THE CLIMATE CHANGE ADAPTION POTENTIAL OF THINNINGS: A SIMULATION STUDY

Master Thesis

Of

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Abstract

Forest ecosystems are affected strongly by changing climate conditions. The mountain forests of the Alps are particularly exposed to climate change, highlighting the importance of adapting forest management to these changing conditions. Adaption aims to reduce negative impacts and to benefit from positive effects of a changing climate, in order to support sustainable forest management and the provisioning of important ecosystem services also in the future. Especially Norway spruce, which is currently the economically most important tree species in Austria, is highly vulnerable to changing climate conditions. The aim of this work was to analyze thinnings as a tool of climate change adaption in Norway spruce forests, using simulation modeling. The specific objectives were: 1) to evaluate the process-based simulation model iLand, with particular focus on its ability to reproduce the thinning responses observed at three thinning trials in Austria, 2) to assess the possible impacts of changing climate conditions at the sites of these thinning trials (Eibiswald, Karlstift, Ottenstein) under three climate scenarios and two representative time periods (2040-2060 und 2080-2100), and 3) to assess the effect of thinnings under climate change in the context of adaption.

To evaluate iLand simulation results were compared with long-term (36-46 years) observations from thinning trials with regard to diameter at breast height (dbh) and dominant height. The results showed that iLand is well able to reproduce the response of trees to a wide variety of different thinning interventions across the range of studied sites. Nearly half of the observed variation in the dbh at the end of the study period could be explained by the model (R^2 between 0.436 and 0.621), while for dominant height the R^2 was between 0.185 and 0.503. Due to satisfactorily performance of the model in this test against independent data it can be deemed suitable for the subsequent assessment of thinning effects under climate change. Scenarios of climate change were found to strongly influence: the net primary production (NPP), mean annual increment (MAI), annual dbh increment and individual tree stress index across sites. The range of the impacts were between -11.5% and + 13.4% for NPP, between -14.8% and +20.4% for MAI, between -5.5% and +8.3% for dbh increment, and between -25.0% and +42.9% for stress index. Effects were most strongly negative at the low elevation site (Ottenstein) under warmer and drier conditions, and were most strongly positive at the high elevation site (Eibiswald). Thinnings did modulate climate effects, with both positive and negative effects. The strongest improvement in growing conditions through thinning was achieved under warm and water-limited conditions. This study underlines the importance of thinnings as an adaption option in forest management in order to deal with the challenges and opportunities of a changing climate.

Keywords: Climate change impacts, thinning, iLand, climate scenarios, Norway spruce, forest management

Kurzfassung

Waldökosysteme werden in der Zukunft mit hoher Wahrscheinlichkeit stark von einem wandelnden Klima beeinflusst werden. Dabei sind die klimatischen Änderungen gerade im Alpenraum besonders hoch, was eine große Herausforderung für die Waldbewirtschaftung darstellt. Um die negativen bzw. auch positiven Einflüssen des Klimawandels zu begegnen, muss die Waldbewirtschaftung angepasst werden, damit auch in Zukunft eine nachhaltige Waldbewirtschaftung möglich ist. Dabei ist gerade die Fichte, die ökonomisch relevanteste Baumart Österreichs, im Vergleich zu anderen Baumarten sehr stark gefährdet. Ziel dieser Arbeit war es, Durchforstungen als mögliches Instrument der Klimaanpassung in Fichtenwäldern in einer Simulationsstudie zu untersuchen. Die speziellen Zielsetzungen waren: 1) die Evaluierung des Simulationsmodelles iLand in Hinblick auf die Simulation von verschiedenen Durchforstungseingriffen, 2) die Abschätzung von möglichen Klimaeffekten auf den Untersuchungsstandorten in Österreich für drei verschiedene Klimaszenarien und zwei Untersuchungsperioden (2040-2060 und 2080-2100), sowie 3) die Effekte von Durchforstungen unter Klimawandel abzuschätzen.

Die Fähigkeit von iLand, Durchforstungsreaktionen realistisch wiederzugeben wurde für die beiden Variablen Brusthöhendurchmesser (BHD) und Oberhöhe gegen unabhängige Ergebnisse aus drei Langzeitversuchen (Eibiswald, Karlstift, Ottenstein) getestet. Dabei konnte gezeigt werden, dass iLand bei der Simulation der BHDs sehr gute Ergebnisse lieferte und am Ende des Beobachtungszeitraumes in etwa die Hälfte der Variation der BHDs durch das Model erklärt wurde (R^2 zwischen 0.436 and 0.621). Für die Oberhöhe lagen die R^2 zwischen 0.185 und 0.503. Aufgrund der zufriedenstellenden Evaluierungsergebnisse kann das Modell in weiterer Folge für die Analyse von Durchforstungsreaktionen im Klimawandel verwendet werden. Für die Variablen Netto-Primärproduktion (NPP), mittlerer jährlicher Volumszuwachs (MAI), BHD Zuwachs und Stress Index wurde gezeigt, dass Klimaszenarien sowohl negative als auch positive Auswirkungen haben können, welche sich zwischen -11.5% und +13.4% beim NPP, zwischen -14,8% und +20.4% beim MAI, zwischen -5.5% und 8.3% beim BHD Zuwachs und zwischen -25.0% und 42.9% beim Stress Index bewegen, abhängig vom jeweiligen Versuchsort und vom gewählten Klimaszenario. Die größten negativen Effekte waren am Tieflagenstandort (Ottenstein) unter warmen und trockenen Bedingungen zu beobachten; und die größten positiven Effekte zeigten sich am höchstgelegenen untersuchten Standort (Eibiswald). Die stärkste Verbesserung des Wachstums durch Durchforstung wurde auf Standorten mit schlechten Wachstumsbedingungen dokumentiert. Diese Arbeit zeigt die Wichtigkeit von Durchforstungen als Anpassungsmaßnahmen an den Klimawandel.

