria (Pietsch et al., 2005). The results demonstrated that the species specific parameters adopted for Austrian oak forest yielded consistent and unbiased predictions, and proved that the biogeochemical ecosystem simulation models are appropriate diagnostic tools to deal with the impacts of forest management on forest growth.

As the validation of models for high forest had already been done in the same area, where this study is focused, and for coppice system has just been done by this study, the comparison of the thinning effects on forest growth among two management regimes will have significance meaning. In this study, the comparison was mainly based on the growth response of oak forest managed under two different systems having their own specific management intervention.

3.1.3 Yield under different management

The yield production of coppice and high forests, each having different management intervention, was presented in the Figure 9. The comparison here was only focused on the oldest stand as all intervention was being applied, and may reflect the growth responses to the respective management intervention well. The study shows that the harvested and total yield was highest in the coppice forests in comparison to the high forests, but the growing stock is higher in the case of the high forests. It showed us that the amount of biomass removal was comparatively less in high forest. As a result the high forest yielded 116 m^3ha^{-1} (25%) less within one complete rotation in comparison to the coppice system.

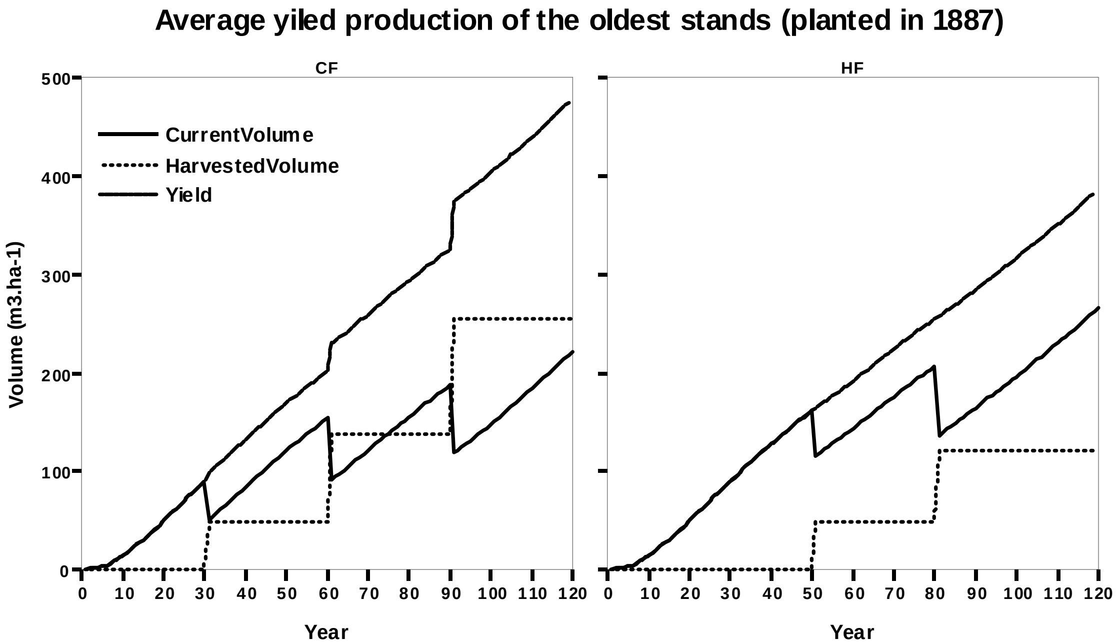

Figure 9: The average amount of growing stock, harvested volume and total yield of the oldest stand, which are planted in year 1887. The values are given in m^3 ha^{-1}.

3.2 Growth responses to thinning

As already described in the chapter 2.3, there are two distinct thinning interventions that have been applied. The thinning intervention was made to mimic the existing thinning practices applied for the high forest and coppice forest systems. As both the interventions have been assumed on the same forest stand the difference on the growth performance could be the effects of thinning itself. The growth responses caused by thinning were analysed by means of growth efficiency, nitrogen use efficiency, water use efficiency and radiation use efficiency.

3.2.1 Growth efficiency (GE)

The Growth efficiency (GE) at stand level is defined as the ratio of the net primary production (NPP) versus the leaf area index (LAI), which can be represented as,

$$GE = \frac{NPP}{LAI} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(3)},$$

Where, GE is growth efficiency ($kgC.m^{-2}.yr^{-1}$), NPP is net primary production ($kgC.m^{-2}.yr^{-1}$); LAI is leaf area index (dimension less).

The production of crown components may be a long term investment for aboveground biomass production, which effects the growth efficiency (also defined as biomass increment per unit leaf area) of the forest stand. While considering growth efficiency, the variation in above ground biomass partitioning (between the stem, branches, and foliage) of mature trees is a key determinant of growth potential (Jack et al., 2002). The greater overall biomass production of longer duration is the result of the investment of photosynthate in crown components. The amount of accumulation of such photosynthate in the crown directly depends upon the management system applied in the forest, and finally affects the growth efficiency of the remaining stand.

The growth efficiency of coppice forest and the high forest system under the current environmental condition was compared. To make it comparable the relative growth efficiency was used, and plotted against the age of the stand or tree. In this study, the growth efficiency in the year of planting was considered as 100 percent (value in terms of relative growth efficiency is 1), and the following years were calculated according to the planting year. The GE analysis was done at oldest stand level once, and the other at forest level. It is assumed that when we assess the oldest stand it will give us the trend for the effects of thinning for a whole rotation cycle, as the oldest stand is 110 - 120 years old. Afterwards, to generalize the effects at forest level, the whole forest is considered for the study.

Figure 10, plotted for average relative growth efficiency of the oldest stand (average of all plots planted in the year 1887) for current rotation age shows the increases in GE in earlier age and reached the maximum at the age of 5 years. Afterwards, the efficiency gradually fell down. As we are interested in studying the effects of the management on growth efficiency, the first thinning intervention was applied to a 30 year old stand on which the coppice system has been applied. Such intervention not only stops the decreasing rate of efficiency, it also uplifts the efficiency level of the situation just before thinning. The big difference between the applied management systems was noticed clearly in the following year and the differences continued for 12 years which fluctuated regularly. As per setup thinning criteria for high forest, the first thinning was done when the stand was 50 years old. Like the coppice system, the growth efficiency increased in the following year of thinning activities. If we compare the duration of the effects of thinning between the two systems, the high forests shows 3-4 years less than the coppice forests. Similarly, the second (at 60 years) and third thinning (at 90 years) in coppice forests and the second thinning (at 80 years) in high forests showed the increasing growth efficiency in the following year. Figure 11 shows that the growth efficiency variation (i.e. 9 and 7% respectively) on these second and third thinning in coppice forests is less in comparison to the first one (14%). More specifically, the third intervention has the lowest variation. It can be seen in the results that the effects of thinning intervention was found to be the highest in the youngest stand and the lowest in the oldest stand. When the stand reached to the age of 105 years there was no variation in GE on the selected management system (Fig. 10 & 11).

Figure 10: The temporal development of relative growth efficiency in coppice and high forests planted in year 1887. The averages of five plots established in 1887 were calculated and then the value of planting year was considered as 1. Values for the following years were assigned accordingly.

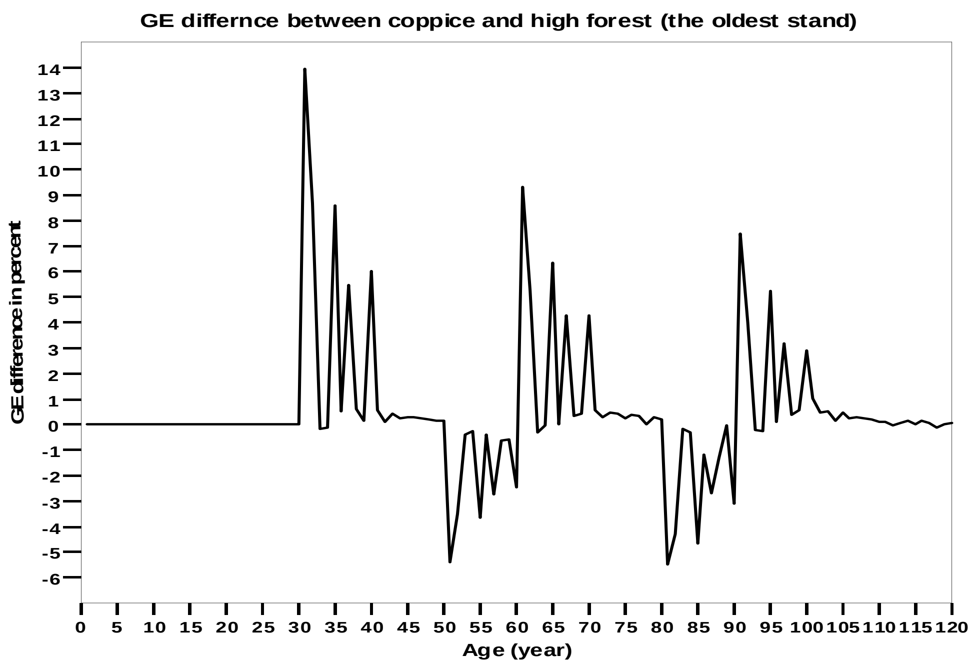

Figure 11: The temporal development in growth efficiency difference between coppice and high forests in percent (efficiency difference between coppice and high forest/efficiency of high forest *100). The average of five stand planted in year 1887 were considered for the study. The positive value shows the higher efficiency in coppice forest and vice versa.

The box plots plotted for the oldest stand showed that the variation in the growth efficiency is noticed just after the management intervention. Figure 12 shows that both the lower and the upper values of the relative growth efficiency changed positively after the intervention. Along with the increases in efficiency, the higher variability was also noticed. If we compared the growth efficiency among two applied management systems, the variability in the GE was high in coppice forests (Fig. 12) due to greater changes in the lower and upper values in GE. It further showed that as a whole the GE is higher in the coppice forests rather than in the high forests.

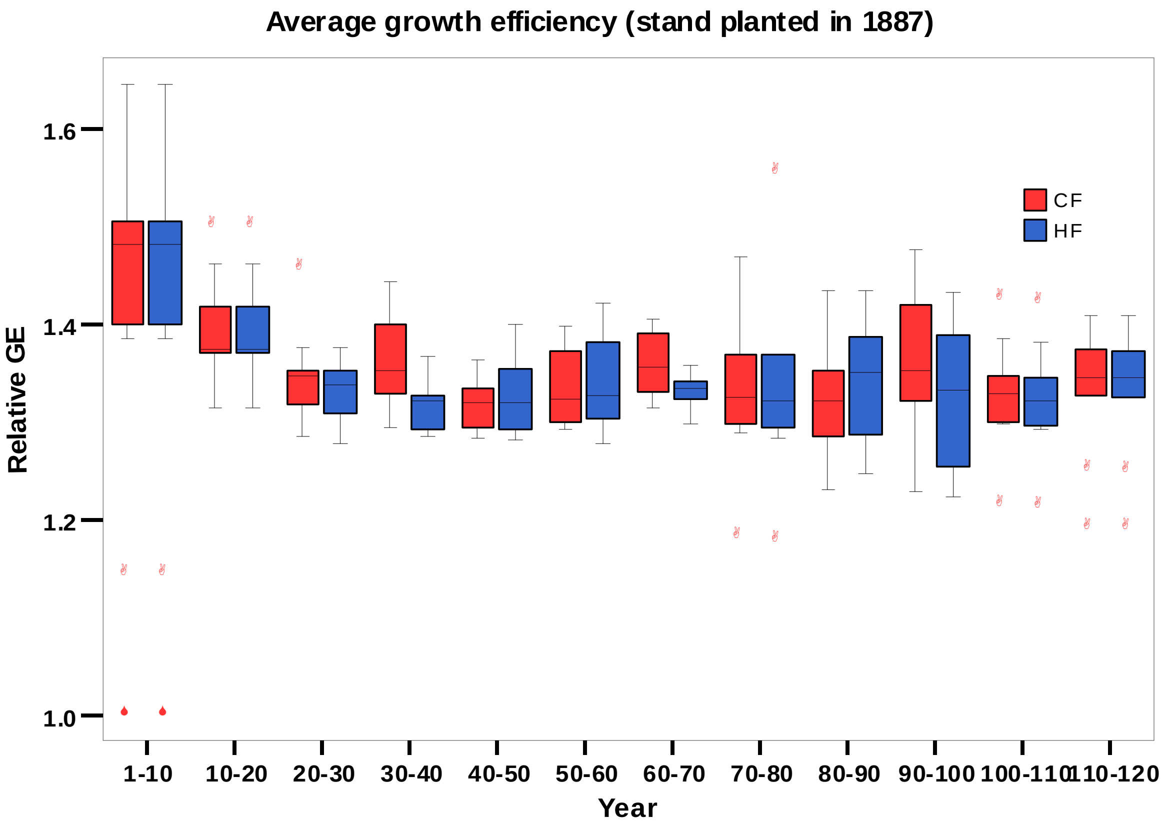

Figure 12 Box plots showing the average relative growth efficiency in coppice and high forests planted in year 1887 by ten years time interval. Value of planting year was considered as 1, and the rest were assigned accordingly. The line within the box shows the value of median.

Although the plotted graph of the trend lines and box plots show the differences among the GE in coppice forest and high forest after thinning, the differences were still statistically insignificant when analysed with a pair wise t test (@α= 5%). It means that the effects of thinning were statistically independent with the selection of management systems. For detail see Table 6 (a, b & c).

Table 6: Summary statistics on descriptive analysis, coefficient of determinant and pair wise t-test related to growth efficiency (GE) of the oldest plot planted in year 1887

a) Descriptive analysis

	Mean	N	Std. Deviation	Std. Error Mean
Coppice forests	1.017	120	0.083	0.0076
High forests	1.012	120	0.082	0.0076

b) Coefficient of determinant

	N	r^2	Significance level
(CF& HF)	120	0.773	<0.001

c) Paired sample test

	Paired differences					t	df	Sig. level (2 tail)
	Mean	std. Deviation	Std. error mean	95% CI of the difference				
				Lower	Upper			
(CF & HF)	0.005	0.056	0.005	-0.005	0.0150	0.975	119	0.332

The presented graphs and tables to describe growth efficiency of the oldest stand gave us an idea about the effects of thinning in GE by age of trees. As we noticed that thinning has effects in growth efficiency of the remaining forest in the oldest plots, we were further interested in generalizing the effects at forest level. When the forest is the mosaic of different stands, from youngest (recently established) to the oldest (near to the rotation age), it should consider a stand of every ages while generalizing the effects of management. The study could be interesting if the analysis is done by stand age, because the above graph clearly shows that the GE of the younger age was highly responsive to the management in comparison to the older. To simplify the analysis process, the whole forest was divided into 12 age classes with 10 years interval. The temporal development and distribution pattern of growth efficiency by age class were analysed.

Although there were forest stands of all ages, the stand age up to 30 years were not shown in graphs plotted to study GE trend, because there was no intervention applied before the stand reached 30 years. Figure 13 shows the thinning has positive effects in GE of forest stand, but the change ratio differs according with the age of the stand. Also

It reflects that the GE differ between two management systems, and the highest in the forest stands which were 30-40 years old, where only the first thinning was applied to the coppice forests. The effects of thinning at stand level show the younger stand has higher response than the older (Fig. 13).

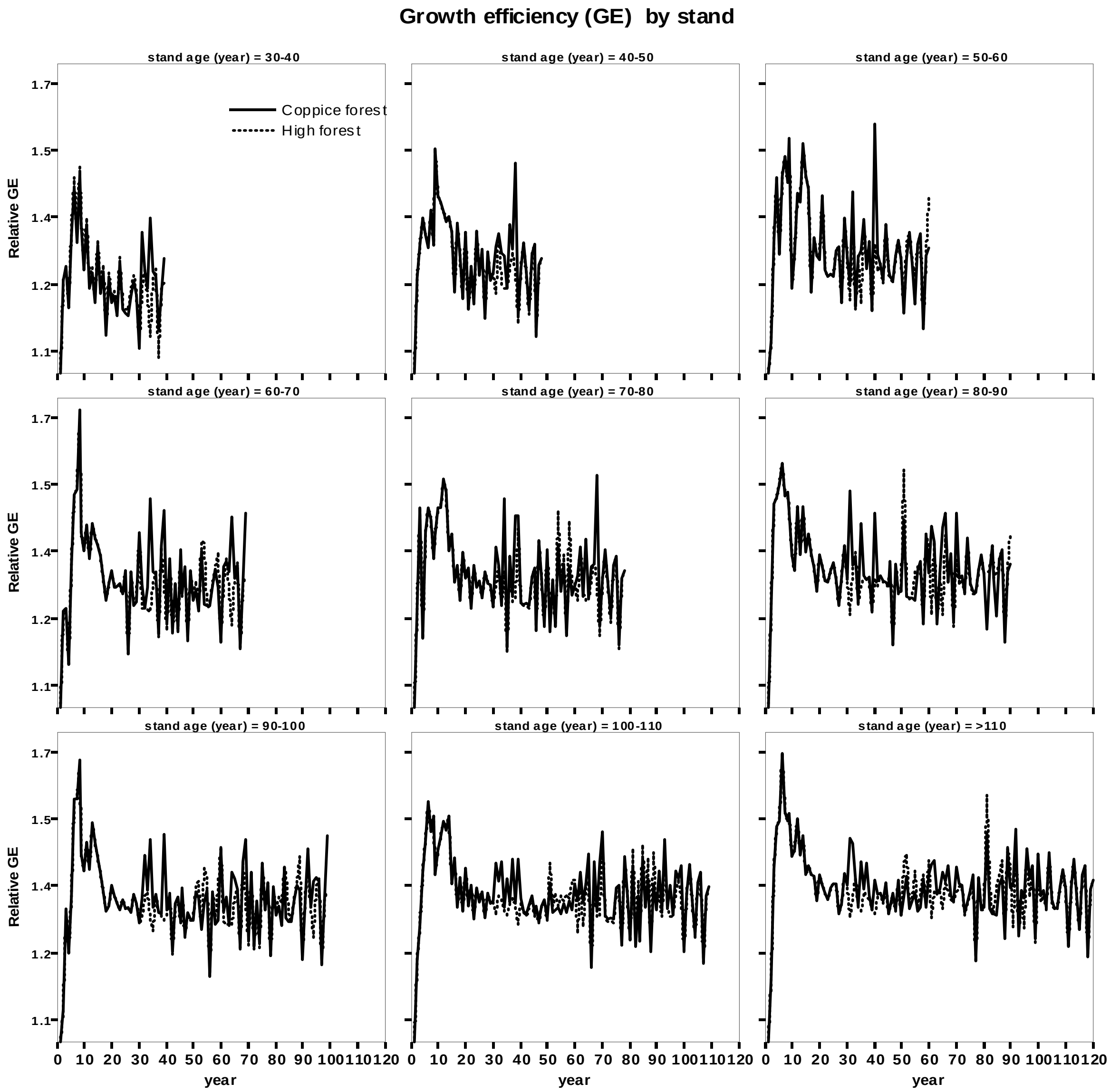

Figure 13: The temporal development of relative growth efficiency in coppice and high forests by stand. The rotation age was divided into 12 age classes and formed 12 different stands in the forest by age. Plots were grouped according to their age. Then the average of plots with same age class was calculated. Value for the planting year was considered as 1 and the rest were calculated accordingly.