Schlagworte: Klimafolgen, Durchforstung, iLand, Klimaszenarien, Fichte, Waldbewirtschaftung

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1 Introduction

Climate change is one of the biggest challenges for European forest ecosystems and current and future forest managers have to deal with the direct and indirect impacts of changing climate conditions. Forest trees and ecosystems could have to cope with the following impacts in central Europe: an increase in temperature, a shift in precipitation with less rainfall in the vegetation period, more frequent weather extremes and an increase in the concentrations of the greenhouse gases (Albert and Schmidt, 2010). In addition to this direct climate effects forest ecosystems are also exposed likely to experience increasing biotic and abiotic disturbances as a result of climate change (Seidl et al., 2014). These change will have enormous effects for forest ecosystems and could change the composition, structure and distribution of forest ecosystems in the future (Malmsheimer et al., 2008). These potential impacts highlight the importance of management strategies to mitigate the negative ecological, social and economic effects from a changing climate, so that forest ecosystems can fulfil their important functions and roles for society also in the future. However the degree of exposure and expected impacts of climate change depend strongly at the local and regional scale, especially in mountainous regions (Lindner et al., 2010). Due to their longevity and the resulting extended production, suitable and timely forest management strategies are very important to reduce the risk for the forest ecosystem through changing climate conditions (Lindner, 2000). In order to provide forest goods and services sustainably also under changing climate conditions, adaption strategies are essential (Seidl et al., 2011). Different adaption measures can help to increase the stress tolerance, the resilience and the dynamic response of ecosystems (Bolte et al., 2009). Lindner et al. (2010) divided the adaptive capacity of European forest ecosystems into two parts: the inherent adaptive capacity of trees and forest ecosystems and the socioeconomic adaptive capacity. Within this adaptive capacity framework silvicultural measures are a part of the socioeconomic adaptive capacity and here thinnings are playing a key role. Some previous studies are underlining the importance of thinnings to enhance the mitigation and the adaption of forest ecosystems to changing climate conditions. (D'Amato et al., 2011; Malmsheimer et al., 2008). Within this management strategies it must be observed, however, that an improvement of one factor can lead to a worsening of another factor, for example the maintenance of higher stocking levels could decrease the structural and compositional intricacy of a forest stand (D'Amato et al., 2011). Trade-offs are thus essential when preparing a forest ecosystem for future changes in the climate system (D'Amato et al., 2011). Due to different impacts of climate change and remaining uncertainties as to future developments no one solution exists, but mix of different adaption strategies should be applied to prepare the forest ecosystems as best as possible. Within the frame of possible silvicultural adaption measures, including an adapted rotation length or a different species composition, thinnings are an important management tool. Through a thinning operation the stand density is reduced and the development trajectory of a forest stand affected. The main objectives of thinnings are: to enhance the stability of the remaining trees, the guidance of the increment to the most qualitative individuals and to produce a saleable product. For a more detailed description of a thinning intervention the following parameters are essential: the kind of thinning, the severity of thinning and timing and frequency of thinning interventions (Pretzsch, 2009). One of the most important parameters in a thinning intervention is the thinning intensity (Ge et al., 2013a), which depends on a determined basal area in a forest stand and which is achieved by the removal of the competitors (Pretzsch et al., 2008). Several previous studies exist, where thinning effects were tested under climate change with different main researches (Garcia-Gonzalo et al. 2007; Jacobsen and Thorsen 2003; Alam et al., 2008). Possible benefits of thinnings under climate change could be the increase of carbon storage and the increment of the individual resistance against abiotic and biotic disturbances (Malmsheimer et al., 2008).

In Austria the Norway spruce (Picea abies (L.) Karst.) is by far the most important economic and ecological tree species, with a share of over 60 % of the total growing stock (Eastaugh et al., 2011). However Norway spruce expected to be particularly vulnerable to the effects of climate change, especially in the lower elevations (sub montane and montane elevation belts) and in areas with increasing temperature and concurrent decrease in precipitation in the vegetation period (Gebert, 2013). Seidl et al., (2011) suggest that in colline areas (300-700 meters) Norway spruce stands should be replaced through more adapted tree species to keep the negative impacts from climate change small. Furthermore also damage from infestation by bark beetle will increase significantly in some parts of Europe (Bolte et al., 2009). Norway spruce is particularly vulnerable to climate change in Central Europe because it was cultivated considerably beyond its natural range in the past, as a result of its economic value. These areas are especially vulnerable to changing climate conditions, because of a lower adaption capacity and increased sensitivity to a changing climate due to a close proximity to the species' range limits (Kahle et al., 2005).

Models are playing an important role in forest management decision making and have a long history of application in forestry, starting with forest yield tables which exist over 250 years. (Pretzsch et. al 2008). According to Weiskittel et al., (2011) the core applications of forest simulation models are: update forest inventories; assess alternative silvicultural measures, determine the influence of abiotic and biotic disturbances, estimate the yield of different products and generalize regional trends. Another reason for the importance of models in forestry is the longevity of trees and the resulting extensive management periods. As a consequence, new silvicultural practices and the effect of changing environmental conditions on forests cannot be tested easily in experiments (Pretzsch, 2009). Notwithstanding the fact that long term experiments cannot be replaced by models, models are an essential decision tool particularly when environmental conditions are changing very rapidly. Especially in the climate change debate forest models were used at regional and national level. Nowadays there existing several different models with a various temporal and spatial resolution, therefore it can be found for each application the suitable model. Pretzsch et al., (2007) distinguish within the European forest ecosystem management framework the following model types: stand orientated management models, individual tree orientated models, gap and hybrid models, matter balanced models, landscape and visualization models. Contrary to empirical models, where the aim is the prediction, process-based models (like iLand) should help to understand the processes in an ecosystem (Burkhart and Tomè, 2012). To examine the effects of changing environmental conditions on the forest ecosystem, process-based models can be used and have to be evaluated to enhance the predictions of climate change (Luckai and Larocque, 2002; Albert and Schmidt, 2010). In the development of each model, the model evaluation plays a key role to guarantee the success and the precision of the chosen model for the respective question and should demonstrate the suitability, the validation and applicability of the model (Pretzsch et al., 2002). The best approach for each model evaluation is to test the model predictions against independent data, which were not part of the model calibration and building. The evaluation of iLand is very essential, because the ability of the model to reproduce the thinning responses has not yet been evaluated in previous studies.

2 Objectives and hypotheses

This study can be divided in two separated parts with different objectives. The first part of this work was an evaluation of the model iLand, addressing the question whether it's able to reproduce the thinning response of trees observed in thinning trials. A positive evaluation was a prerequisite for the subsequent aim of this study, which was to test and to compare the effects of thinning under different climate change scenarios.

2.1 Evaluation of iLand with regard to the response to thinning

In previous studies iLand was tested successfully against independent data. The model had demonstrated that is able to simulate forest ecosystem dynamics in different ecosystems (Seidl et al. 2012 a) and also to simulate successfully the carbon flow at the landscape level (Seidl et al. 2012 a). Here, the objective was to evaluate the ability of iLand to reproduce different thinning responses. For the evaluation I tested the simulated thinning responses under current climate conditions against the long term observations from the thinning trials.