Figure 14 shows that the GE variation increased after the implementation of thinning activities in forests. The effects of thinning were noticed after 10 years and lasted for 10 - 20 years. Like in the oldest stand the variation in GE was highest on the stands where thinning was carried out. It also increased the lower and upper values of the GE. As a whole the GE variation was highest in coppice forest as compared with high forest. Also, the higher variations on lower and upper values were noticed in the coppice forests (Fig. 14). The median plotted in the figure 14 showed that the GE is higher in the coppice forests in comparison to the high forests.

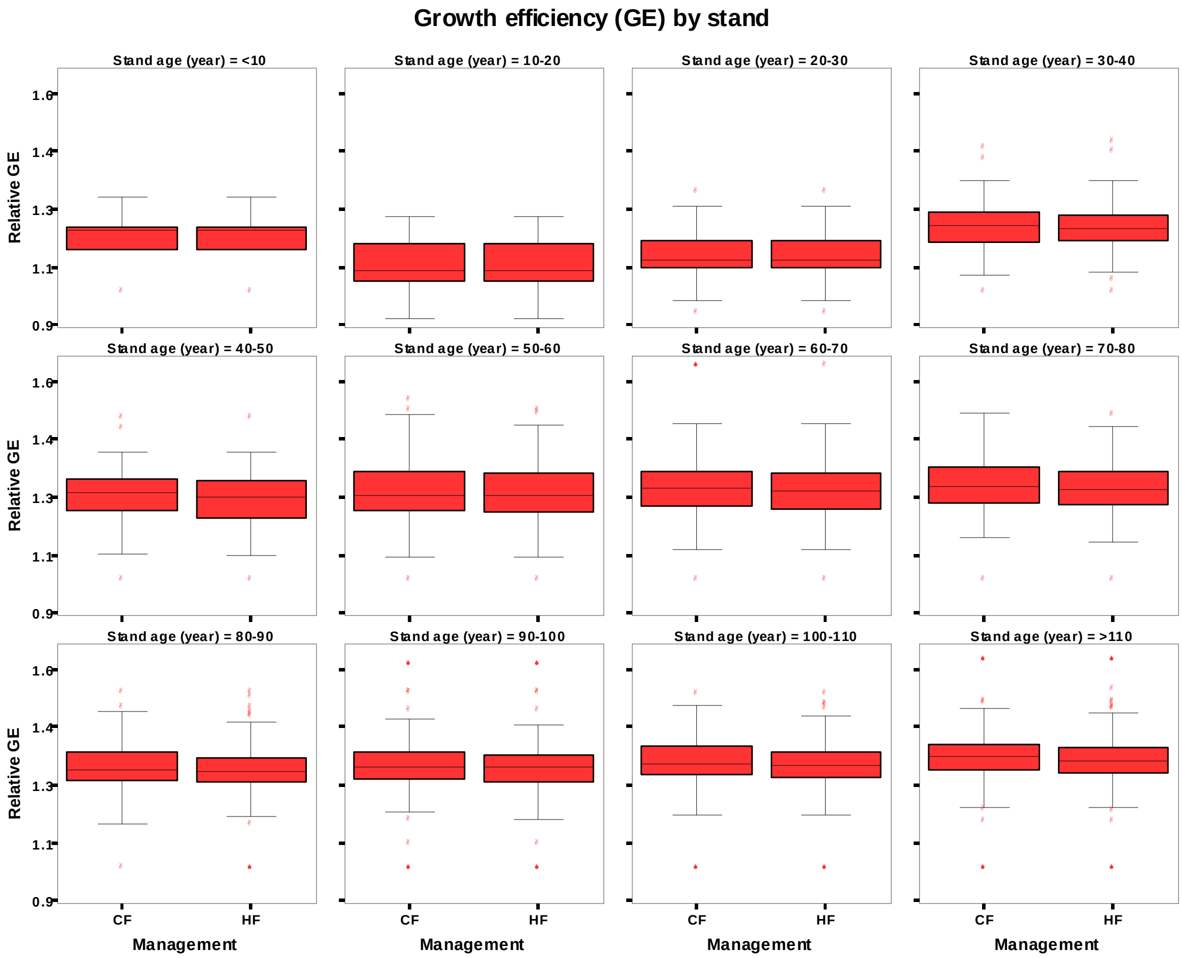

Figure 14: Box plots showing the average relative growth efficiency in coppice and high forests by stand age. The rotation age was divided into 12 age classes and formed 12 different stands in the forest by age. Plots were grouped according to their age. Then the average of plots with same age class was calculated. Value for the planting year was considered as 1 and the rest were calculated accordingly.

Although graphical representation in GE variation due to thinning did not show clear picture of difference, it shows statistically significant (@α= 5%) in GE difference by stand between the two management systems. The results of the statistics are shown in Table 7 (a, b & c). From this it can be concluded that the GE by stand is significantly dependent on the management system.

Table 7: Summary statistics on descriptive analysis, coefficient of determinant and pair wise t-test related to growth efficiency (GE) in coppice and high forests by stand

a) Descriptive analysis

	Mean	N	Std. Deviation	Std. Error Mean
Coppice forests	1.30	763	0.108	0.0039
High forests	1.29	763	0.105	0.0038

b) Correlation analysis

	N	r^2	Significance level
(CF& HF)	763	0.921	<0.005

c) Paired sample test

	Paired differences					t	df	Sig. level (2 tail)
	Mean	std. Deviation	Std. error mean	95% CI of the difference				
				Lower	Upper			
(CF & HF)	0.008	0.042	0.001	0.0049	0.101	5.093	762	0.001

3.2.2 Nitrogen use efficiency (NUE)

Nitrogen is one of the most important mineral nutrients that limit plant growth in many natural and managed ecosystems (Aerts and Chapin 2000). Since, the large fraction of leaf nitrogen is in the photosynthetic apparatus, a strong correlation holds between photosynthetic capacity and nitrogen content of leaves (Hikosaka 2004). Thus while describing the growth response of forest, an area with the collection of trees, the situation of input and output of nitrogen pool, i.e. nitrogen use efficiency, should be analysed.

The nitrogen use efficiency (NUE) measures the amount of biomass produced per unit of N taken up from the soil, where the NPP and N_{uptake} are measured in units of dry matter production or N taken up from the soil per square meter of land surface per unit of time (i.e. g of DM $M^{-2}.yr^{-1}$ or g of N $M^{-2}.yr^{-1}$). The NUE can be described by two processes i.e. N productivity and mean residence time of N in biomass in years (Finzi et al. 2007).

$$NUE = \frac{NPP}{N_{content}} * \frac{N_{content}}{N_{uptake}}, \ldots\ldots\ldots\ldots\ldots\ldots(4)$$

$$= \frac{NPP}{N_{Uptake}}$$

Where, NUE is nitrogen use efficiency (C/N)

$NPP/N_{content}$ is the $N_{productivity}$, and

$N_{content}/N_{uptake}$ is known as mean residence time of biomass in years.

NPP is net primary production ($kgC.m^{-2}.yr^{-1}$)

N_{Uptake} is the nitrogen taken by plants ($kgN.m^{-2}.yr^{-1}$)

Most forested ecosystems have relatively tight N cycles (Johnson and Van Hook 1989) because the nutritional needs of forest are supplied almost entirely by internal recycling rather than from external sources. To maintain high rates of production and large stocks of organic matter, N has to be recycled internally and retained efficiently (Townsend and Rastetter, 1994). Changes in the N capital of an ecosystem are obliviously the result of an imbalance between sources (atmospheric deposition and fixation) and losses (leaching, erosion, trace gas emissions, and deep burial). The ecosystem has little control on the rate of N supply as many forests have less N fixing species (Jordan 1985), but the ecosystem processes has strong control over N losses. A disturbance such as clear cutting, however, which decouples the tight linkages between soil and vegetation pools, can dramatically increase N losses from the system (Vitousek et al. 1991).

As described in the GE, the graph with average relative NUE by age in the oldest stand (average of all plots planted in the year 1887) was plotted to study effects of thinning. Figure 15 shows the distinct effects of thinning on NUE. The relative efficiency increased in the earlier age of stand and reached to the maximum at the age of 20 years. Afterwards, the efficiency gradually falls down. Then the first thinning intervention was applied to 30 year old forests on which the coppice system has been applied. Such intervention not only stops the decreasing rate of efficiency, it also uplifts the efficiency level from its previous level, just before thinning. Then, the differences in NUE between two management systems was noticed just a year after the thinning intervention and reached maximum after 12 years (Fig. 16). The differences in efficiency were reduced when the thinning intervention was also done in the high forests when the stand reached 50 years of age. When the second thinning was applied in the coppice forests to the stand turned 60 years old, it increased the NUE of the coppice forests, and the differences again continued. Unlike the first thinning, the relative NUE of coppice forests after thinning was increased for 15 years (Fig. 15). While comparing the trend on increasing NUE, it was found to be as its maximum within 3-4 years after the first thinning in both forests. The second thinning applied in both forests shows that the effects was lasted for about 14 years in the coppice forests and 11 years in the case of the high forests. When the third thinning was applied in the coppice forests the NUE increased just like after second thinning, but the increasing intensity is lower than the first and second. The second thinning intervention applied in the high forests also increased the NUE and the rate was highest 11 years after thinning. As the NUE increased in the high forests after 80 years and decreased NUE in the coppice forests after 83 years, the both system culminate when the stand reached to 87 years old. After 3 years when there was next thinning was applied in coppice forests, the NUE increased and went up than the level of high forests. The difference in the NUE continues up to the rotation age, i.e. 120 years in both management regimes (Fig. 15 & 16).

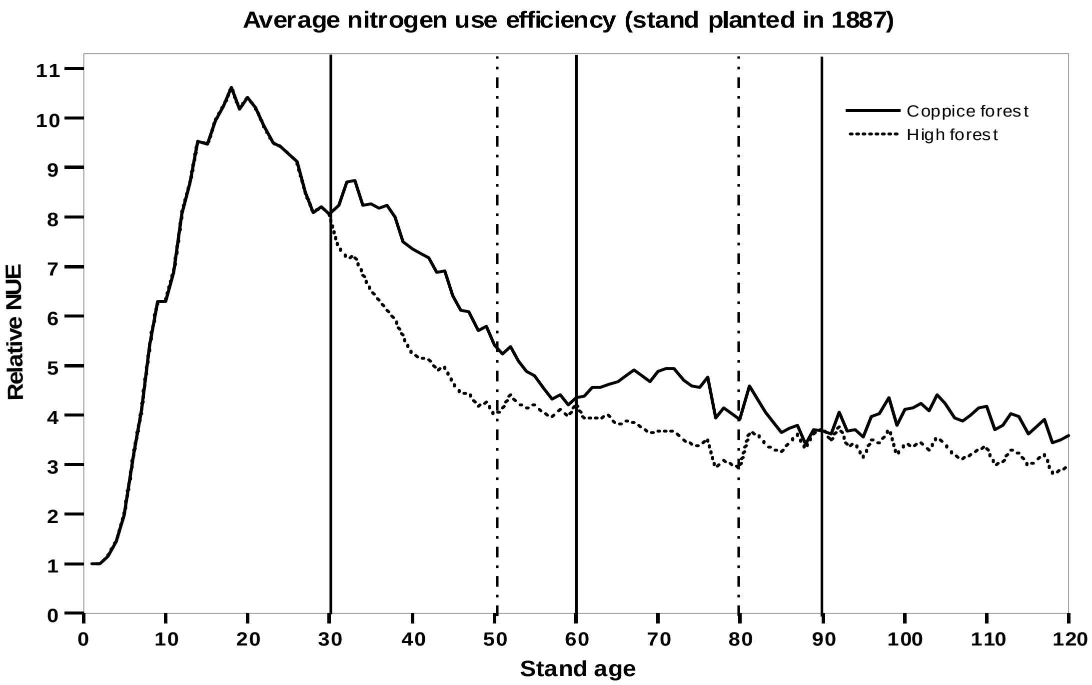

Figure 15: The temporal development of relative nitrogen use efficiency in coppice and high forests planted in year 1887. The averages of five plots established in 1887 were calculated and then the value of planting year was considered as 1. Values for the following years were assigned accordingly.

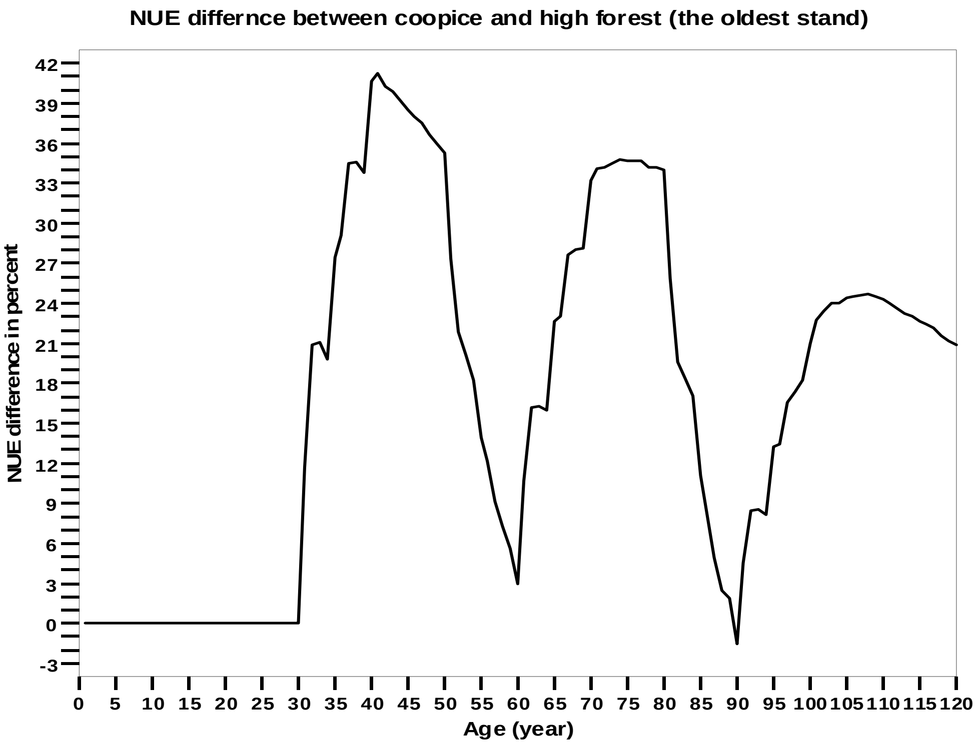

Figure 16: The temporal development in nitrogen use efficiency difference between coppice and high forests in percent (efficiency difference between coppice and high forest/efficiency of high forest *100). The average of five stand planted in year 1887 were considered for the study. The positive value shows the higher efficiency in coppice forest and vice versa.

Figure 17 describes the changes in relative NUE in coppice and high forests by age in the oldest plot. The high variability in relative NUE was noticed during the first 10 years after planting. Afterwards the lower values and the upper values of relative NUE were increased by 800 and 150 percent respectively, and reduce the efficiency variation by 300 percent when the tree was 20 years old. Then the variability stays constant for the next 10 years with decreasing the lower and upper values (Fig. 17). When thinning intervention was applied in the coppice forests, when the stand was 30 years, it decreased the variability of the NUE within these forests, which was less than that of high forests. If we compared the NUE of coppice forests and high forests, it shows that thinning reduces the decreasing rate of NUE and show higher efficiency in coppice forests if we compared it with high forests. Furthermore, the difference in the NUE between two management systems was lessened when the thinning conducted in the high forests. The result showed minimum difference after 10 years of thinning done in the high forests. Figure 16 & 17 further showed that the coppice forests had higher efficiency than the high forests except the tree was 89-91 years old. The thinning intervention applied in both forests has reduced the decreasing rate of NUE. When the second thinning applied in the coppice forests, it reduced the NUE variation. Although the upper value of NUE was less than its previous stage, the large number showed higher performance on the NUE as the lower value was increased by thinning (which is shown by the median line). Even though previous two thinning did not increase the NUE from its previous level, the third intervention uplifted it to some extent. In the case of thinning applied in the high forests, it was not able to uplift the NUE from its previous level, but it lowered the decreasing rate of efficiency.