<u>The main question addressed in this evaluation is therefore:</u>

Is the model iLand able to satisfactorily reproduce the observed thinning responses from the three thinning trials?

For the evaluation and the comparison between the simulated and the observed thinning responses the following indicators were used:

- The mean diameter at breast height (dbh)
- The dominant height

<u>With regard to these indicators the following hypothesis were tested:</u>

ILand is able to reproduce successfully observed patterns, due to its individual tree structure and through its high spatial resolution

2.2 Testing the effects of various thinning regimes under different climate scenarios

In the second part of this study I reanalysed the thinning responses from the three thinning trials under three different climate scenarios.

The main question addressed in this part is:

Are thinnings able to help forest management adapting to climate change, through an improvement of the positive climate impacts and through a reduction of the negative climate impacts?

Thinning responses under climate change are assessed for the following indicators:

- Stand-level indicators:
  - Net primary production (NPP)
  - Mean annual increment (MAI)
- Tree-level indicators:
  - Dbh increment
  - Stress

With regard to these indicators the hypotheses tested were:

1. There is a significant difference between the impact of different climate scenarios, depending on their individual combination of changes in different climate parameters
2. The reduction in the tree density in a forest stand leads to a significant change of the two stand-level indicators NPP and MAI
3. The stronger the reduction in the tree density through thinning the higher is the individual diameter increment and the lower the individual tree stress level, because the competition for resources decrease through the reduction of resource consumer through thinning

3 Material and Methods

3.1 The iLand – Model

3.1.1 Model structure

iLand stands for the individual-based forest landscape and disturbance model, and iLand Version 0.8.7 was used in this study. This model is able to simulate forest ecosystem dynamics with high spatial grain over large landscapes and is applicable in various ecological topics, for example to identify the ecosystem resilience to different disturbances, to simulate the carbon flux or to simulate ecosystems under various climate scenarios to develop climate change strategies. Within the framework of forest simulation models iLand can be categorized to the individual tree models, where the individual tree is the core entity of the simulation and the main agent of forest ecosystem dynamics, the forest stand information is therefore the sum of the individual trees. In the development of the model the focus was on creating a model, which integrates processes of ecosystem functional, structure and composition and their interactions in a dynamic simulation framework (Seidl et al., 2012a). With iLand it's possible to simulate forest dynamics over long time frames, and assess the effect of different climate scenarios and disturbance regimes (Seidl et al. 2012a).

For simulating the interactions of individual trees, ecological field theory (EFT) is used in iLand. EFT was established by Wu et al. (1985) with the goal to describe the process of individual plant competition for essential resources, i.e. water, light and nutrients (Ponce and Senespleda 2010). To estimate the influence from a plant to his neighbour in the EFT the domain (the spatial distribution) and the intensity of the influence are essential. To demonstrate the implementation of the EFT to iLand, the Figure 1 illustrates as an example the competition for the resource light, where the light interference pattern (LIP) is the domain and the individual tree interference intensity at the coordinates x and y ($i^{x,y}$) is the intensity of the influence.

One of the most important and also the most difficult aspects of forest ecosystem modelling is scaling in time and space (Wolfslehner and Seidl 2010). Due to the hierarchical organisation of the ecosystems the actions at the lowest spatial and temporal level influence the whole ecosystem. Which is implemented by iLand through a hierarchical framework, where the processes at the lower level serve the higher hierarchical processes (which could serve otherwise as constraints for the lower hierarchical processes) and through a daily resolution of the required data (Seidl et al. 2012a).

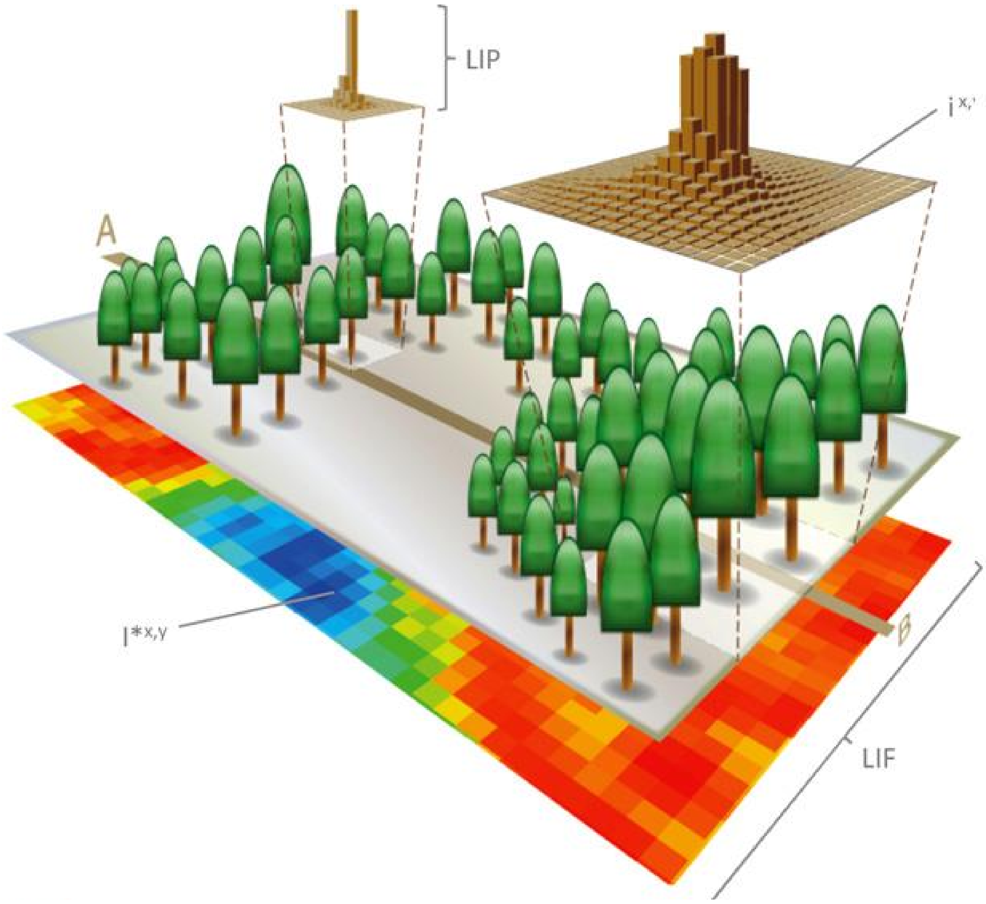

Figure 1: This graphic demonstrates the competition for the resource light for two individuals with a different tree size. LIP= individual interference pattern, i ^{x,y}=interference intensity, LIF=light interference field depending on the individual LIPs, I ^{*x,y}=the aggregated interference intensity at the coordinates x and y. Source: Seidl et al., 2012a

3.1.2 Key Processes

The three key processes of forest ecosystem dynamics are: regeneration, growth and mortality. Each of these processes are influenced by biotic and abiotic factors, such as competition for resources, reproduction, diseases, silvicultural practices, etc. (Liu and Ashton, 1995). iLand uses the following approaches to simulate the main processes of forest ecosystem dynamics:

- Regeneration

The regeneration phase includes all processes from the forest stand initiation phase, which start with the seeding of a tree until the trees goes into the stem exclusion stage of iLand. The seed dispersal is the first and the most important regeneration process, which is simulated spatially through a regeneration module, for a detailed description see Seidl et al. (2012b).