The pair wise t test statistics by age in the oldest plot exhibited that the NUE between two management systems differ significantly (@α= 5%). This means the NUE depends on the management regime. The detail values are shown in Table 8 (a, b & c).

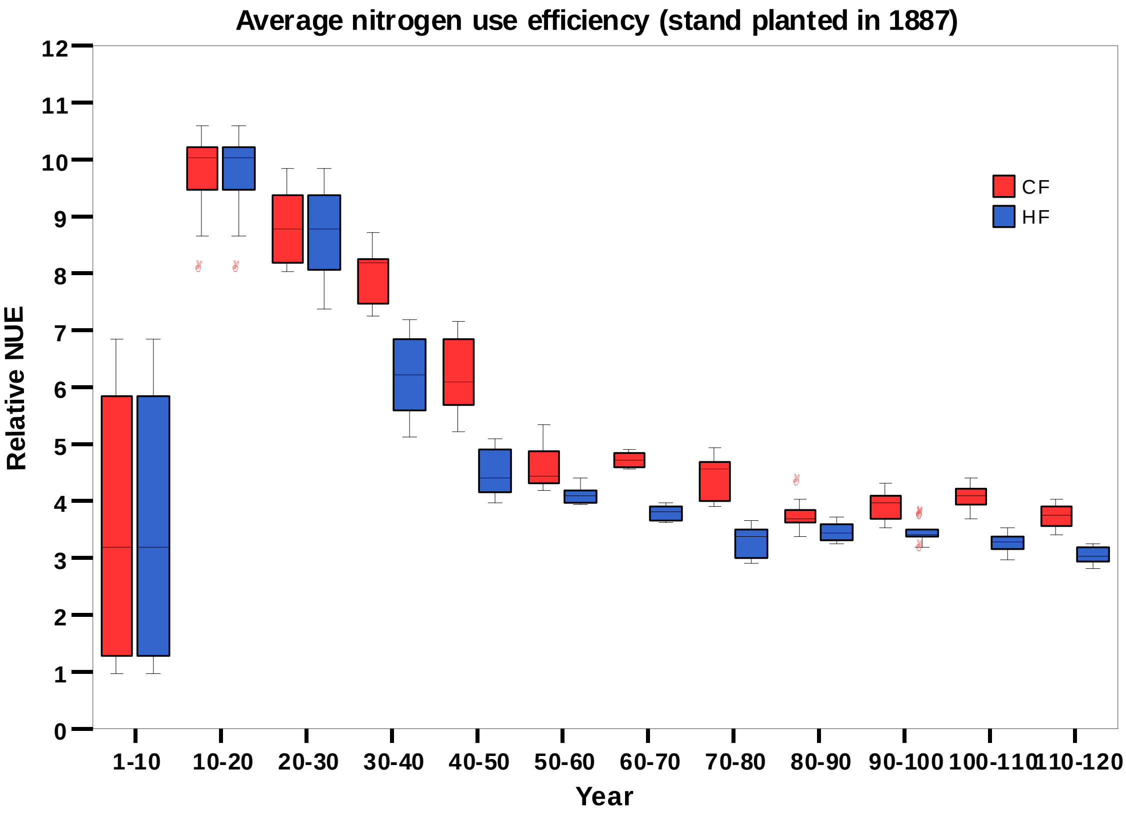

Figure 17: Box plots showing the average relative nitrogen use efficiency in coppice and high forests planted in year 1887 by ten years time interval. Value of planting year was considered as 1, and the rest were assigned accordingly. The line within the box shows the value of median.

Table 8: Summary statistics on descriptive analysis, coefficient of determinant and pair wise t-test related to nitrogen use efficiency (NUE) of the oldest plot planted in year 1887

a) Descriptive analysis

	Mean	N	Std. Deviation	Std. Error Mean
Coppice forests	0.754	120	0.331	0.030
High forests	0.657	120	0.339	0.030

b) Coefficient of determinant

	N	r^2	Significance level
Coppice and high forests	120	0.956	<0.001

c) Paired sample test

	Paired differences					t	df	Sig. level (2 tail)
	Mean	std. Deviation	Std. error mean	95% CI of the difference				
				Lower	Upper			
(CF & HF)	0.096	0.010	0.009	0.080	0.1143	10.593	119	<0.001

As in the GE, we were further interested in generalizing the effects of thinning on NUE at forest level. Figure 18 show that thinning has positive effects in NUE of all stands. But the increasing trends differ by the age of trees. The stand with age 40-50 and 70-80 shows the sharp increase in NUE in coppice forests after the first thinning. In general, the NUE of forests follow the same trend that we noticed in the oldest stand (Fig. 15). Like in coppice forests, high forests also show the thinning effects in increasing NUE, when the first thinning was applied to 40-50 years old stands. In all stands the higher NUE after thinning was found in coppice forests in comparison to high forests, except in the year 60 and 90 where both shows equal efficiency in nitrogen use (Fig. 18).

The variation in NUE at stand level was shown in Figure 19. The thinning reduced the variability of the NUE. By stands, the upper values in NUE were found to increase in both forest up to the age of 20 years and remained same for another 10 years. Then, the NUE was decreased in high forests but increased in coppice forests, where the first thinning was done. By stand, the level of NUE was not evident to increase by second and third thinning, but it reduces the decreasing rate of efficiency. The variation in NUE within the system was continued to irrespective of the thinning applied. The highest variation was noticed when the stand was 50-60 years old. As a whole, the thinning applied in coppice forests has more effects than the one applied in high forests (Fig. 19). While comparing the median value of NUE by stand, it is clear that the coppice forests have always higher values than the one with the high forests.

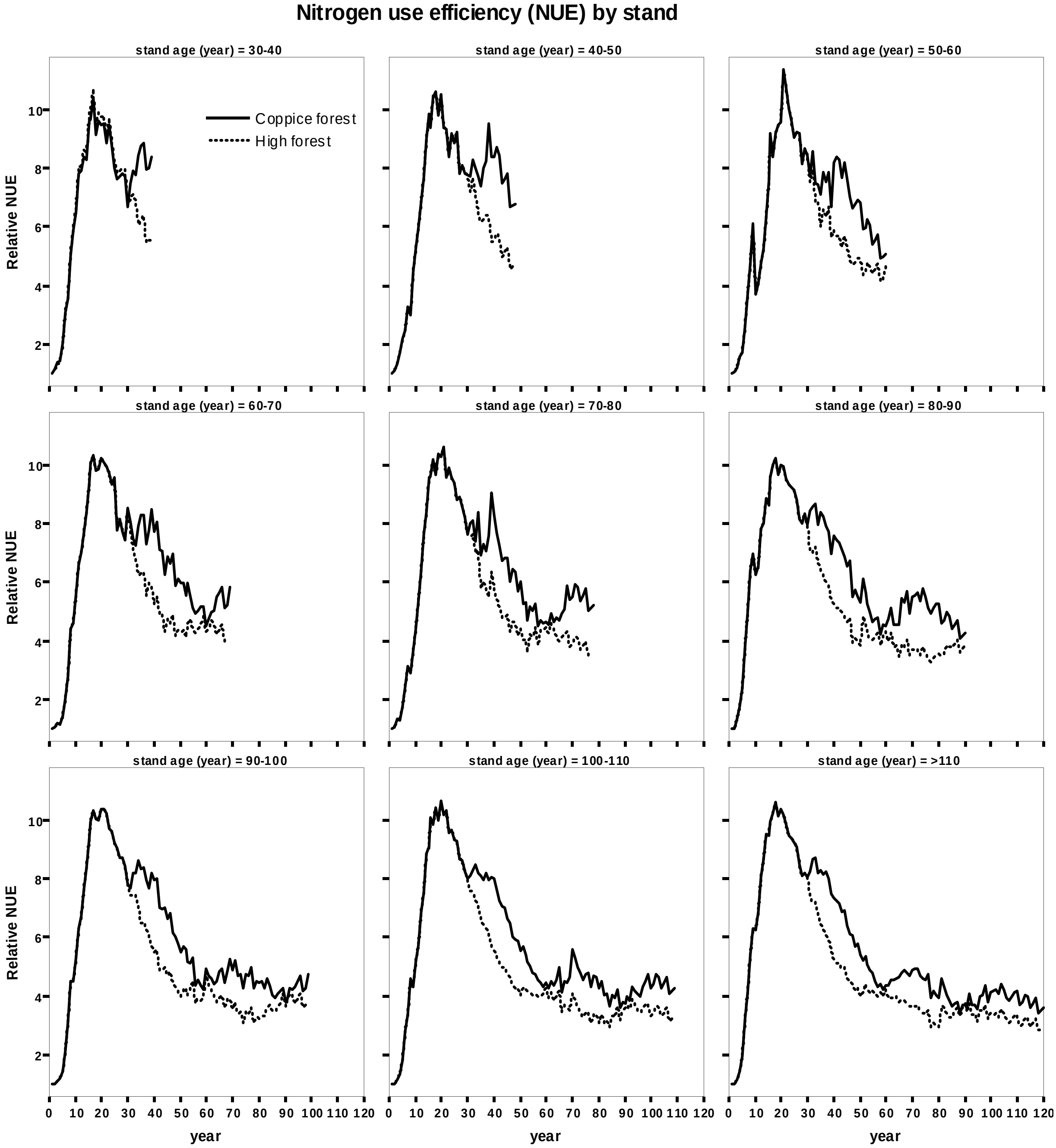

Figure 18: The temporal development of relative nitrogen use efficiency in coppice and high forests by stand. The rotation age was divided into 12 age classes and formed 12 different stands in the forest by age. Plots were grouped according to their age. Then the average of plots with same age class was calculated. Value for the planting year was considered as 1 and the rest were calculated accordingly.

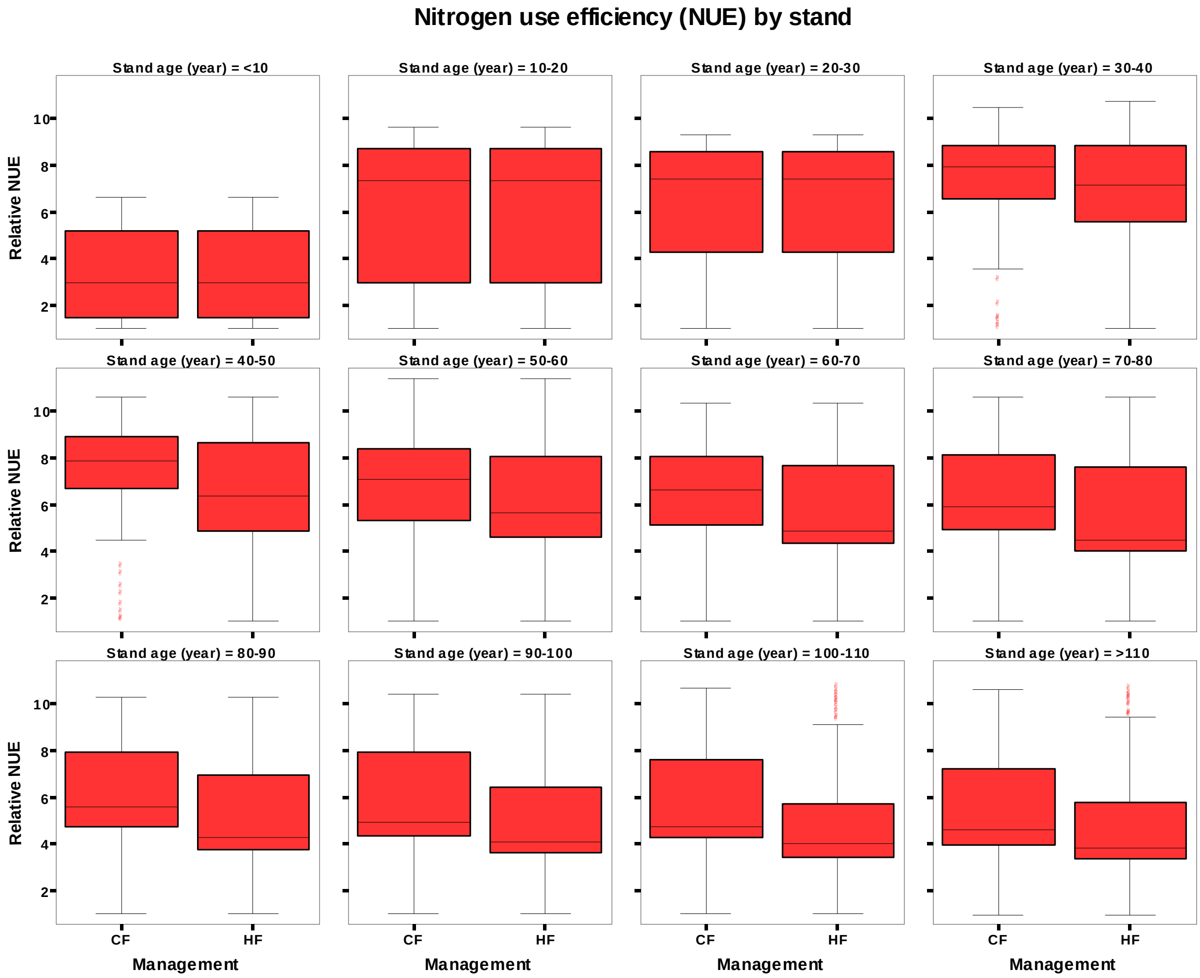

Figure 19: Box plots showing the average relative nitrogen use efficiency in coppice and high forests by stand age. The rotation age was divided into 12 age classes and formed 12 different stands in the forest by age. Plots were grouped according to their age. Then the average of plots with same age class was calculated. Value for the planting year was considered as 1 and the rest were calculated accordingly.

The pair wise t test statistics by stand exhibited that the NUE between two management systems differ significantly (@α= 5%). It means the NUE depends on the management regime. The detail values are shown in the Table 9 (a, b & c).

Table 9: Summary statistics on descriptive analysis, coefficient of determinant and pair wise t-test related to nitrogen use efficiency (NUE) in coppice and high forests by stand

a) Descriptive analysis

	Mean	N	Std. Deviation	Std. Error Mean
Coppice forests	6.12	763	2.422	.088
High forests	5.43	763	2.509	0.091

b) Correlation analysis

	N	r^2	Significance level
Coppice and high forests	763	0.949	<0.001

c) Paired sample test

	Paired differences					t	df	Sig. (2 tail)
	Mean	std. Deviation	Std. error mean	95% CI of difference				
				Lower	Upper			
(CF & HF)	0.692	0.793	0.0288	0.6358	0.7486	24.112	762	<0.001

3.2.3 Water use efficiency (WUE)

Although water has no tight relation to carbon and nitrogen as the C/N ratio, it influences them in many ways. Water is used by plants as the raw material for photosynthesis. Also nitrogen uptake is done via water in the soil and on the other hand nitrogen may be leached by the soil water outflow. So, the water use efficiency is another important parameter which play main role in the growth of plants.

Water use efficiency (WUE) is an important eco-physical measure quantifying the ratio of net CO_2 uptake from the atmosphere during photosynthesis versus net H_2O loss (Larcher, 2003). It is the ratio of CO_2 assimilation into the photosynthetic biochemistry to water lost, via transpiration through the stomata. It describes the water lost by the plant for the unit of carbon production.

$$WUE = \frac{NPP}{Transpiration} \qquad (5)$$

Where, WUE is water use efficiency ($kgC.mm^{-1}$)

NPP is net primary production ($kgC.m^{-2}.yr^{-1}$)

Transpiration is the water lost ($kgH_2O.m^{-2}.yr^{-1}$)

Generally, WUE depends on the environmental and management condition of the forest. Analysis has shown that it is essential to distinguish between wet and dry canopy evaporation to know better on WUE. The leaf area index has significant role on the interception of the precipitation and also on the very efficient transfer mechanism of water vapour, even under the condition of marginal net radiation (Dolman et al., 2003).

The combination of a high aerodynamic roughness, with a relative low and strongly controlled surface resistance, was the main cause for high evaporation rates from the wet canopies and somewhat low transpiration rates from dry canopies.

Figure 20 is the result received from the analysis of the oldest stand. From figure it is seen that the thinning has positive changes in WUE. The first thinning applied in coppice forests changed WUE by 700% in the following year and reduced gradually. But the effects in WUE changes lasted for almost 20 years. Similarly the same trend was noticed high forests when the first thinning was done in 50 years old stands. The next thinning applied in the coppice and high forests show the similar trend that has been noticed in the first one. The value of WUE was directly dependent on the applied thinning. The management, which has recent interventions showed the greater WUE (Fig. 20 & 21). Figure 19 shows a sudden increased in WUE of both systems in the same trend as when the stand was 74 years old. From the climatic data it was found that these changes were due to the effects of extremely dry summer in the year 2003. As described earlier in the methodology the repeated climatic data of 46 years (year 1960-2005) were used to simulate the required forest ecosystem, the sudden change shown here was due to dry climatic year 2003. So, it is clear that the increased in WUE was not effects of thinning. The final thinning was done in coppice and high forests when the stand was 90 and 80 years old respectively. Their effects on WUE were seen up to the end of rotation. But the differences were decreased sharply when the stand turned 105 years old (Fig. 20 & 21).

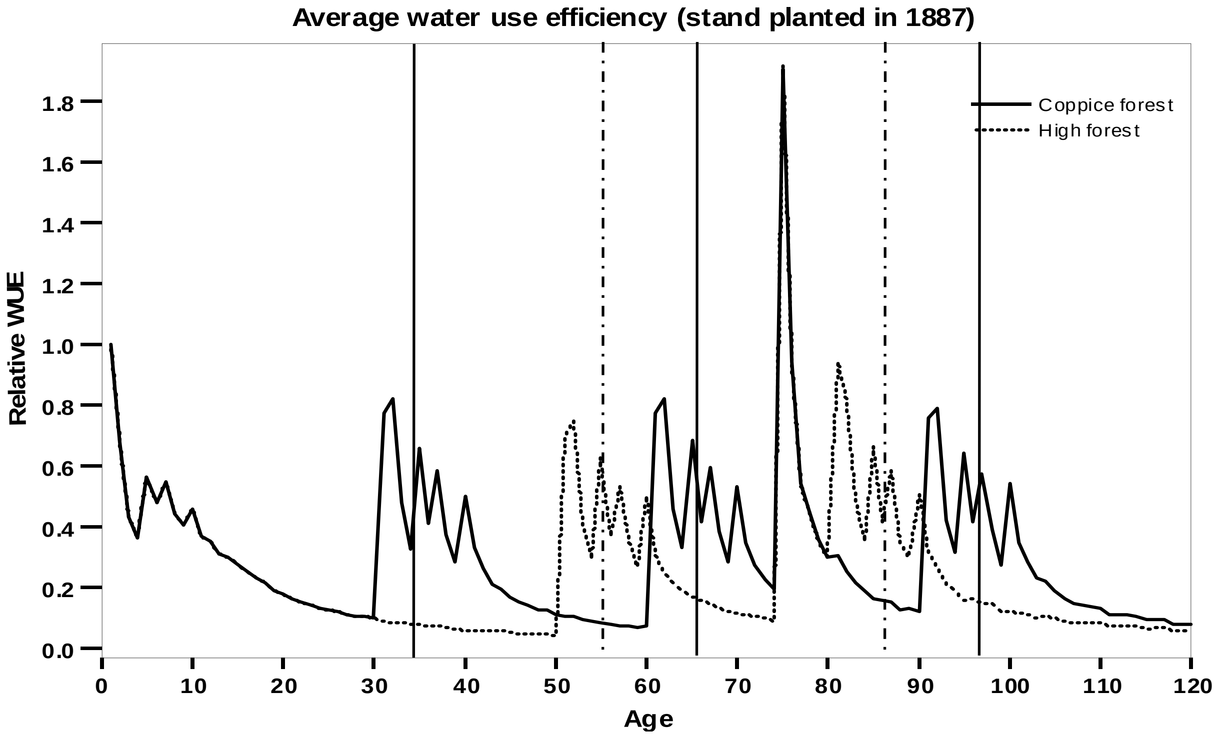

Figure 20: The temporal development of relative water use efficiency in coppice and high forests planted in year 1887. The averages of five plots established in 1887 were calculated and then the value of planting year was considered as 1. Values for the following years were assigned accordingly.

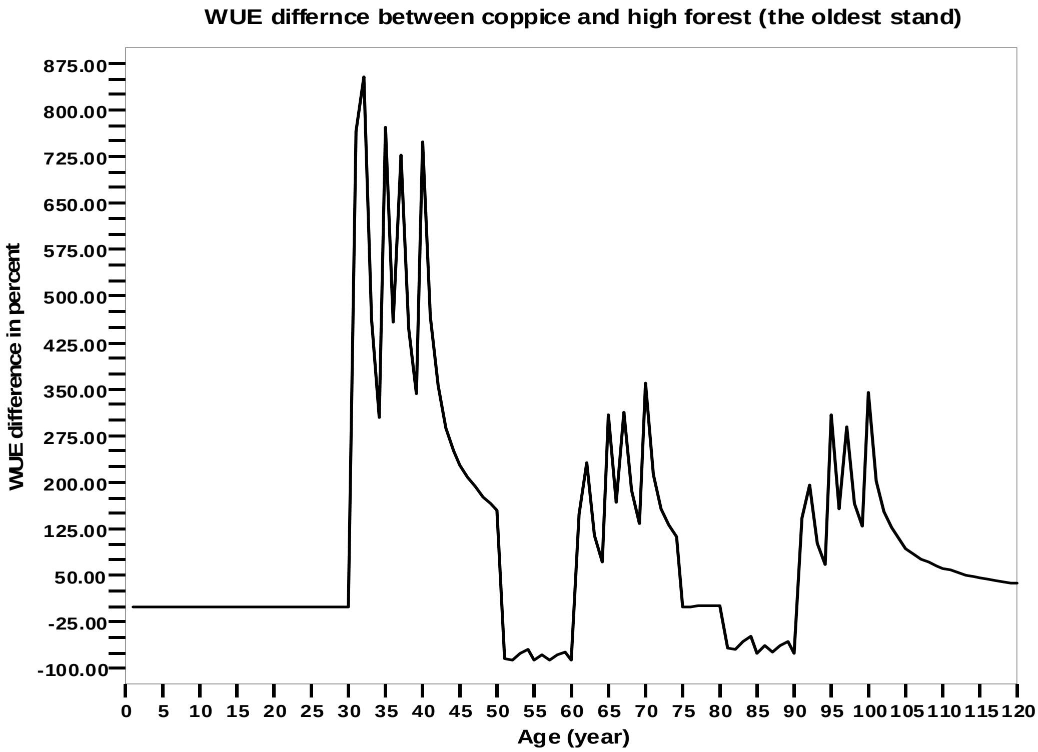

Figure 21: The temporal development in water use efficiency difference between coppice and high forest in percent (efficiency difference between coppice and high forest/efficiency of high forest *100). The average of five stand planted in year 1887 were considered for the study. The positive value shows the higher efficiency in coppice forest and vice versa.

The box plot (Fig. 22) plotted for WUE by age for the oldest plot shows that the variability and the value of relative WUE decreases as the age of the stand increases. The WUE and the variability of its values decreased in both systems before applying the thinning was applied. As the thinning was applied in the coppice forests when the stand was 30 years old, it increased the WUE by 400 percent. Meanwhile the decreasing trend in WUE was seen in the high forests. The stand shows the highest differences within its rotation when the stand is 31 years old, just one year after thinning in coppice forests (Fig. 21 & 22). Like in the coppice forests, the WUE and variability on its value increased in the high forests when the first thinning done on a 50 years old stand. The second and third thinning in coppice forests, and the second thinning in high forests showed the same trend as seen after the first.

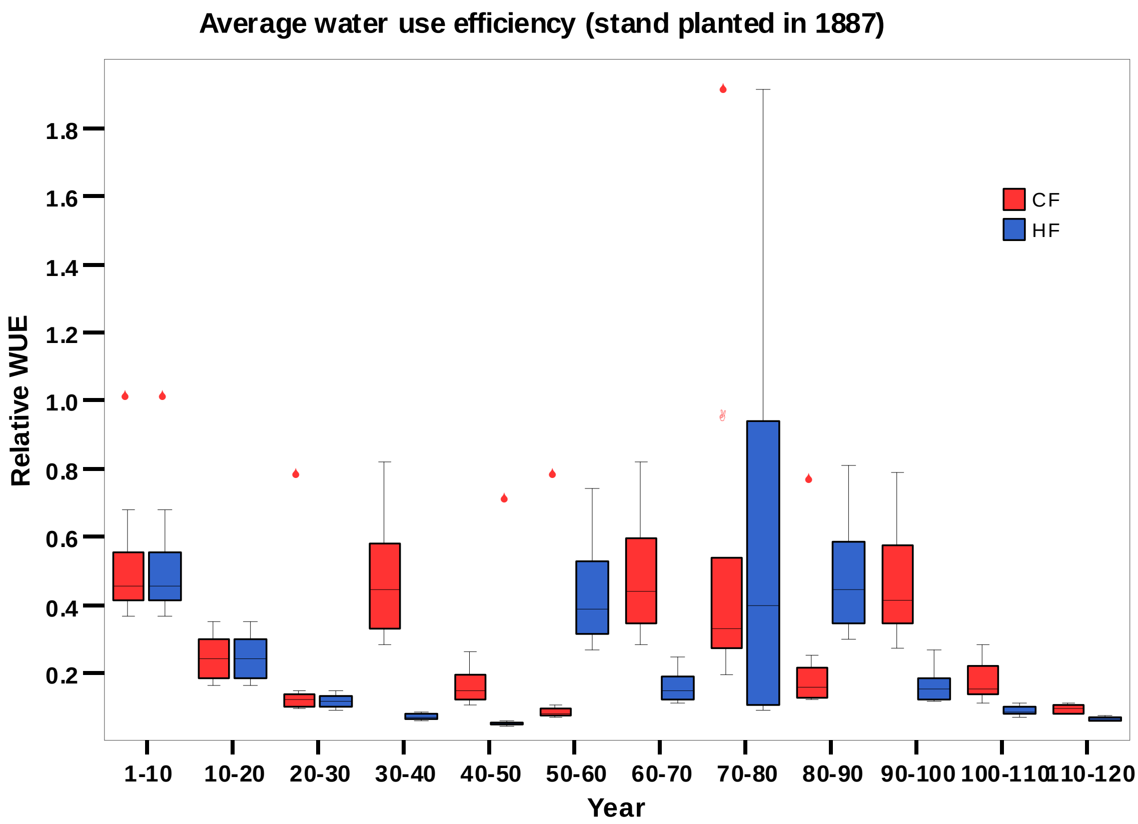

Figure 22: Box plots showing the average relative water use efficiency in coppice and high forests planted in year 1887 by ten years time interval. Value of planting year was considered as 1, and the rest were assigned accordingly. The line within the box shows the value of median.

The pair wise t test statistics by the age of trees in the oldest plot exhibited that the WUE between two management systems does not differ statistically significant (@α= 5%). It means the WUE does not depend on the management regime. The detail values are shown in the Table 10 (a, b & c).

Table 10: Summary statistics on descriptive analysis, coefficient of determinant and pair wise t-test related to water use efficiency (WUE) of the oldest plot planted in year 1887

a) Descriptive analysis

	Mean	N	Std. Deviation	Std. Error Mean
Coppice forests	3.533	120	4.571	0.417
High forests	2.813	120	4.104	0.374

b) Correlation analysis

	N	r^2	Significance level
Coppice and high forests	120	0.232	0.011

c) Paired sample test

	Paired differences					t	df	Sig. level (2 tail)
	Mean	std. Deviation	Std. error mean	95% CI of difference				
				Lower	Upper			
(CF & HF)	0.720	5.389	0.492	-0.254	1.694	1.463	119	0.146

The effect of thinning on WUE by stand was shown in Figure 23. Before entering to the thinning effects it would be better to recall the sharp increase in both forests, which was the effect of the dry climatic summer in the year 2003. So, it was excluded while studying the effects of thinning. Except the effects on this year, the rest are the effects of the applied thinning. From figure 23 it can be generalized, that the thinning has positive effects in increasing WUE in both forests. But the duration of effects of thinning was seen longer in case of coppice forests than it was in the high forests.

As found in the oldest stand, the variation in WUE by stand was also noticed due to thinning (Fig. 24). When the first thinning was applied to 30 years old trees in coppice forests it increased the upper level of WUE, and finally showed more variation in WUE in comparison with the high forests. If we compare the forest stand in the coppice forests along with the number of thinning done, the stand where only one thinning was done (stand with 30-40 years) showed higher WUE than the stand where 2nd and 3rd thinning applied. The similar trend was noticed when we consider stands in high forests, those having a 1st thinning and stands with 1st and 2nd thinning (i.e. stand with ages 50-60 and 80-90 years). The upward shift of median values in both systems shown in the figure 24 tells us that the efficiency for larger number of plots under this stand age was increased. Although the WUE was increased after thinning in the stands there were distinct differences between two forests. In all stands the coppice forests have higher values in efficiency than the high forests (Fig.24).

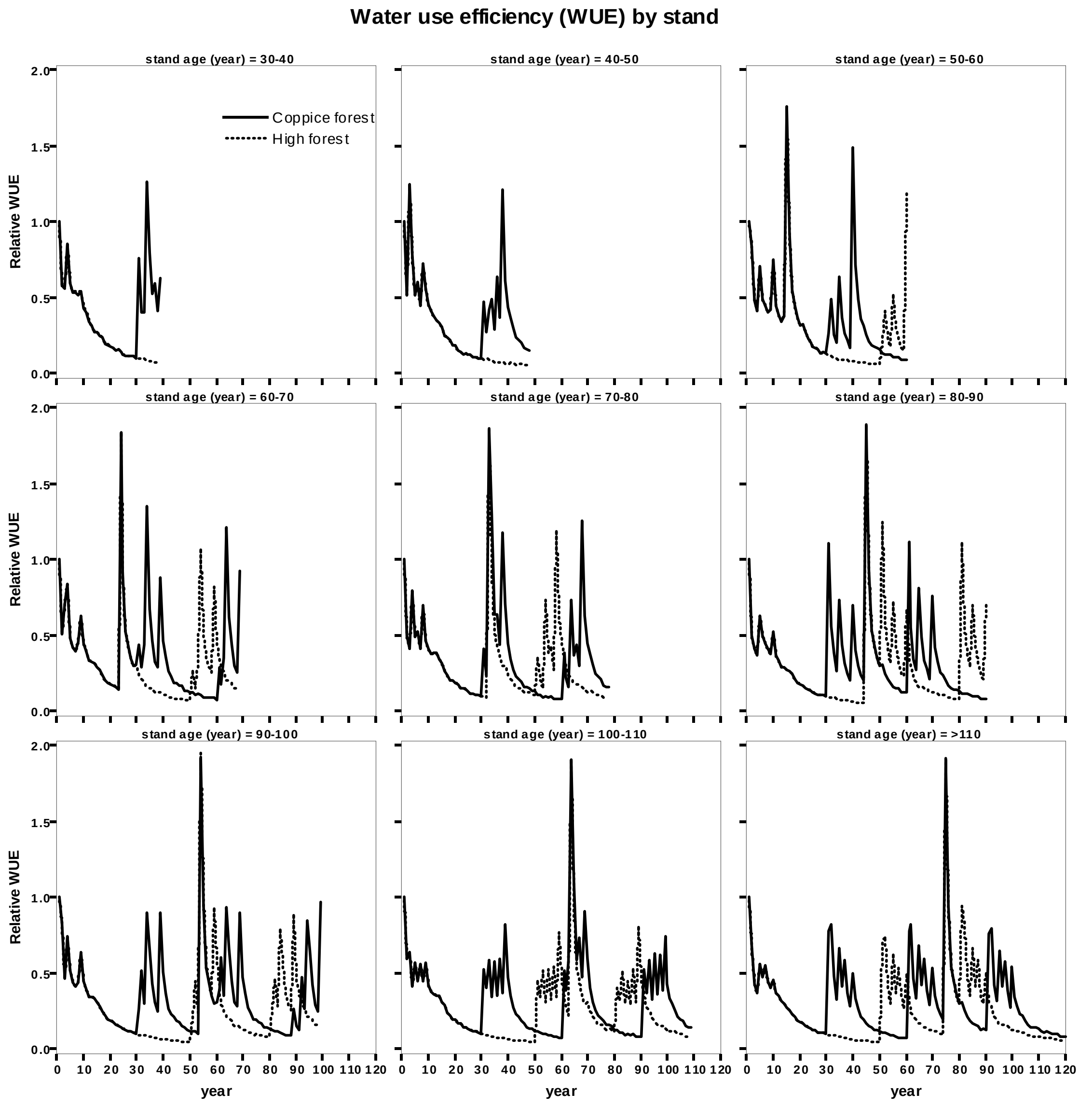

Figure 23: The temporal development of relative water use efficiency in coppice and high forests by stand. The rotation age was divided into 12 age classes and formed 12 different stands in the forest by age. Plots were grouped according to their age. Then the average of plots with same age class was calculated. Value for the planting year was considered as 1 and the rest were calculated accordingly.