The establishment of a tree is the second step, followed by the sapling stage until the tree goes in to the individual based model structure of iLand (Seidl et al., 2012b). The resource light and the environment are playing the most important role in the regeneration phase.

- Growth

As soon as a tree established itself in the simulation process, the individual growth of this tree has to be simulated. The simulation of the individual tree growth has three important steps: the primary production, allocation and stem growth. For individual tree growth the individual resource availability and the competitive ability is important. In this context iLand use a light use efficiency approach to simulate the primary production. Allocation in iLand is implemented through compartment specific allometric ratios. Allocation regime, which is a hierarchical framework, start with the roots and the foliage, following by the reserve and stem pools (Seidl et al. 2012a). After allocation of the biomass increment to the different sections of a tree, individual stem growth can be simulated.

- Mortality

The last key process of every ecosystem model is the simulation of the individual tree mortality. Tree mortality in iLand is simulated through the individual carbon balance, which is used as an indicator of the stress level of a tree (Seidl et al. 2012a). An individual tree experience stress if the individual carbon balance sink into the negative zone, which increase on the other hand the mortality Other reasons for tree mortality include natural ecosystem disturbances like wind or bark beetles, which can be simulated explicitly with iLand.

3.2 Thinning trials

The three thinning trials studied here were implemented and managed by the Austrian Research Centre for Forests (BFW), the main objective of the trials was to study the effect of different timings and thinning intensities on forest growth. In all three trials the focal tree species was Norway spruce. To compare the different thinning regimes (studied in the thinning trials), I calculated the percentage of annual harvested volume from the remaining volume of a stand. Named as mean annual removal percentage, this indicator demonstrate how much volume from a stand will be removed annual.

3.2.1 St. Oswald ob Eibiswald– Thinning trial number: 220

The first thinning trial was started in 1968 and was last measured in 2013, with a tree age of 40 years in the beginning and 85 years in the end. The objective was to study the impacts of different thinning intensities in pole-stage stands with a high damage from bark peeling by deer (Rössler, 2013a). To analyse different thinning intensity, which are demonstrated in Table 1, four different thinning variants were implemented and replicated between three and six times. The area of each parcel was 1733 m² (Rössler, 2013a).

Table 1: Overview of the mean annual removal percentage of volume, number of thinning interventions, average time between thinnings and average volume removed per thinning.

	Mean annual removal percentage of volume	Number of thinning interventions	Average time between thinnings in years	Average volume removed per thinning [in m³]
Variant 0: no treatment	-	-	-	-
Variant 1: too high basal-area density (55-60 m² per hectare)	1.16 %	8	5	35.76
Variant 2: optimal basal-area density (50 m² per hectare)	1.20 %	4-8	5-10	36.13
Variant 3: critical basal-area density (40 m² per hectare)	1.40 %	4-8	5-10	43.15

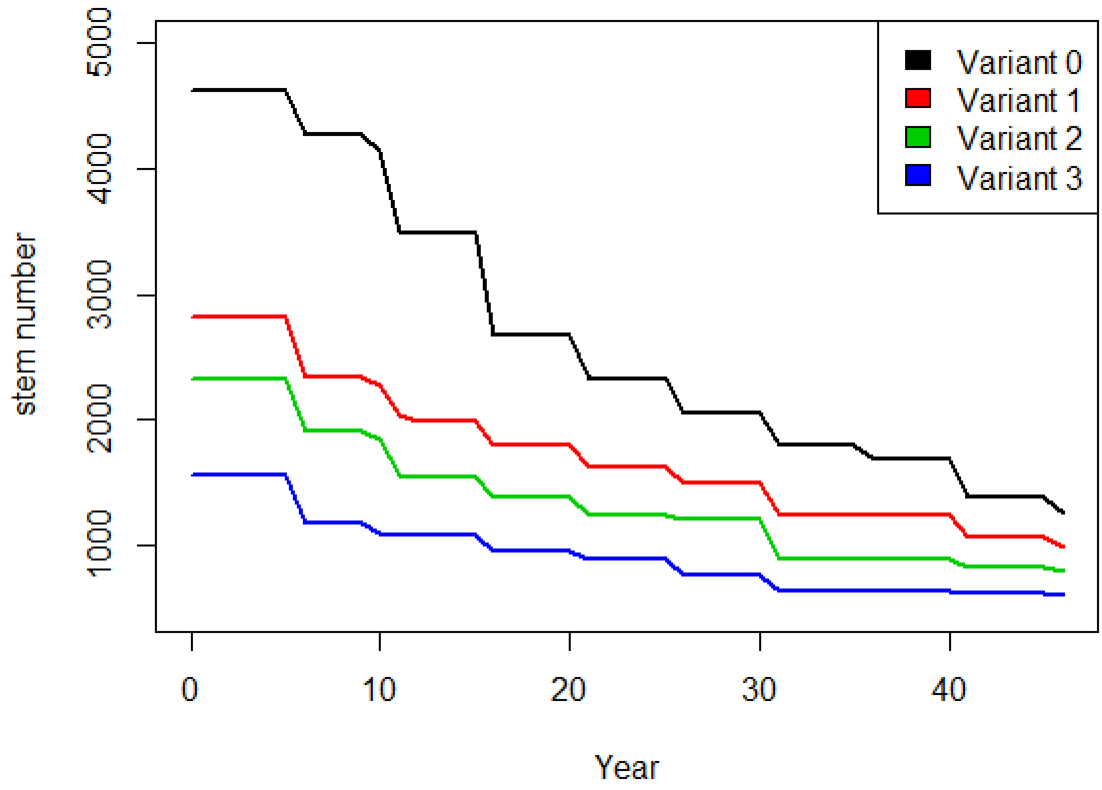

Figure 2: The result of the thinning trial regarding the stem number. Black line = no treatment. Red line = too high basal-area density. Green line = optimal basal-area density. Blue line = critical basal-area density.

St. Oswald ob Eibiswald is located in the ecoregion: 5.4 "Weststeirisches Bergland" (Kilian et. al. 1994) in the south of Styria, near the border to Carinthia (Figure 3) at an average altitude of 1250 meters asl (Rössler, 2013a).

Figure 3: Location of the thinning trial in the map of Austria.

3.2.2 Karlstift – Thinning trial Nr. 301

The thinning trial Karlstift was started in 1964 and was last measured in 2010. At the beginning of the trial the trees were between 15 and 20 years old. The main objective at Karlstift was to analyse the effects of an early first thinning in naturally regenerated Norway spruce with very high stem densities. For this trial the BFW implemented 16 parcels, with an area of 0.12 hectare (Rössler, 2014). The study design consisted of four different treatment-variants, which are described in Table 2, and four replicates per variant. With this thinning trial it was shown how important the role of thinning is to increase the stability of densely stocked stands (Rössler, 2014).

Table 2: Overview of the mean annual removal percentage of volume, number of thinning interventions, average time between thinnings and average volume removed per thinning.

	Mean annual removal percentage of volume	Number of thinning interventions	Average time between thinnings in years	Average volume removed per thinning [in m³]
Variant 0: no treatment	-	-	-	-
Variant 1: moderate thinning intensity in longer intervals	3.40 %	6	7	38,76
Variant 2: lower thinning intensity in short intervals	4.00 %	9	5	37,2
Variant 3 high thinning intensity in the sapling stage	2.50 %	4	11	38,36

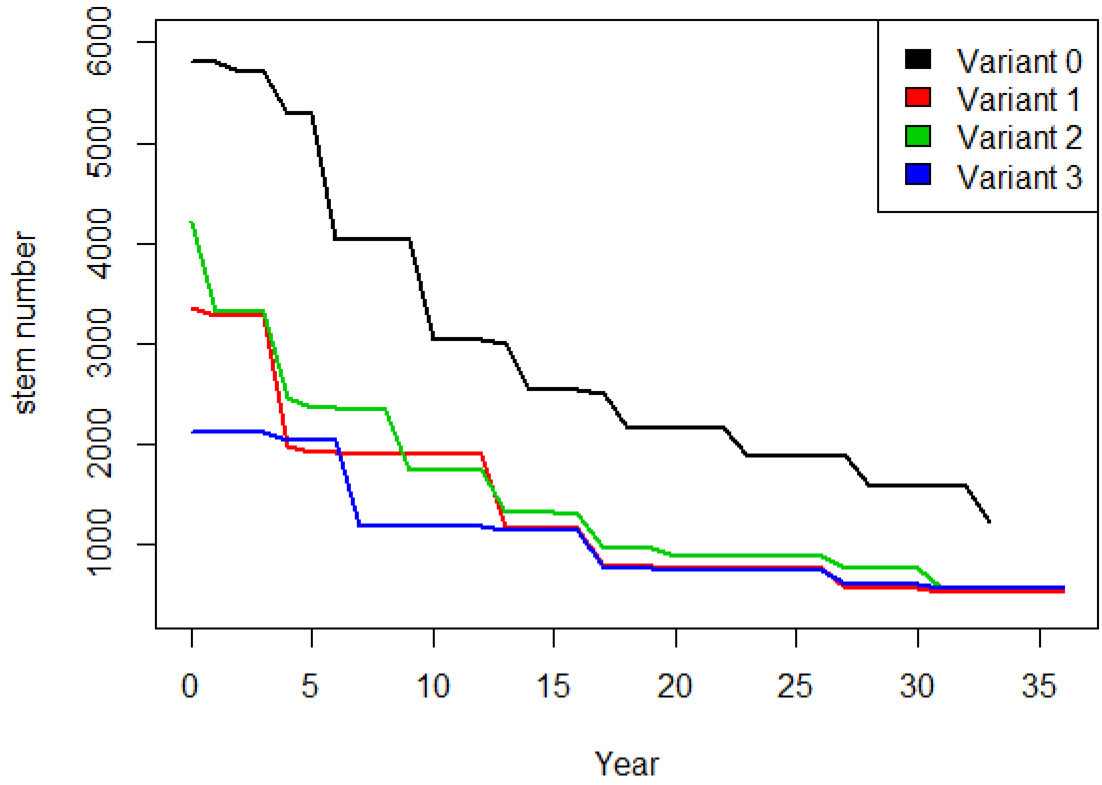

Figure 4: The result of the thinning trial regarding the stem number. Black line = no treatment. Red line = moderate thinning intensity in longer intervals. Green line = lower thinning intensity in shorter intervals. Blue line = high thinning intensity in the sapling stage.

This thinning trial is located near the village of Karlstift, in the north-west part of Lower Austria close to the Czech border (Figure 5). The trials altitude is about 930 meters asl and it is situated in the ecoregion: 9.2 "Waldviertel" (Kilian et. al. 1994).

Figure 5: Location of the thinning trial in the map of Austria

3.2.3 Ottenstein - Thinning trial Nr. 304

The third thinning trial was a part of the “European Stem Number Experiment in Norway Spruce” from the International Union of Forest Research Organizations (IUFRO). It was planted in the year 1959 with 6500 trees per hectare. In the year 1970 the thinning trial started and it was last measured in the year 2014, with an average tree age of 59 years (Rössler, 2013b).The objective of this experiment was to compare the productivity and the stability of stands with a different initial stems density. For the sake of international comparison this experiment was implemented in 14 European countries, studying 5 different density treatments, (see Table 3) (Kohnle et. al., 2006).

Table 3: Overview of the mean annual removal percentage of volume, number of thinning interventions, average time between thinnings and average volume removed per thinning.

	Mean annual removal percentage of volume	Number of thinning interventions	Average time between thinnings in years	Average volume removed per thinning [in m³]
Variant 0: no treatment	-	-	-	-
Variant 1: early thinning and partially mechanised thinning at the dominant height of 5, 10, 12.5, 15 and 27.5 meters	4.80 %	5	5	42.67
Variant 2: early thinning and partially mechanised thinning at the dominant height of 5, 10, 20, 22.5 and 27.5 meters	5.50 %	5	5	33.87
Variant 3: late thinning and partially mechanised thinning at the stem number of 3000, 1500, 1200, 900 and 700	5.50 %	5	5	32.35
Variant 4: late thinning and partially mechanised at the stem number of 4500, 3000, 1600, 1200, 900 and 750	3.60 %	6	5	29.98

Also this thinning trial has underlined the essential role of thinning treatments to increase the stability and the growing capacity of forest stands (Rössler, 2013b). The results of this thinning trial regarding the stem number are demonstrated in Figure 6.