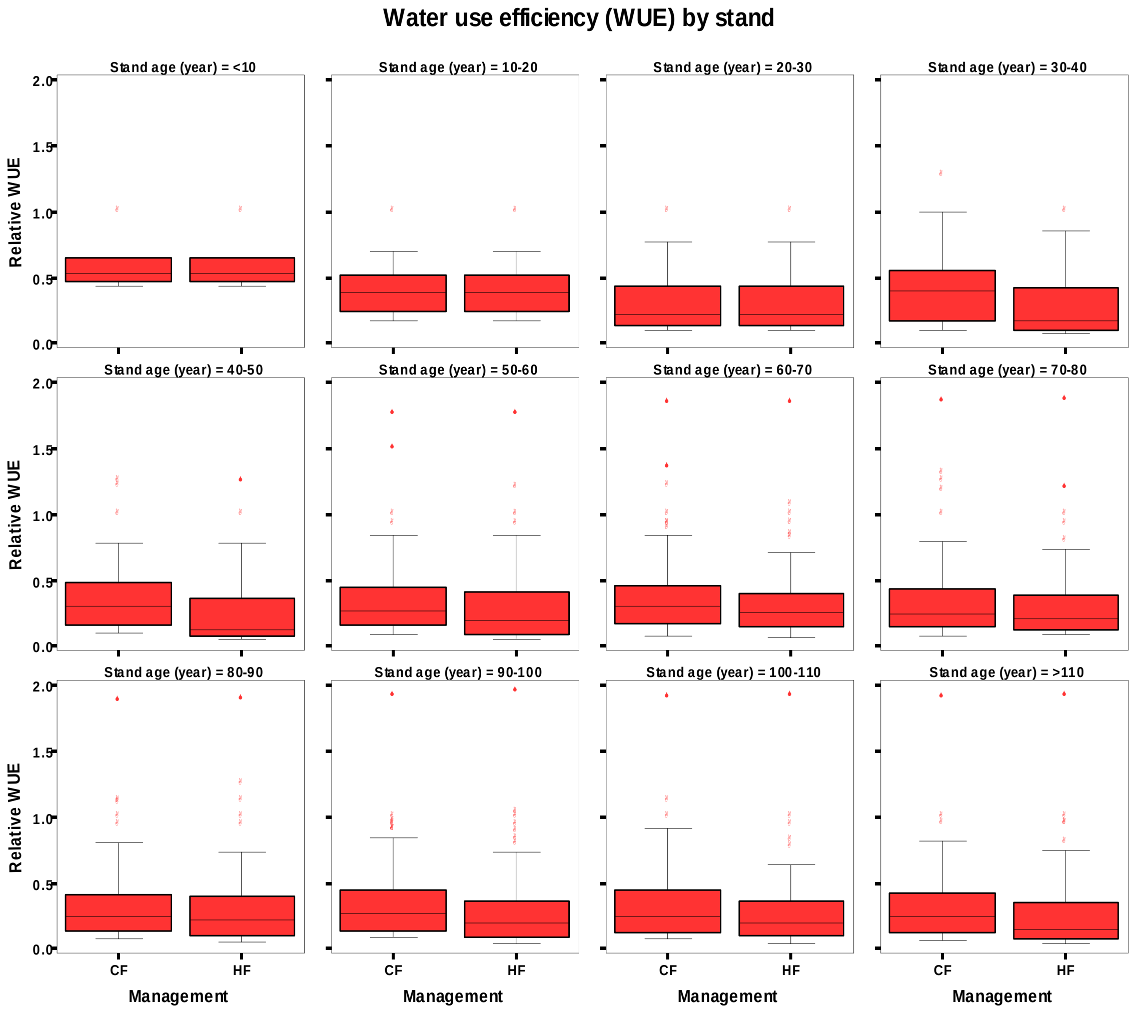

Figure 24: Box plots showing the average relative water use efficiency in coppice and high forests by stand age. The rotation age was divided into 12 age classes and formed 12 different stands in the forest by age. Plots were grouped according to their age. Then the average of plots with same age class was calculated. Value for the planting year was considered as 1 and the rest were calculated accordingly.

The pair wise t test statistics, at forest level, concluded that the WUE by stand between two management systems differ significantly (@α= 5%). It means the WUE is statistically dependent to the selection of management. The detail values are shown in the table 11 (a, b & c).

Table 11: Summary statistics on descriptive analysis, coefficient of determinant and pair wise t-test related to water use efficiency (WUE) in coppice and high forests by stand

a) Descriptive analysis

	Mean	N	Std. Deviation	Std. Error Mean
Coppice forests	0.35	763	0.286	0.0103
High forests	0.30	763	0.278	0.0100

b) Correlation analysis

	N	r^2	Significance level
Coppice and high forests	763	0.550	<0.05

c) Paired sample test

	Paired differences					t	df	Sig. level (2 tail)
	Mean	std. Deviation	Std. error mean	95% CI of the difference				
				Lower	Upper			
(CF & HF)	0.056	0.267	0.001	0.0375	0.0754	5.844	762	<0.001

3.2.4 Radiation use efficiency (RUE)

The radiation use efficiency represents the integration of all photosynthetic and respiratory processes (Medlyn, 1998) and is a simple yet robust variable describing growth (Sinclair and Muchow 1999). Radiation use efficiency may be affected by site conditions (e.g. fertility, climate, water availability) and by cultural practices like thinning and harvesting. Thinning increased RUE in *Eucalyptus regnans* as it attributed to the extra belowground resources and irradiance made available (West and Osler 1995).

$$RUE = \frac{NPP}{Absorbed\_radiation} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(6)}$$

Where, RUE is water use efficiency (kg $C.W^{-1}$)

NPP is net primary production (kgC.$m^{-2}.yr^{-1}$)

Absorb radiation is canopy absorbed shortwave flux (W.$m^{-2}.yr^{-1}$)

The RUE was another studied parameter in generalizing the growth responses of oak forest to thinning. Figure 25 describes the averages RUE of the oldest stands, which were planted in year 1887. As already mentioned in the study of other variables, the effects of thinning was analysed by temporal development of trees in the corresponding plot. As shown in the figure 25, after the first thinning done in the coppice forests, the RUE was increased in the following year by 6.5%, and decreased after one year. The decreasing trend in RUE was continued for few years. Like in coppice forests the high forests also show the same response to thinning when the first thinning applied to 50 years old. Figure 26 was plotted to see the RUE differences among the coppice and high forests. It shows that the RUE in the coppice forests was higher than the one in the high forests for one year after the thinning, and then was lower when the forest stand was 32 to 36 years old. The RUE of coppice and high forests fluctuated to the age before the high forests were treated with thinning. When the first thinning was applied in the high forests to 50 years old forests, it increased the RUE of forests by 2% in the following year. The efficiency of high forests was decreased in the next year and finally went below the level of coppice forests. Then the coppice forests continuously showed higher RUE than the high forests. As the second thinning applied in coppice forests, it increased the RUE by 6.5% in the following year and went below the high forest's level after 3 years of thinning. Similarly, when the second thinning was applied in high forests, it increased the RUE for one year and then fell down below the level of coppice forests. Moreover, it is also prevalent to the third thinning applied in the coppice forests. The thinning increased the RUE level for 2 years, and then it went below the high forest for another 15 years. When the stand reached 108 years, both showed the same efficiency for 7 years. Finally, the coppice forests have higher RUE when the stand reached to 115 years and continues to the rotation age of oak stand (Fig. 25 & 26).

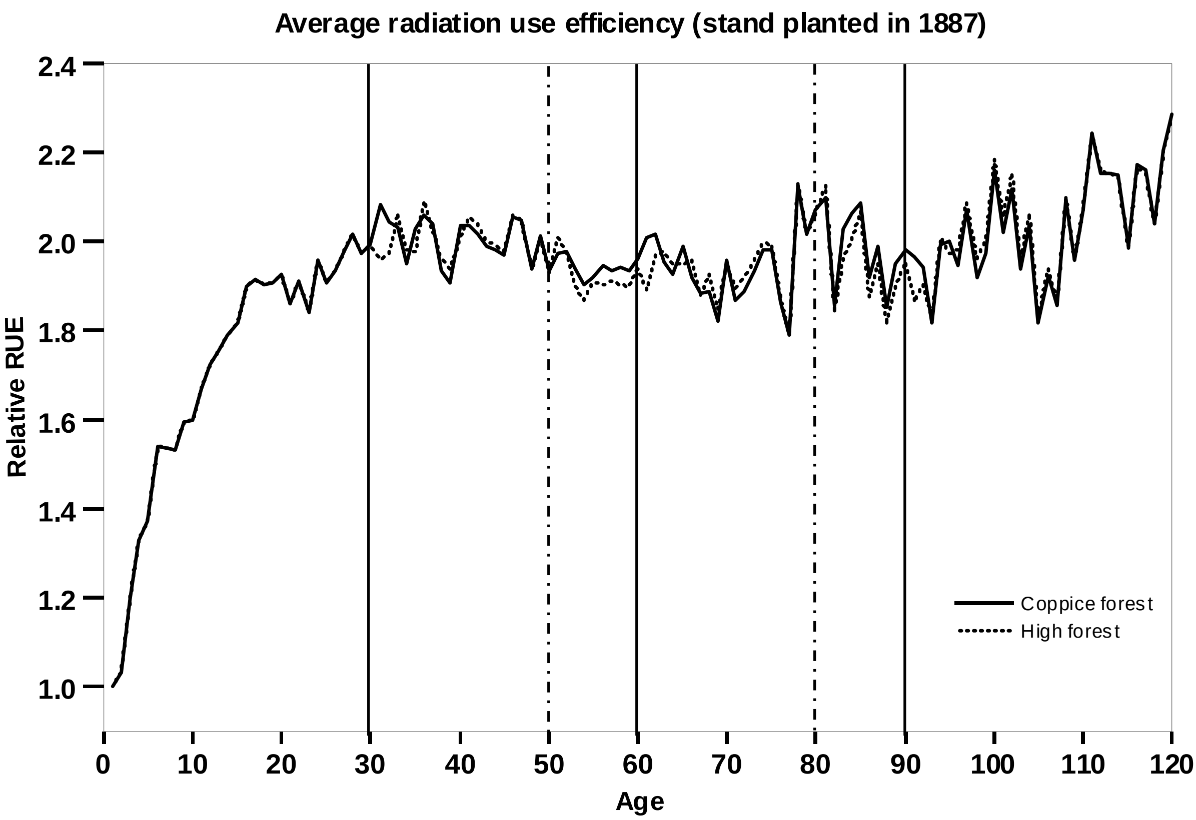

Figure 25: The temporal development of relative radiation use efficiency in coppice and high forests planted in year 1887. The averages of five plots established in 1887 were calculated and then the value of planting year was considered as 1. Values for the following years were assigned accordingly.

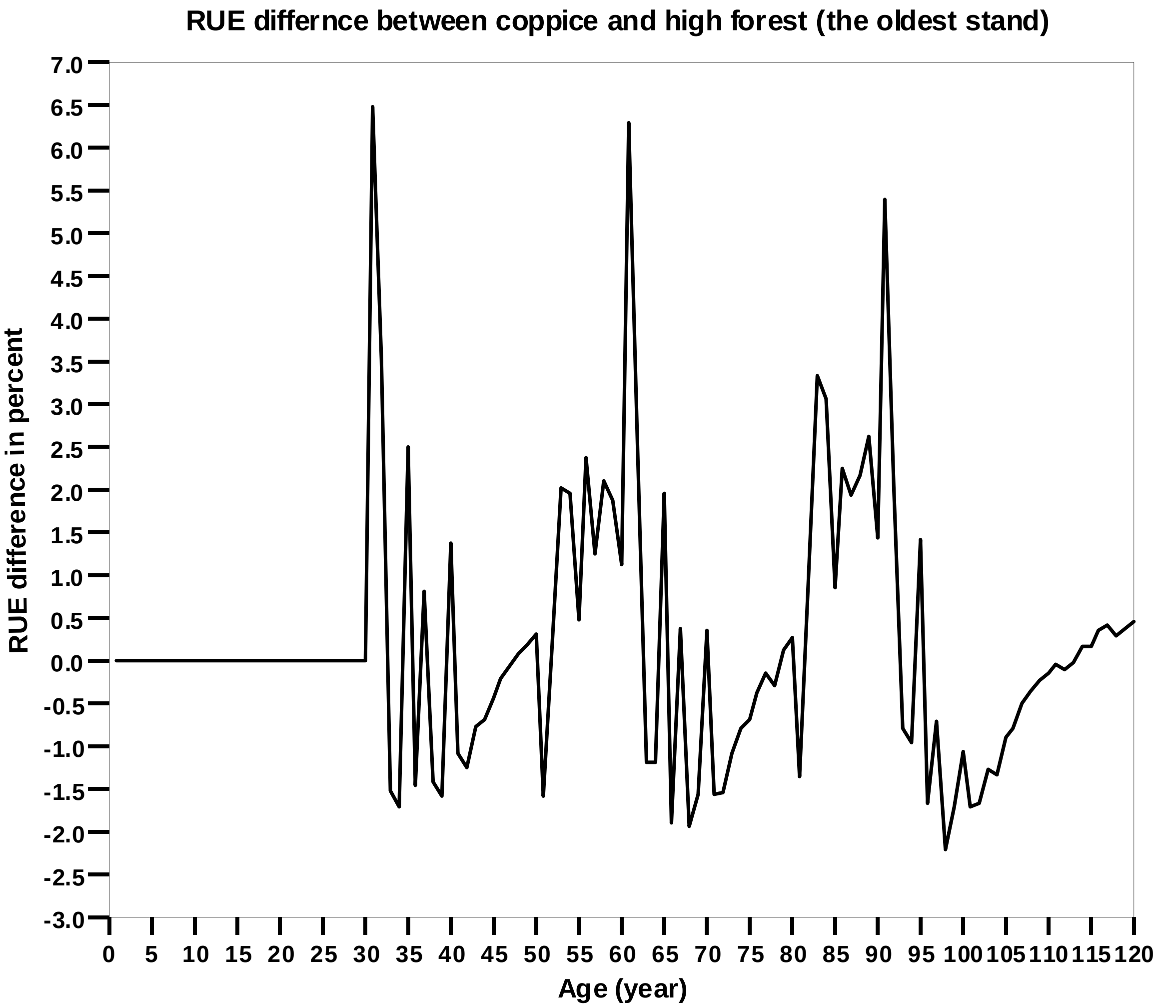

Figure 26: The temporal development in radiation use efficiency difference between coppice and high forests in percent (efficiency difference between coppice and high forest/efficiency of high forest *100). The average of five stand planted in year 1887 were considered for the study. The positive value shows the higher efficiency in coppice forest and vice versa.

The box plot, figure 27, shows that the radiation use efficiency of forest stand increased with age, except for when the tree was 50-60 years old. The variation in RUE was reduced by increasing age and reached its minimum when the tree was between 50 and 60 years old. After that, the RUE went better and reached its maximum at the final stage of rotation. While considering the whole rotation period, the RUE of the coppice forests were greater than high forests except when the tree was 70-80, 90-110 years old (Fig. 27).

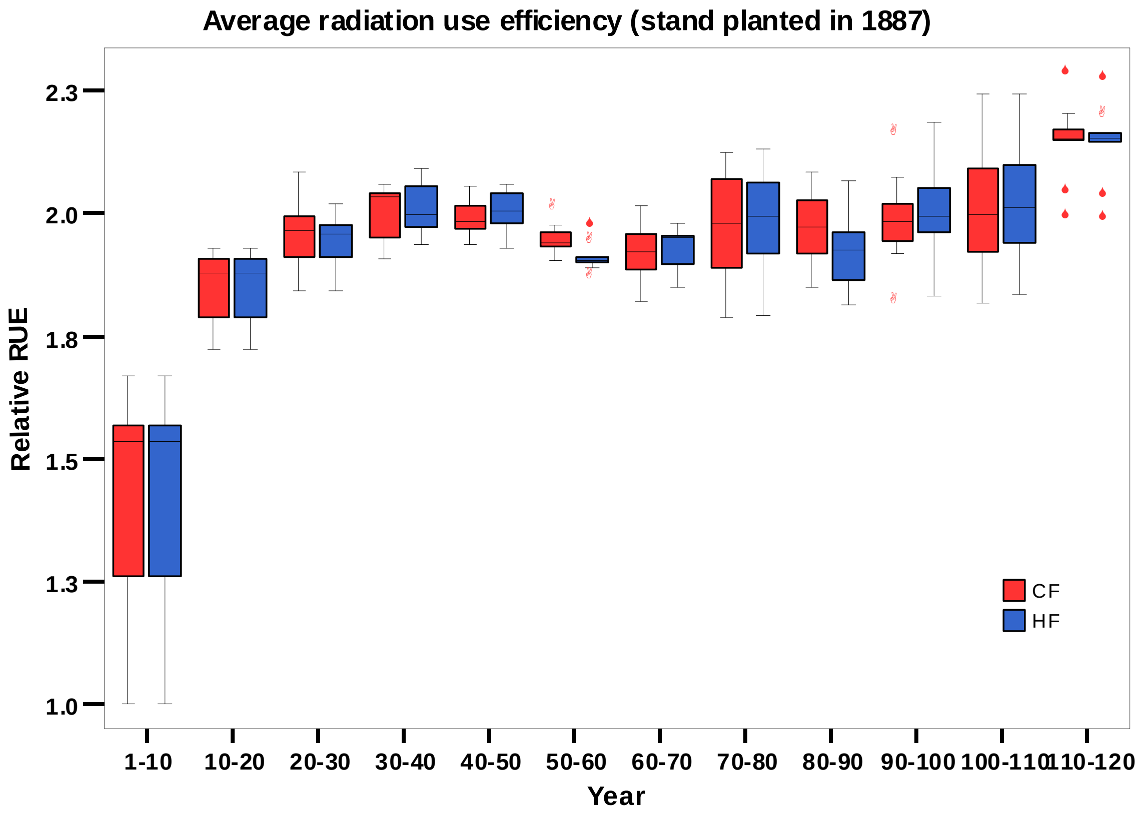

Figure 27: Box plots showing the average relative radiation use efficiency in coppice and high forests planted in year 1887 by ten years time interval. Value of planting year was considered as 1, and the rest were assigned accordingly. The line within the box shows the value of median.

The test statistics showed that the thinning has no statistically significant difference (@α= 5%) in RUE of the coppice and high forests by age of trees in the oldest plot. It means the effect of thinning in RUE in the oldest stand is independent to the selection of system. Details on statistical values are given in Tables 12 (a, b & c).