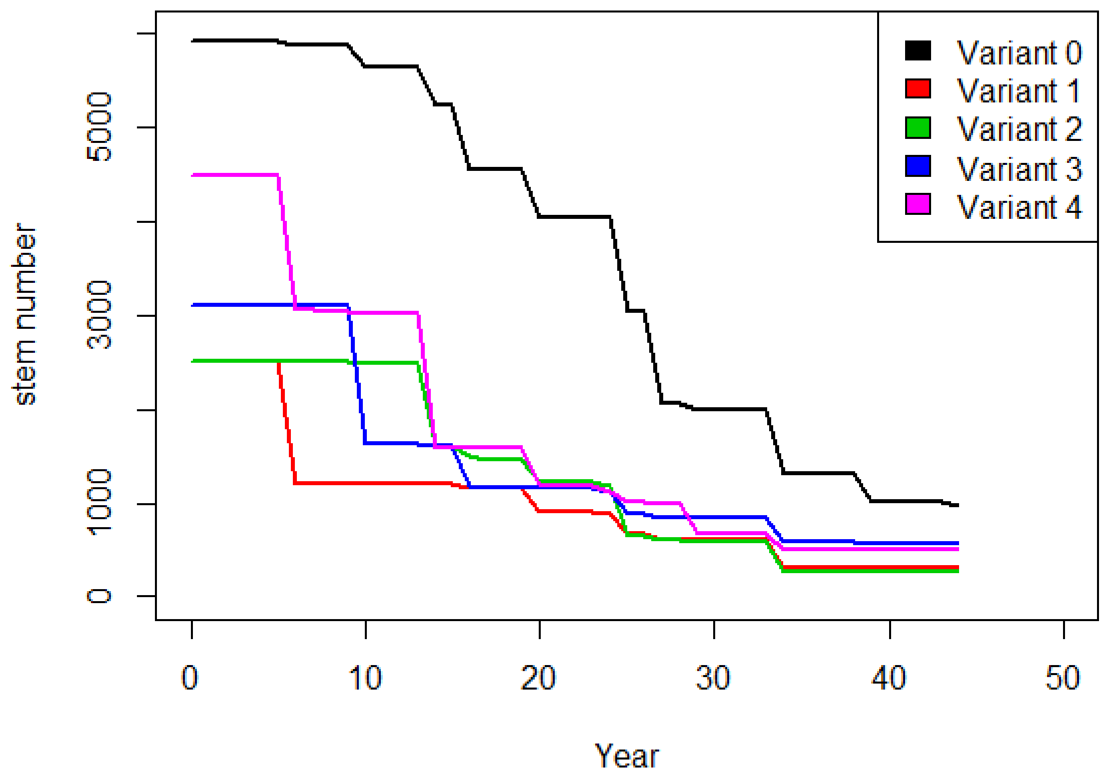

Figure 6: The result of the thinning trial regarding the stem number.

This thinning trial was located in Lower-Austria in the north-west of the village Ottenstein (Figure 7). The area's altitude is 540 meters and is located in the growth area: 9.2 "Waldviertel" (Kilian et. al., 1994).

Figure 7: Location of the thinning trial in the map of Austria (Rössler, 2013b).

3.3 Soil data

Soil data are important for the initialization and as a driver data for the simulation of forest ecosystems (Seidl et al., 2009). For the simulations of the thinning trials the following parameters are needed to describe the soil conditions for each site: the soil depth in centimetre, the percentage of sand, silt and clay and the available Nitrogen content (kg/m²/year).

For the thinning trials Karlstift and Eibiswald the soil data required for simulation with iLand were taken from a large soil data base for the plot locations of the Austrian National Forest Inventory (Seidl et al. 2009), based on the data of the Austrian forest soil survey. This survey started in the 1980s and the measurements, descriptions and analyses are made on 514 different plots, which are distributed over the whole Austrian national territory (Blum et al., 1999). To identify the plots most representative for the two thinning trials, I searched similar plots with the same ecoregion, same elevation band and a close geographical proximity to the trials. Soil data for the third thinning trial Ottenstein were measured directly during the trial period from the BFW and were taken from Rössler (2013b).The bedrock, which has a strong influence on all soil parameters, is mica slate in Eibiswald, and fine-grained granite in Karlstift and in Ottenstein.

The first soil property, which is required for the simulations with iLand is the effective soil depth, i.e. the maximum rock free soil depth that can be used by plants through their roots (see Table 4).

Table 4: Overview of the effective soil depth in centimetre.

Thinning trial	Ottenstein	Karlstift	Eibiswald
Soil depth [cm]	23	150	149

After the soil depth, the next important soil property is the soil texture, which is described by the distribution of the substrate over three different grain size classes:

Sand: 2 mm bis 63 µm

Silt: 2 µm bis 63 µm

Clay: < 2 µm (Jandl and Wentzel, 2011).

The distribution of grain sizes is a very important physical soil property of soils, especially for the water holding capacity of a soil. Sand, silt and clay fraction were derived with the help of the texture triangle, demonstrated in Figure 8, for the respective soil types at the thinning trials (Jandl and Wentzel, 2011).

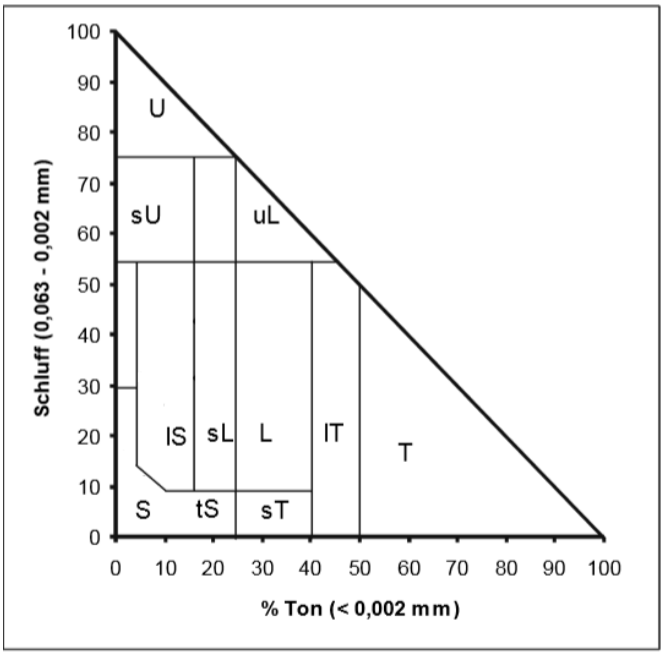

Figure 8: The texture triangle (Staffler et al., 2003)

In Eibiswald and Karlstift the soil physical properties were determined as 50% sand, 30% silt and 20% clay. In Ottenstein the distribution is slightly different with 69% sand, 26% silt and 5% clay. Besides the soil depth and physical properties, the available nutrients are important environmental factors for the simulation of forest dynamics (Seidl et al., 2008).

For simulations at the location Ottenstein the plant available nitrogen was set to 62 kg per hectare and year. For Eibiswald and Karlstift the plant available Nitrogen content was derived from nearby representative plots of a large soil data base (Seidl et al. 2009), as for the other soil variables (Table 5).

Table 5: The annual plant available Nitrogen in kilogram per hectare at the three thinning trials.

Thinning trial	Ottenstein	Karlstift	Eibiswald
Plant-available nitrogen [kg/ha/year]	62	45	50

3.4 Climate Data

The past climate data required for simulations with iLand are at a daily resolution. Past climate data were derived from a 1 km gridded climate database based on observations of the "Zentralanstalt für Meteorologie und Geodynamik" (ZAMG). Climate data for the parameters were extracted:

- Minimum temperature [°Celsius]
- Maximum temperature [°Celsius]
- Precipitation [mm]
- Radiation [MJ/m²/day]
- Vapour pressure deficit [kPa]

3.4.1 Temperature

An important climate variable is air temperature, because all physiological processes are strongly temperature dependent. For the simulations in iLand the minimal and the maximum temperature were used and are demonstrated in Table 6.

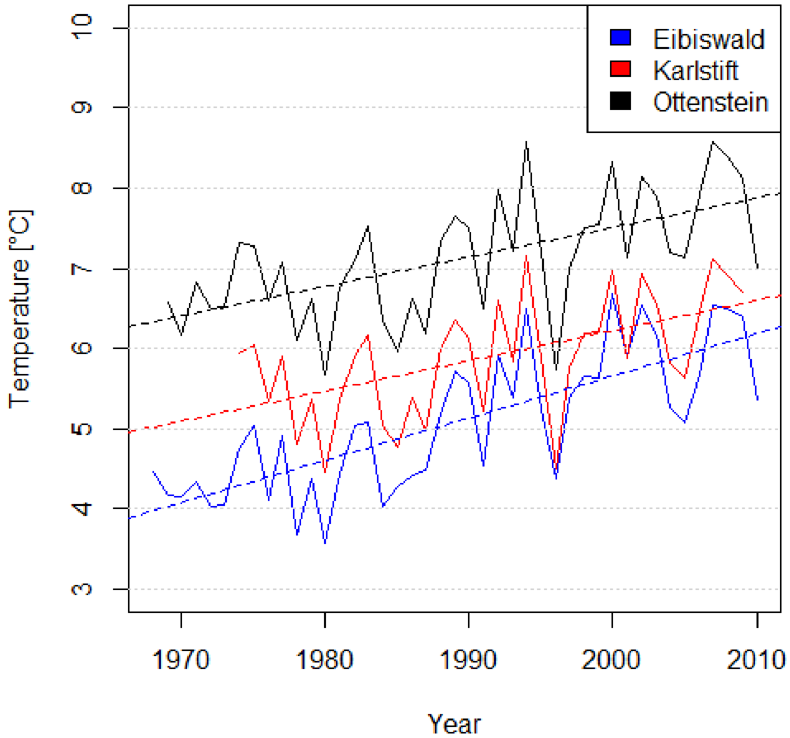

Figure 9: The mean annual temperature of the three thinning trials during the trial period. The dashed lines demonstrate the linear trend during the trial period for each study site.

The mean temperature shows a continuously increase during the trial period of all three study sites (Figure 9). The table 6 gives an overview of the mean, the minimal and maximum annual temperature during the trial period for the study sites.

Table 6: Overview of the mean annual temperature in degrees Celsius during the trial period for the three study sites.

Thinning trial	Ottenstein	Karlstift	Eibiswald
Mean annual temperature [°C]	7.1	5.9	5.1
Mean minimum temperature [°C]	2.7	2.3	1.5
Mean maximal temperature [°C]	11.5	9.5	8.7

3.4.2 Precipitation

Another important climate variable is precipitation. In Table 7 the annual precipitation sum is demonstrated, although for the forest growth particularly the precipitation in the vegetation period is decisive.

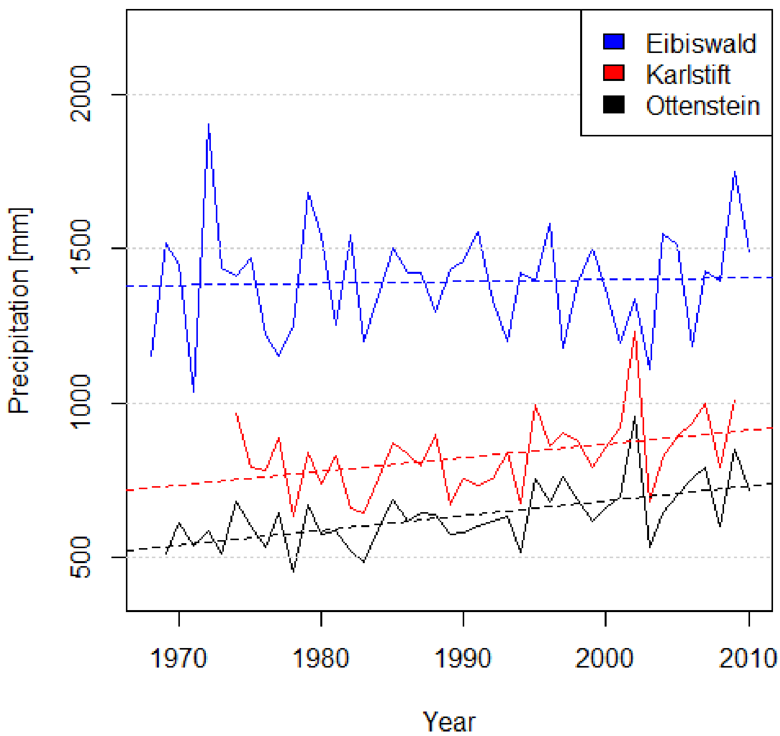

Figure 10: The mean annual precipitation in millimetre of the three thinning trials. The dashed lines demonstrate the linear trend during the trial period for each study site.