Table 12: Summary statistics on descriptive analysis, coefficient of determinant and pair wise t-test related to radiation use efficiency (RUE) of the oldest plot planted in year 1887

a) Descriptive analysis

	Mean	N	Std. Deviation	Std. Error Mean
Coppice forest	0.952	120	0.960	0.009
High forest	0.950	120	0.952	0.009

b) Correlation analysis

	N	r^2	Significance level
Coppice and high forests	120	0.954	<0.05

c) Paired sample test

	Paired differences					t	df	Sig. level (2 tail)
	Mean	std. Deviation	Std. error mean	95% CI of the difference				
				Lower	Upper			
(CF & HF)	0.002	0.029	0.003	-0.003	0.007	0.673	119	0.502

Unlike other parameters of growth response, the figure plotted to observe the effects of thinning on RUE at stand level showed no clear differences. Figure 28 showed that there were differences between the two management systems for single year in various stages of development. For example, the stand having 30-40 year old trees showed that the difference in RUE when the trees were 31 years old. This is because the first thinning to 30 years old forest was done in the coppice forests. In the next year the coppice forests showed lower RUE than in the high forests, where there has been no intervention yet. Similar differences in RUE in remaining stands were noticed. From the figure, it is really difficult to distinguish which system has the higher efficiency at stand level because most of their development phase they showed the same efficiency. Only statistical tests, which is presented later on, would tell us more on this matter.

Figure 29 shows that the RUE within applied management system increased with increasing age up to certain level. It is clearly seen that the efficiency was increased up to the point when the stand reached to 30-40 years old. While comparing between two systems, the increasing rate was reduced by the first thinning applied to 30 years old trees in coppice forests. As a result, stand having 30-40 years old trees and treated by the first thinning in the coppice forests had lower RUE than the high forests, where there was no intervention up to the age of 50 years. But no clear differences were noticed to the stand treated with second and/or third thinning applied. From figure 29, it is clear, that variation in RUE differs among the stand age, i.e. the younger aged stand (20-30 years) had higher variation and the older stand (110-120 years) had lower variation.

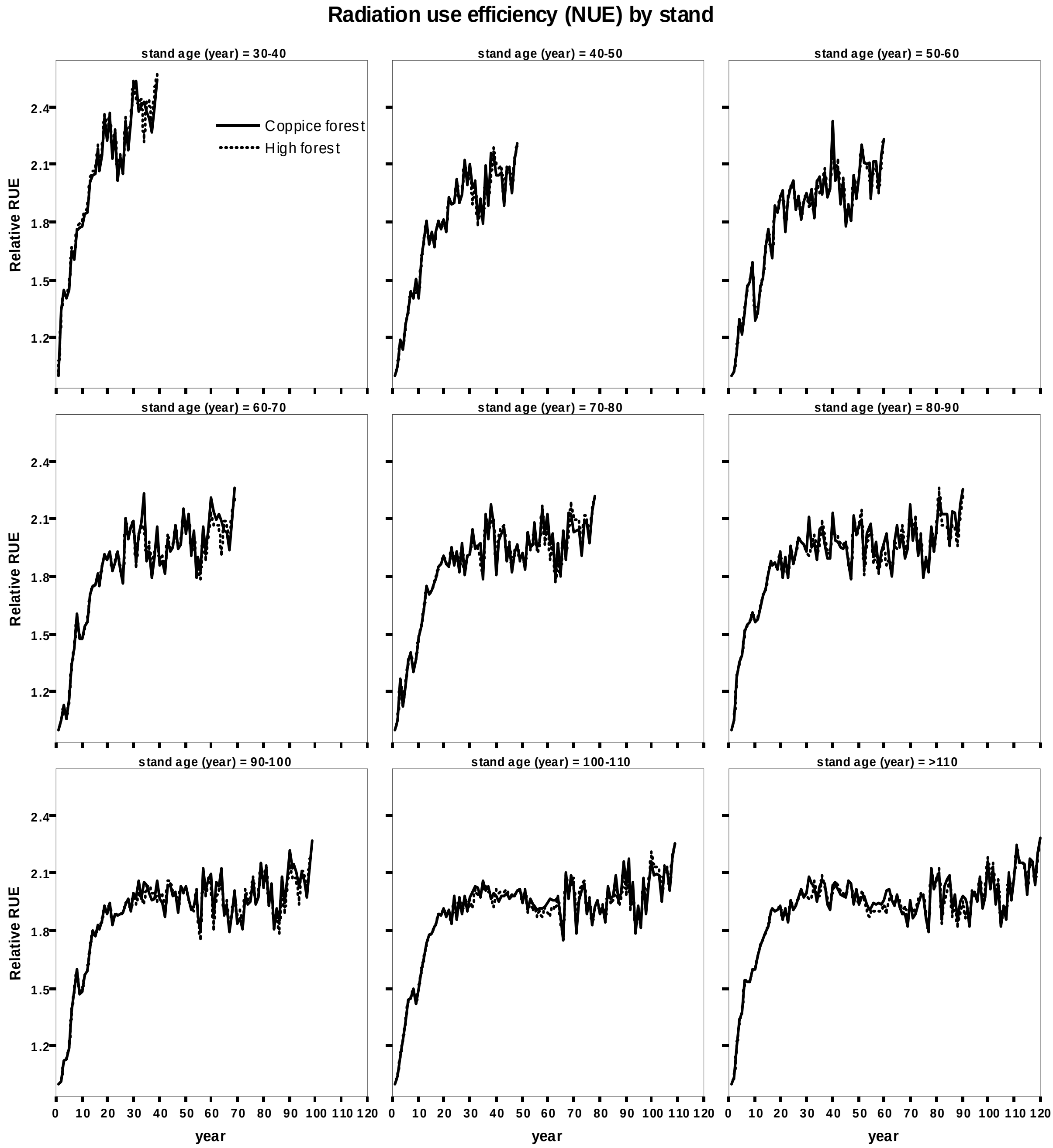

Figure 28: The temporal development of relative radiation use efficiency in coppice and high forests by stand. The rotation age was divided into 12 age classes and formed 12 different stands in the forest by age. Plots were grouped according to their age. Then the average of plots with same age class was calculated. Value for the planting year was considered as 1 and the rest were calculated accordingly.

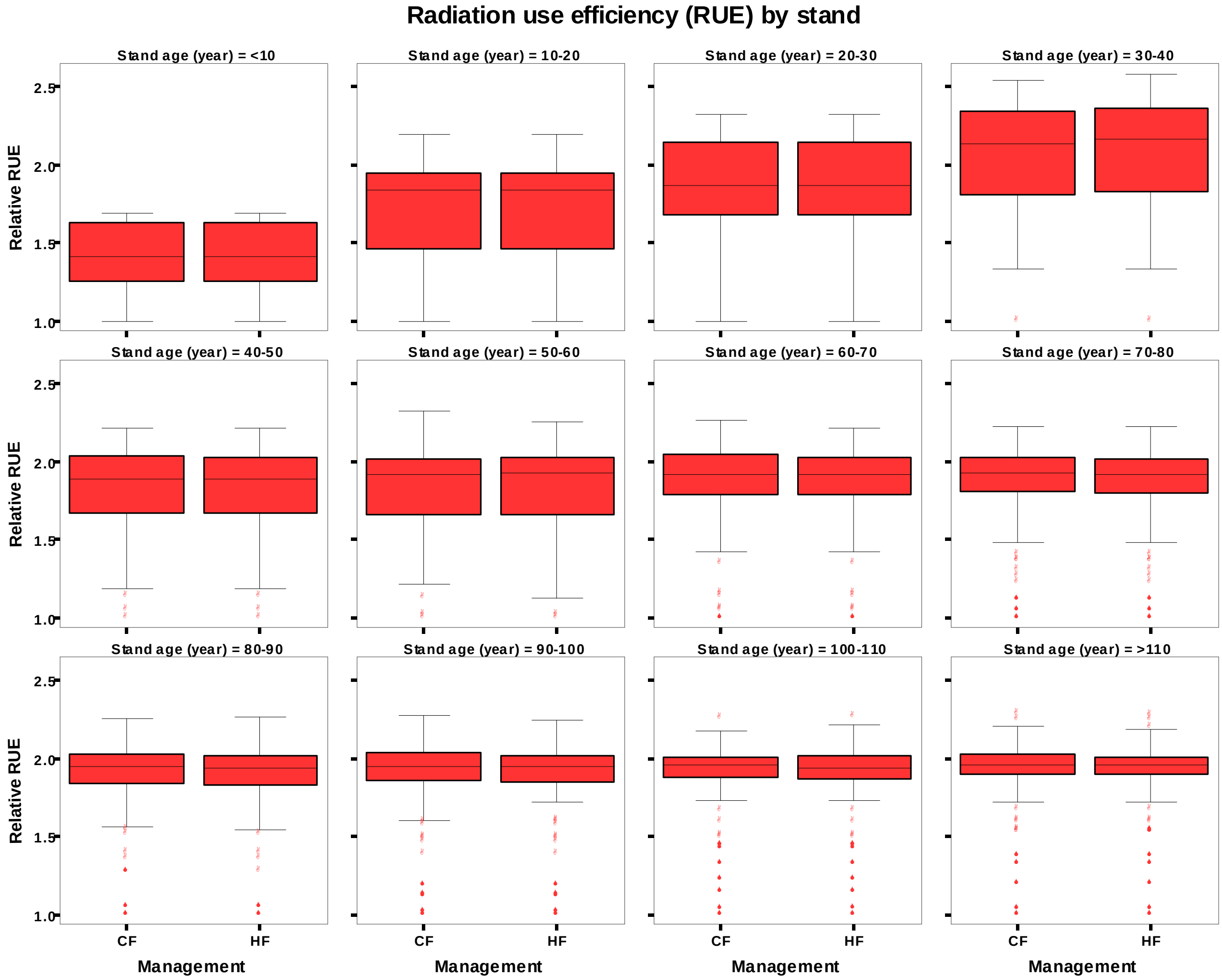

Figure 29: Box plots showing the average relative radiation use efficiency in coppice and high forests by stand age. The rotation age was divided into 12 age classes and formed 12 different stands in the forest by age. Plots were grouped according to their age. Then the average of plots with same age class was calculated. Value for the planting year was considered as 1 and the rest were calculated accordingly.

Although the differences in RUE at stand level were not clearly visible in presented figure, the test statistics shows thinning has statistically significant difference (@α= 5%). in RUE between coppice and high forests when the whole forest is considered under study. For detail values of statistical test follow the Table 13 (a, b & c).

Table 13: Summary statistics on descriptive analysis, coefficient of determinant and pair wise t-test related to radiation use efficiency (RUE) in coppice and high forests by stand

a) Descriptive analysis

	Mean	N	Std. Deviation	Std. Error Mean
Coppice forest	1.876	763	0.273	0.001
High forest	1.873	763	0.271	0.001

b) Correlation analysis

	N	r^2	Significance level
Coppice and high forests	763	0.992	<0.05

c) Paired sample test

	Paired differences					t	df	Sig. level (2 tail)
	Mean	std. Deviation	Std. error mean	95% CI of the difference				
				Lower	Upper			
(CF & HF)	0.003	0.033	0.001	0.0010	0.0059	2.868	762	0.004

4 Discussions

4.1 Models application

The simulation result of BIOME-BGC shows that model is sensitive to applied forest management interventions. The regular extension in application of models by introducing species specific parameterization has developed the model as diagnostic tools to assess the impacts of management to the forest ecosystems. Here, the adapted model by incorporating extensions on hydrology (Pietsch et al., 2003), specific species parameterisation (Pietsch et al., 2005) and self initialisation (Pietsch and Hasenauer, 2006) was used to study forest ecosystems in Austria. An extended model shows significant relationship (r^2=0.90) between the predicted and observed volume (Fig. 7). The trend analysis of the standardised volume residual shows no systematic trend while the plotted volume residual with stand parameter and characteristics (Fig. 8). Furthermore, the pair wise t-test also proves that there is no statistically significant difference (@α= 5%) between the predicted and the observed volume. The confidence interval of the mean of differences between predicted and observed volume shows no bias results with the prediction interval of -31.90 to 30.37% in the future (Table 5). As the model seems sensitive to management intervention applied in the coppice forests, it could be suitable diagnostic tool to assess the required ecosystems parameter under this forest management regime.

4.2 Growth Response

The analysis of the model's sensitiveness towards coppice forests (by this study) and high forests (Pietsch et al., 2005) shows that models could be used on diagnostic ecosystem mechanisms within both forest systems. As we were further interested to compare the growth responses, in terms of growth efficiency, nitrogen use efficiency, water use efficiency and radiation use efficiency, of the forests to thinning intervention in both forests, the modelling of temporal development of stand using extended BIOME-BGC was conducted. The differences in results on growth response after thinning has been summarised in Figure 30, which shows the difference in values. The positive value shows higher efficiency in coppice forests, and vice versa.

Thinning applied to forests increased the efficiency in GE, NUE and WUE, and decreased in RUE. On an average the coppice forests have higher efficiency in growth, nitrogen use, water use and radiation use (Table 6-13). But the intensity and duration of effects in efficiency differs according to parameters as well as the selection of systems. Figure 30 exhibited the duration of the effects of thinning was the longest in NUE, followed by WUE, GE and the shortest in the case of RUE. Also the intensity of effects was highest in NUE, followed by WUE, GE, and the lowest in the case of RUE. Although the graph plotted about old stands shows differences in efficiency in all parameters, only the NUE shows the statistically significant difference between systems, which is reflected by the pair wise t test (Tables 6, 8, 10 & 12). Moreover, if we analysed at forest level, the growth responses of the stand to thinning shows all four parameters have statistically significant differences between the two applied management practices (Tables 7, 9, 11 & 13). This is because the response to thinning was noticed higher in earlier ages of stand development (Fig. 10, 15, 20 & 25), and the forest composed of high number middle aged plots (Fig. 5).

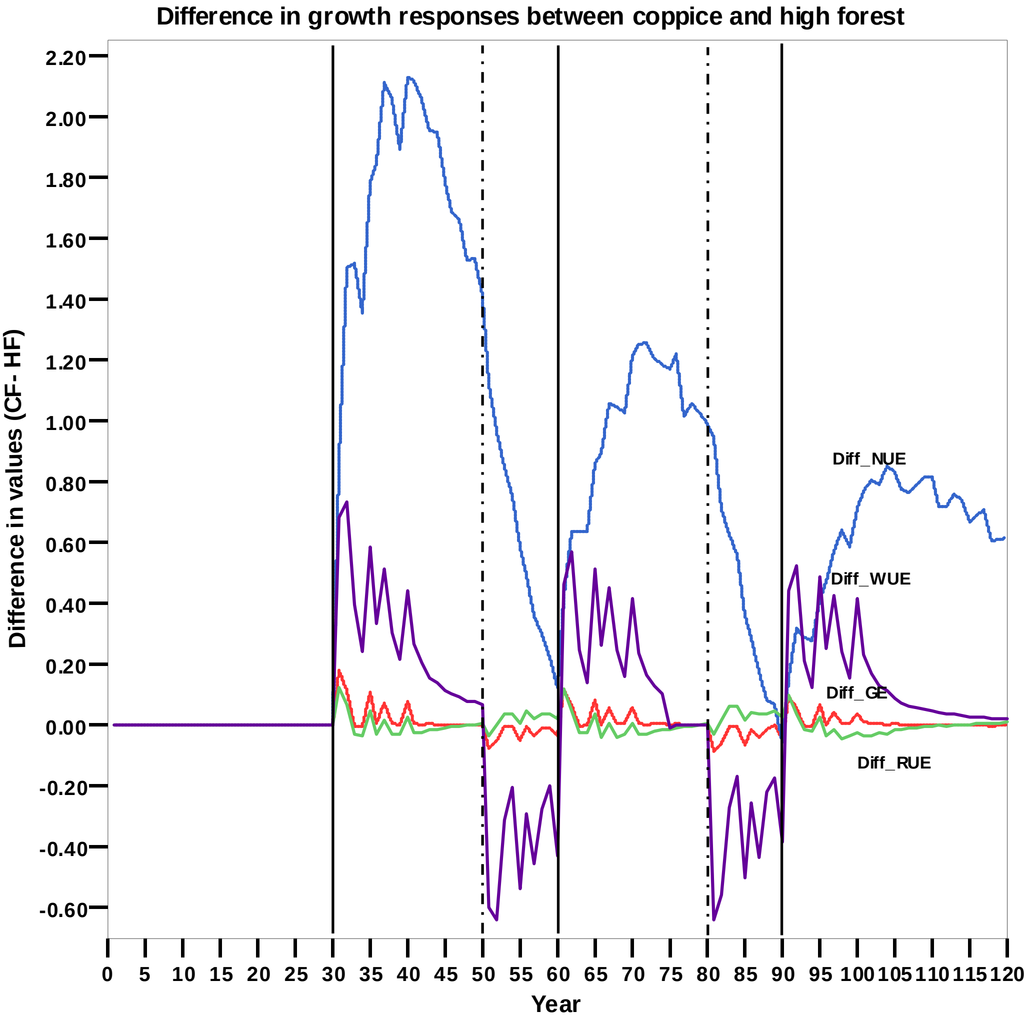

Figure 30: The difference in value in relative efficiency of growth parameters between coppice and high forests. The efficiency value of planting year was considered as 1, and the rest of the years were assigned accordingly. Then differences in coppice and high forests were calculated, and presented in their respective units (i.e. GE in kgCm^{-2}, NUE in CN^{-1}, WUE in gCmm^{-1} and RUE in kgCW^{-1}). Positive value shows the higher efficiency in coppice forest and vice versa.

As described in section 2, the model output is based on photosynthesis which assimilates carbon in plants as biomass. Such processes in the model are simulated by using an integral of the leaf photosynthetic capacity and the leaf nitrogen profile over the entire canopy (dePury and Farquahar, 1997). The photosynthetic assimilation is regulated by daily meteorological conditions, namely minimum and maximum air temperature, vapour pressure deficit, solar radiation, precipitation, and canopy leaf area. The rate of photosynthesis is affected not only by photosynthetic rates in the leaves but also by leaf area index (LAI) in the canopy (Hikosaka et al. 2005). Since the study plots, located in the same flat area, have no significant variation on the climatic conditions (Table 1), the differences between the growth responses is only caused by the changes in leaf area of the stand. The temporal difference in leaf area between coppice and high forests is noticed according to thinning and the age of stand when the intervention is applied (Fig. 31).

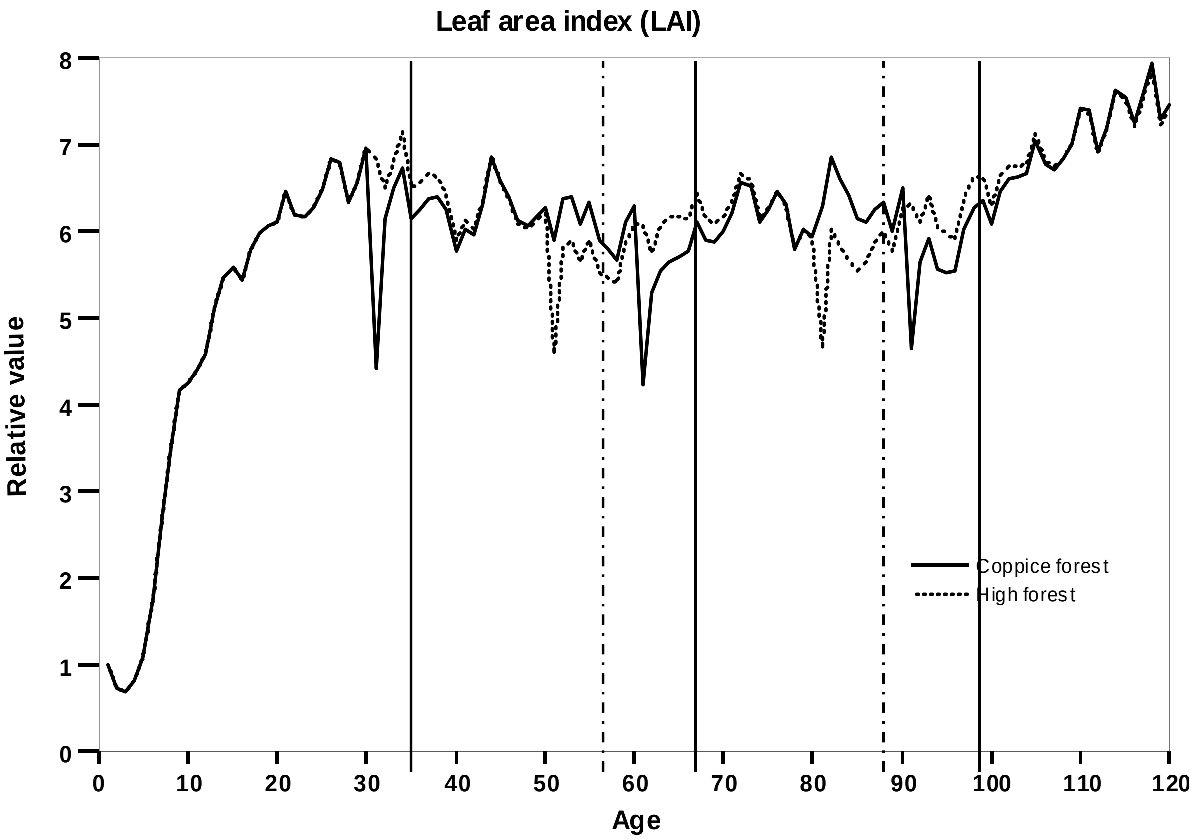

Figure 31: The temporal development of relative leaf area index (LAI) in coppice and high forests. The LAI of planting year was considered as 1, and the rest of the years were assigned accordingly.

Figure 31 shows that thinning reduced LAI on the remaining stand and lasted for a few years. As the coppice forests have been treated one more time than high forests, the coppice forests shows comparatively lower LAI for few more years than high forests. According to model structure the lower simulated growth should be expected in coppice forest rather than in high forests, because it has lower LAI than high forests for some more years on its rotation. But the better growth was seen in coppice forests rather than in high forests (Fig. 9). This is because the growth parameter responds in a different way as per the applied management interventions. So, the detail study of GE, NUE, WUE and RUE with corresponding management intervention is significant. It was found the efficiency has been increased for certain years in both systems after thinning (Fig. 10, 15, 20 & 25). Although the thinning increases the efficiency in both management systems, the differences in intensity and duration of the effects have been seen between selected management practices (Fig. 11, 16, 21 & 26).

4.2.1 Growth efficiency

Thinning reduced pool sizes of vegetation, LAI (Fig. 31) and living stem of the stand (Fig. 32). In the following year the LAI reached a maximum whereas the stem is still increasing. Applying management intervention increased the GE up to the age when maximum LAI, and then fell down gradually with the increase in living stem as the LAI already reached its climax. It is evident that the GE declined with stand age as the LAI already reached maximum early and living stem is still increasing (Hunt et al., 1999). As the thinning applied in coppice and high forests affect in LAI and living stem it has impacts on the GE. The highest increases in GE, due to increase in NUE (Fig. 15), in the following year and lasted for 10-12 years, and the intensity is highest in the earlier age (Fig. 10). The study shows that the thinning enhances the GE as a result of NUE (Merganicova et al., 2005).

The comparison of the GE of two management systems, shows that the growth efficiency at the oldest stand shows the higher values (Fig. 11) in coppice forests than the high forests although it is statistically insignificant at α= 5% (Table 6). It also shows that the higher growth efficiency in those forest are seen which are recently treated with thinning. The increasing rate in GE is higher in the coppice forest in comparison to the high forest as the thinning intensity was higher in coppice forests and it helps to optimal distribution of nitrogen in above ground biomass. Moreover the coppice forests show a higher level of variation in increasing GE than high forests after intervention (Fig. 12). Also the study at forest level shows the higher GE in coppice forests. The statistical significant difference at forest level has been noticed at α= 5% (Table 7). As the forest has the highest number of plots having young forests (Fig. 5) and the highest rate of GE in young stages of stand, the differences at forest level are significant. As like in the oldest stand, the higher variation in GE is noticed in coppice forests than high forests after the intervention.

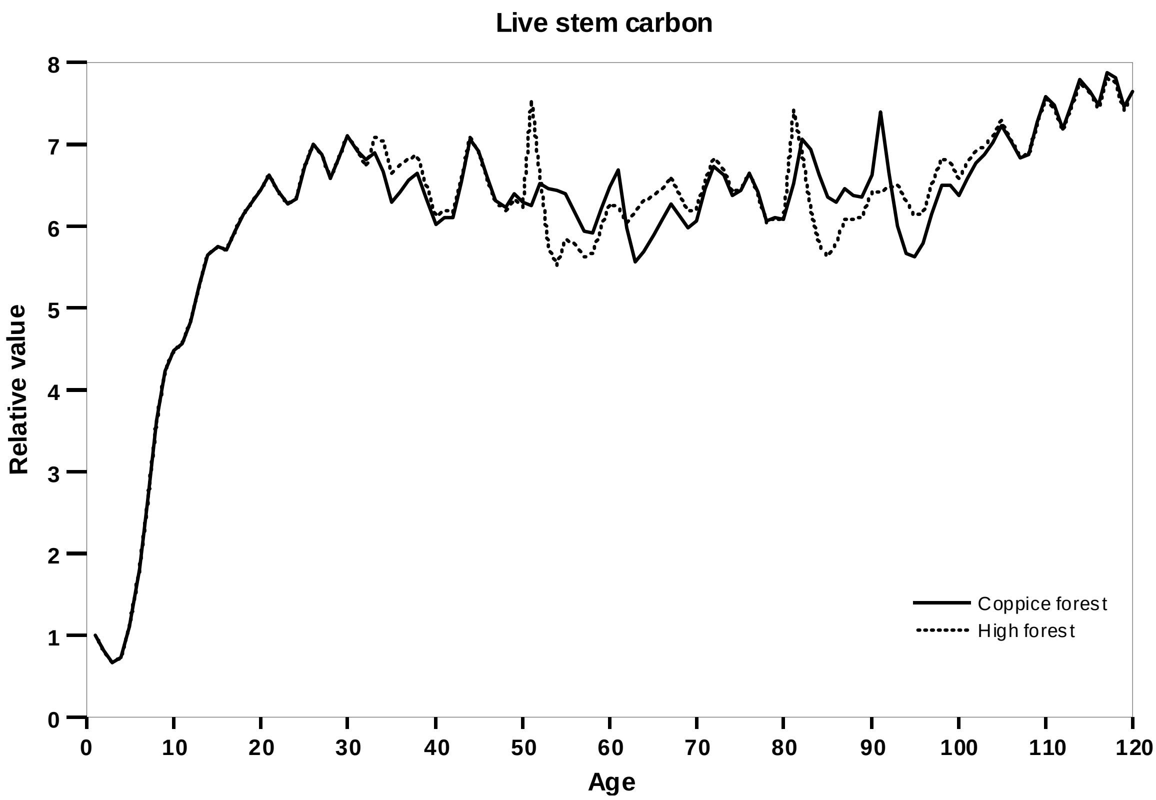

Figure 32: The temporal development of relative live stem carbon (kgCm^{-2}) in coppice and high forests. The value of planting year was considered as 1, and the rest of the years were assigned accordingly.

4.2.2 Nitrogen use efficiency

The NUE in coppice forests is relatively high in all ages of stand development. The higher performance in NUE in this forest is caused by the optimal distribution of nitrogen after thinning, which increases the NUE per unit leaf area. Increase in nitrogen efficiency is evident in the coppice forests (Fig. 15 & 16) even decreased LAI after thinning (Fig. 31). Increasing NUE when LAI is reducing tells us that the forests might have limited nitrogen availability, and the thinning improved the efficiency by promoting optimal distribution of nitrogen. If the nitrogen in the canopy is limited, the higher LAI enhances canopy photosyntesis due to increased light interception but reduces leaf nitrogen per unit leaf area and finally leads to the decline of the photosynthetic capacity of leaves. An optimal LAI at which the canopy photosynthetic rate for a given canopy nitrogen is maximized (Hirose et al. 1997) exists. The canopy photosynthesis is maximized if the nitrogen is distributed optimally rather than uniformly (Hirose and Werger, 1987 b), and the leaves in microenvironments that receive the highest radiation have the highest nitrogen concentration (Field 1983).

Although the thinning decreased the nitrogen content in the leaf to both forests after intervention, the duration and extent of the effects differ to each other. During current stand development, the coppice forests show higher nitrogen in the leaf for most of the years, except for the 10 years after each thinning (Fig. 33). It has been found out that more than 50% of leaf nitrogen is directly related to photosynthesis (Evans and Seemann, 1989) and strong correlations have been demonstrated between leaf nitrogen and photosynthesis (Evans, 1989). As the coppice forests have more leaf nitrogen in comparison to the high forests, they have higher efficiency in production than the high forests, and finally have a higher yield (Fig. 9).

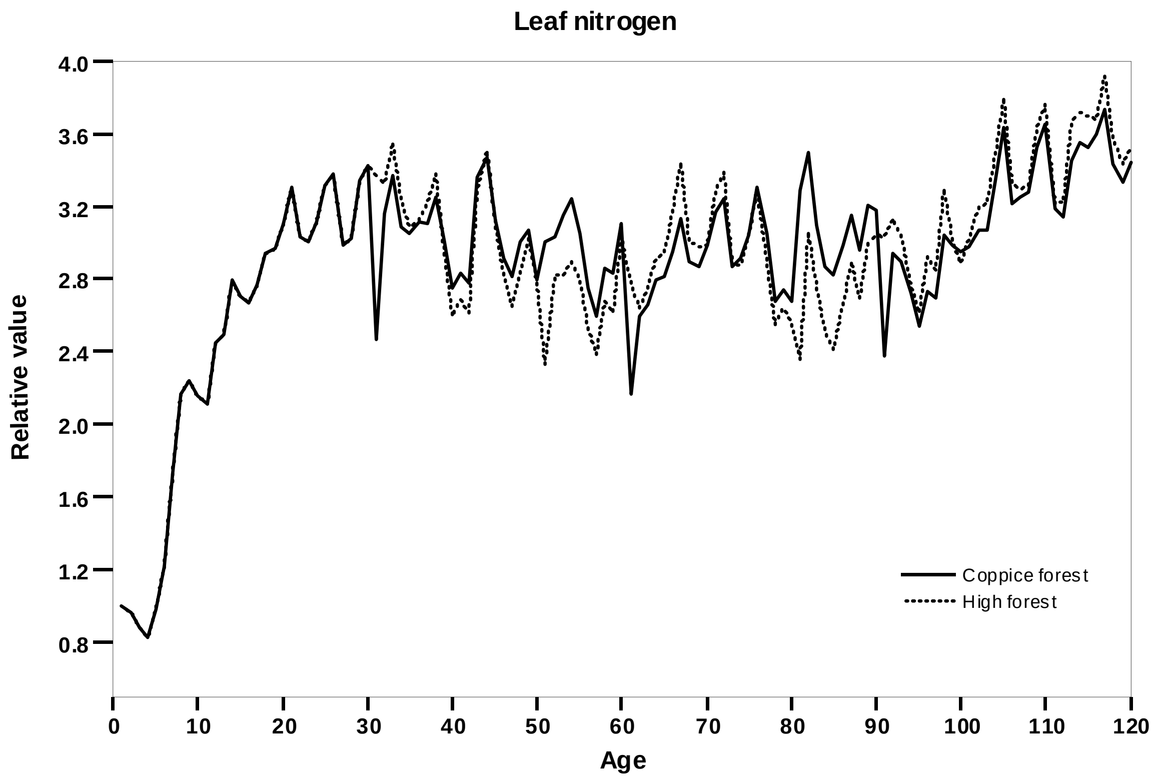

Figure 33: The temporal development of relative leaf nitrogen ($kgNm^{-2}$) in coppice and high forests. The value of planting year was considered as 1, and the rest of the years were assigned accordingly.

The comparison of nitrogen use efficiency between two management practices shows that the coppice forests have higher NUE, by age of trees (Fig. 15, 16 &17) and by stand (Fig. 18 &19) as well, than the high forests. The effects of thinning in NUE is statistically significant (@ α= 5%) between two management practices both by age of trees and by stand (Table 8 & 9). Moreover, the variation in the values after thinning is higher in the coppice forests (Fig. 17 and 19).

4.2.3 Water use efficiency

Although few studies say there will be a trade off between the NUE and WUE, this study shows different results. Any increase in stomatal conductance tended to increase intercellular CO_2 concentration, which led to an increase in nitrogen use while decreasing WUE. Compromises exist between water and nitrogen use efficiency among Californian evergreens (Field, Merino and Mooney, 1993). But this study does not support, and shows that both WUE and NUE have been increased after thinning (Fig. 30). After thinning, it increases the NUE (Fig. 15) and decreases the transpiration (Fig. 34). As the NUE is increased even with the decrease in LAI, it increases the production potential per unit leaf having lower rate of transpiration. It finally increased the production per unit loss of water by transpiration. Consequently it increased NUE and WUE on the same time.

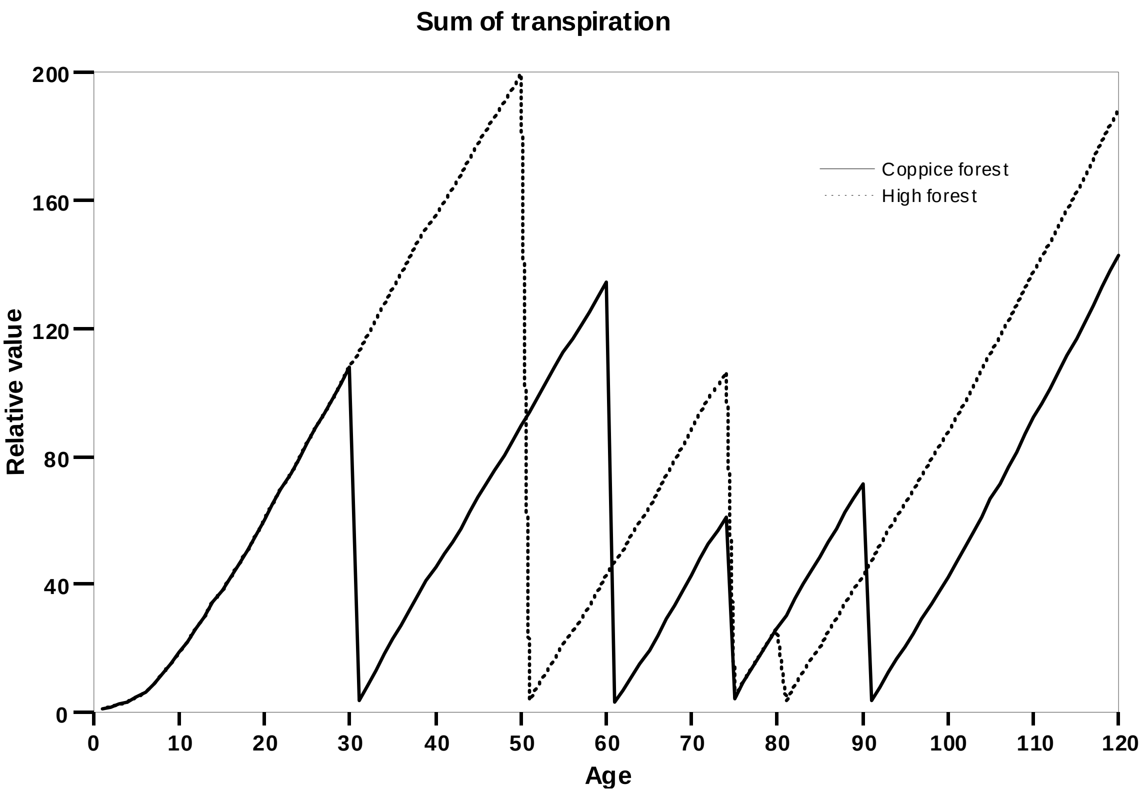

Figure 34: The temporal development of relative transpiration (kgH_2Om^{-2}) in coppice and high forests. The value of planting year was considered as 1, and the rest of the years were assigned accordingly.

The effects of thinning have been noticed in WUE of forest stands in both forests, but the trends in increasing intensity and duration of effects after thinning differ from each other (Fig. 20 & 21). The result of the oldest stand shows higher increment in WUE of coppice forests than in the high forests has been noticed after thinning (Fig. 21). Although the results show clear differences in WUE by age of the trees between two systems due to thinning, they are statistically insignificant (@ α= 5%) as long as the study only based on oldest stand (Table 10). On the contrary, the pair wise test statistics by stand shows statistical significant difference in effects due to thinning between two forest practices (Table 11). Like in others studied parameters, more variation in WUE after thinning has been noticed in the coppice forests in comparison to the high forests (Fig. 22 & 24).

4.2.4 Radiation use efficiency

During this study, the effects of thinning in RUE and the comparison of efficiency by applied management practices were analyzed. It is known that the production of plant biomass depends on both light interceptions by leaves and on the efficiency with which the intercepted light is used to produce dry matter. Applying thinning intervention has effects in RUE by reducing the leaf area (Fig. 31) and the nitrogen content in the leaf (Fig. 33), which controls the photosynthesis activities of plants. Although both in photosynthetically absorbed radiation (Fig. 35) and NPP (Fig. 36) is reduced after thinning, the increases the nitrogen use efficiency of the stand (Fig. 15) help to increase the RUE in the following year of thinning. The thinning increases the RUE for 1-2 years following the intervention (Fig. 25 & 27), and then it gradually goes down as the absorbed radiation increased without increased in NPP. The reduced efficiency is evident for about 10 years (Fig. 26). While comparing the effects of thinning in RUE, the length of effects is seen almost the same between two management practices, but the intensity in increasing efficiency is found higher in the coppice forests. This is because the coppice forest has significantly high NUE rather than high forests. Forest stands show higher efficiency for the following 1-2 years of thinning, and show lower RUE for about 10 years afterwards (Fig. 30). Even though graphs plotted for temporal development shows that thinning has effects on RUE in both forest practices, the differences in RUE is statistically insignificant (@ α= 5%) bye age of the trees in the oldest plot (Table 12). But stand wise comparison shows significant differences in RUE (@ α= 5%) due to thinning within the two management practices (Table 13) as the effects of thinning has been found higher in younger stands and the forest is composed of larger number of younger plots.

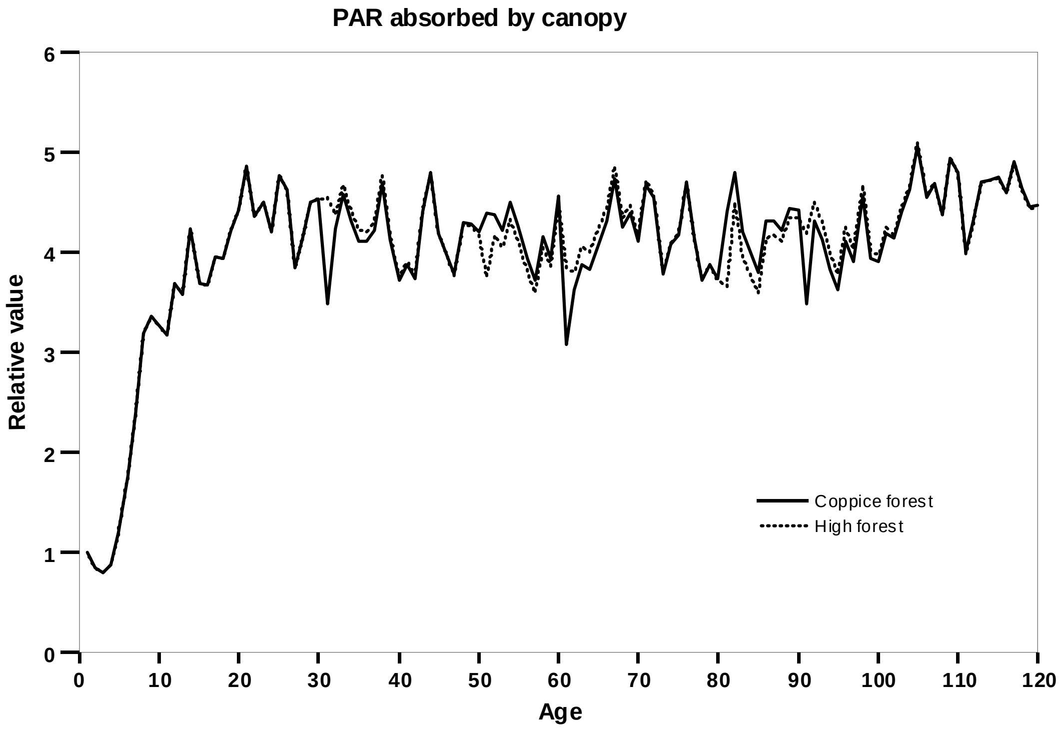

Figure 35: The temporal development of relative PAR absorbed by canopy (Wm^{-2}) in coppice and high forests. The value of planting year was considered as 1, and the rest of the years were assigned accordingly.

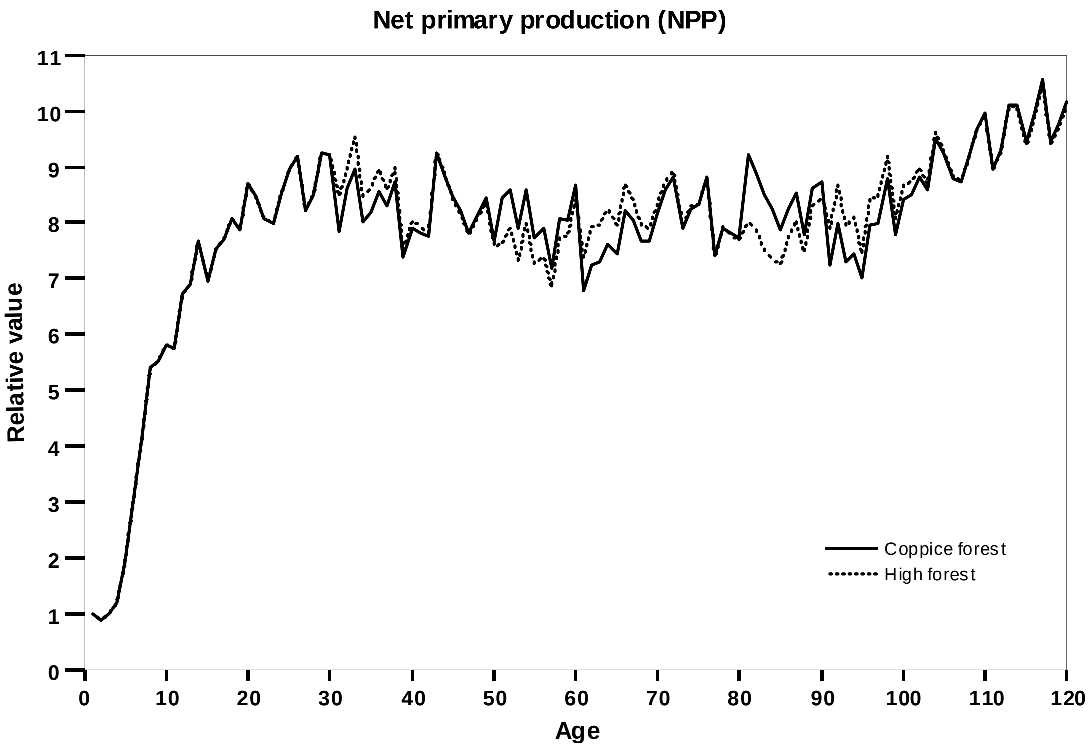

Figure 36: The temporal development of relative NPP ($kgCm^{-2}$) in coppice and high forests. The value of planting year was considered as 1, and the rest of the years were assigned accordingly.

5 Conclusions

The study concludes that the extended BIOME-BGC model is sensitive to management intervention in coppiced oak forests. The strong positive relationship between the predicted and observed volume with no biased results verifies that the model can be used as a diagnostic tool to assess management effects. In case of coppice forests, the model was able to explain 90% of the observed variation in standing volume of the stand. Although the model underestimated the volume by one percent in total, it overestimated the volume for trees which are over 110 years old. Such variation is evident as the age of trees was estimated by using a yield table. That is why there are, still possibilities to further improve the model's application by using the age of trees measured directly in the field.

The extended BIOME-BGC model is used to analyze the effects of thinning on growth response in the coppice and high forests. Simulations with the extended model exhibited the effects of thinning on growth response of the remaining forests. It is evident from the simulated results that the extraction of biomass is more in coppice forests than in high forests. The high forest shows the higher stock of carbon in forest ecosystems. The result further shows that thinning has increased the growth efficiency, the nitrogen use efficiency, the water use efficiency but decreased the radiation use efficiency in both forest types. Among them the changes in NUE is significant because thinning helps to optimally distribute nitrogen in above ground biomass which increased the physiological efficiency of leaf per unit area.

The comparison of growth responses between two forests shows the difference in duration and intensity of thinning effects. The study also revealed that the effects differ by the age of the trees within the same forests. The higher level of effects has been noticed in the younger trees, and it decreases with increase in the age of tree. The comparison between two practices shows that on an average the coppice forests have higher values in growth efficiency, nitrogen use efficiency, water use efficiency and radiation use efficiency. Among four parameters of growth responses, only the difference in NUE is significant (@ α= 5%) as the study was based on temporal development of stand. Moreover the comparison of effects of thinning by stand also shows higher values in all parameter of growth responses in coppice forests. But in this case, the differences in all studied parameter's are significant (@ α= 5%) between two practices. Although the coppice forests show better productivity in the current time, the variation in efficiency after thinning in coppice forests ensure that it has a higher management risk in comparison to high forests.

The results presented conclude that the extended BIOME-BGC used in this study is able to simulate forest ecosystems under coppice forests, and can be used as a diagnostic tool to assess the management intervention in coppice forests. Among the studied parameters of growth responses, the NUE has been highly influenced due to thinning intervention. On the basis of simulated results the coppice forests show higher growth efficiency than the high forests. As the coppice forest, which has comparatively higher amount of biomass removed, shows the higher growth efficiency after thinning emphasized the further study to be focus on the effects of thinning in nutrient cycling.

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Annex

Annex 1: The average climatic data (1960-2005) of the study area by stands

Site	Particular	Daily Tmax (°C)	Daily Tmin (°C)	Tday (°C)	Annual Prcp ($mm.yr^{-1}$)	VPD (Pa)	Srad ($W.m^{-2}$)	Average daylen (h)
	Average	13.71	4.98	11.31	593.03	574.42	249.53	12.00
	Min	-16.04	-24.55	-18.18	372.00	18.36	19.22	8.10
1	**Max**	37.32	22.49	32.48	821.10	2505.27	522.47	15.90
	SD	9.67	7.35	8.92	93.15	438.69	125.33	2.69
	Mode	19.52	-0.45	17.04	680.30	165.66	252.11	15.90
	Average	13.81	5.04	11.39	584.02	579.34	249.37	12.00
	Min	-16.05	-24.54	-18.18	369.90	18.39	19.81	8.10
2	**Max**	37.40	22.58	32.50	810.30	2516.38	522.29	15.90
	SD	9.67	7.34	8.91	90.35	442.07	125.35	2.69
	Mode	19.50	-0.84	19.52	678.20	290.34	252.07	15.90
	Average	13.92	5.08	11.49	573.64	585.59	249.30	12.00
	Min	-16.10	-24.59	-18.24	367.60	18.23	20.42	8.10
3	**Max**	37.51	22.69	32.53	798.90	2537.77	522.23	15.90
	SD	9.68	7.34	8.91	87.43	446.40	125.40	2.69
	Mode	19.20	11.30	14.81	510.50	104.56	82.92	15.90
	Average	13.87	5.05	11.45	576.89	583.40	249.43	12.00
	Min	-16.11	-24.61	-18.25	367.10	18.16	20.11	8.10
4	**Max**	37.48	22.65	32.53	801.70	2535.21	522.35	15.90
	SD	9.68	7.34	8.92	88.27	444.88	125.39	2.69
	Mode	23.04	1.89	15.81		147.56	154.50	15.90
5	**Average**	13.84	5.04	11.42	580.37	581.36	249.44	12.00
	Min	-16.10	-24.59	-18.24	368.30	18.24	19.89	8.10
	Max	37.44	22.62	32.51	806.80	2528.71	522.44	15.90
	SD	9.67	7.34	8.92	89.28	443.44	125.36	2.69

	Mode	19.25	10.15	18.49		167.03	300.20	15.90
	Average	13.85	5.04	11.43	578.98	582.25	249.47	12.00
	Min	-16.12	-24.62	-18.26	367.80	18.13	19.93	8.10
6	**Max**	37.46	22.63	32.52	804.00	2534.48	522.47	15.90
	SD	9.68	7.34	8.92	88.82	444.07	125.38	2.69
	Mode	16.87	10.77	22.01	44.05	169.45	97.50	15.90
	Average	13.92	5.08	11.49	573.53	586.03	249.34	12.00
	Min	-16.13	-24.61	-18.26	367.30	18.14	20.39	8.10
7	**Max**	37.52	22.70	32.54	797.70	2542.97	522.34	15.90
	SD	9.68	7.34	8.92	87.09	446.69	125.39	2.69
	Mode	16.94	13.33	16.93	553.70	98.29	121.01	15.90
	Average	14.06	5.14	11.61	563.27	594.12	249.16	12.00
	Min	-16.18	-24.69	-18.32	366.50	17.91	20.58	8.10
8	**Max**	37.67	22.82	32.58	786.80	2567.59	522.05	15.90
	SD	9.68	7.33	8.92	85.14	452.39	125.49	2.69
	Mode	23.21	10.56	17.47	546.90	238.23	112.55	15.90
	Average	13.89	5.05	11.46	573.99	584.85	249.50	12.00
	Min	-16.16	-24.68	-18.30	366.10	17.94	20.15	8.10
9	**Max**	37.51	22.66	32.54	798.90	2545.79	522.40	15.90
	SD	9.68	7.34	8.92	87.88	445.92	125.40	2.69
	Mode	19.81	2.55	17.71	523.70	288.88	265.34	15.90
	Average	13.97	5.08	11.53	567.38	589.57	249.43	12.00
	Min	-16.20	-24.71	-18.34	366.50	17.82	20.62	8.10
10	**Max**	37.59	22.75	32.56	789.00	2562.04	522.36	15.90
	std. deviation	9.68	7.34	8.92	85.65	449.19	125.46	2.69
	Mode	18.45	11.29	14.86	612.80	132.91	107.11	15.90
11	**Average**	13.90	5.04	11.46	572.30	585.77	249.59	12.00
	Min	-16.20	-24.72	-18.34	365.80	17.81	20.16	8.10
	Max	37.53	22.68	32.54	793.90	2553.18	522.48	15.90
	SD	9.68	7.34	8.92	87.04	446.56	125.44	2.69

	Mode	25.41	-0.03	21.84		107.70	290.03	15.90
	Average	13.95	5.06	11.51	567.60	589.45	249.59	12.00
	Min	-16.28	-24.79	-18.42	366.60	17.59	20.41	8.10
12	**Max**	37.60	22.75	32.56	789.00	2572.38	522.62	15.90
	std. deviation	9.69	7.34	8.92	85.35	449.08	125.47	2.69
	Mode	21.12	-1.19	17.88	519.80	213.14	167.32	15.90
	Average	13.98	5.08	11.53	566.70	590.42	249.48	12.00
	Min	-16.25	-24.75	-18.39	368.00	17.70	20.61	8.10
13	**Max**	37.61	22.77	32.56	789.30	2570.01	522.50	15.90
	SD	9.69	7.34	8.92	85.24	449.75	125.47	2.69
	Mode	5.64	0.92	23.76		154.25	132.57	15.90
	Average	13.86	5.01	11.43	575.24	584.31	249.71	12.00
	Min	-16.26	-24.76	-18.40	368.10	17.67	19.80	8.10
14	**Max**	37.51	22.67	32.53	797.80	2559.32	522.85	15.90
	SD	9.69	7.34	8.92	87.42	445.50	125.45	2.69
	Mode	16.46	-0.48	20.21		178.03	230.63	15.90
	Average	13.77	4.97	11.35	584.34	579.59	249.83	12.00
	Min	-16.24	-24.73	-18.37	369.40	17.76	19.25	8.10
15	**Max**	37.42	22.59	32.51	807.20	2546.92	523.05	15.90
	SD	9.68	7.35	8.92	90.29	442.22	125.41	2.69
	Mode	23.74	10.12	15.58	666.70	123.20	150.14	15.90

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