The mean annual precipitation of the locations Karlstift and Ottenstein shows a continuously increase during the trial period (see Figure 10). The precipitation in Eibiswald – the by far wettest of the three study sites - shows considerable variation between years, but remained relatively constant over the study period. At Ottenstein it can be assumed that the Norway spruce is already water limited. This is in line with the findings from Leitgeb et al. (2011), where they assumed that the Norway spruce has a high cultivation risk at stands with an annual precipitation sum of 600 mm, a medium risk between 600-800 mm and a small cultivation risk between 800-1000 mm.

Table 7: Overview of the mean annual precipitation in millimetre during the trial period, in spring (MAM), summer (JJA) and autumn (SON).

Thinning trial	Ottenstein	Karlstift	Eibiswald
Sum of the annual precipitation [mm]	633	831	1394
Sum of the annual precipitation in Spring [mm]	147	193	317
Sum of the annual precipitation in Summer [mm]	258	325	515
Sum of the annual precipitation in Autumn [mm]	134	174	366

3.4.3 Radiation

Solar radiation is the main energy source for plant growth. More broadly, it is the main driver of a wide range of processes in the climate system of the Earth (Henderson and Robinson, 1986). Table 8 gives an overview the mean daily radiation during the year and also during spring, summer and autumn.

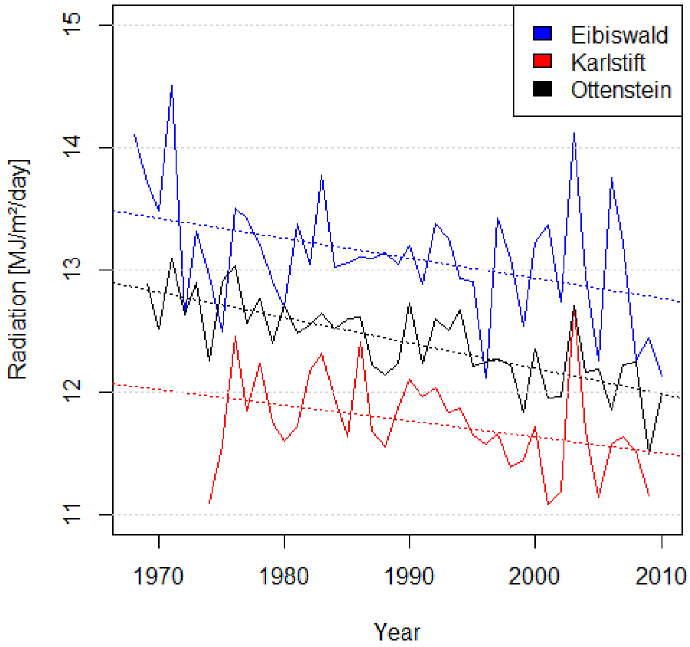

Figure 11: The mean annual radiation of the three thinning trials. The dashed lines demonstrate the linear trend during the trial period for each study site.

The yearly averaged daily solar radiation in the three locations decreased over the trial period (see Figure 11).

Table 8: Overview of the mean daily radiation of the three thinning trials during the trial period, in spring (MAM), summer (JJA) and autumn (SON).

Thinning trial	Ottenstein	Karlstift	Eibiswald
Mean annual daily radiation [MJ/m²]	12.4	11.7	13.1
Mean daily radiation in spring [MJ/m²]	15.8	16.7	16.2
Mean daily radiation in autumn [MJ/m²]	21.0	21.4	21.5
Mean daily radiation in autumn [MJ/m²]	9.6	9.8	9.4

3.4.4 Vapour pressure deficit (VPD)

The last of the climatic parameters required for iLand simulations is vapour pressure deficit, which affects stomatal conductance. With an increasing VPD the stomata of a plant close and photosynthesis decreases and eventually ceases completely (Turner et al. 1984). Consequently, VPD is an important variable in the water balance of a forest and a strong driver of the productivity of a tree.

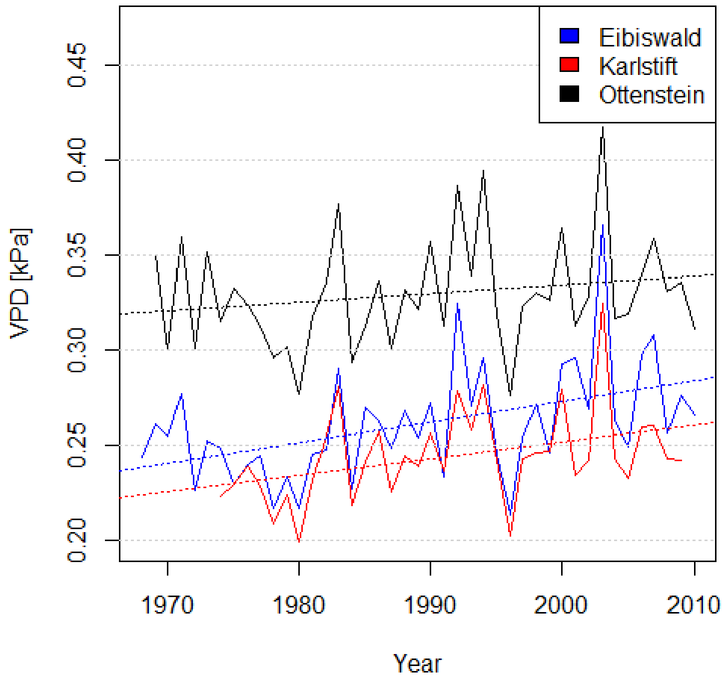

Figure 12: The mean annual vapour pressure deficit of the three thinning trials. The dashed lines demonstrate the linear trend during the trial period for each study site.

Figure 12 illustrates that the mean daily VPD increased slightly at all study sites during the trial period (see also Table 9 for an overview of the mean daily VPD).

Table 9: Overview of the mean daily VPD of the three thinning trials during the trial period, in spring (MAM), summer (JJA) and autumn (SON).

Thinning trial	Ottenstein	Karlstift	Eibiswald
Mean daily VPD [kPa]	0.33	0.24	0.26
Mean daily VPD in Spring [kPa]	0.30	0.20	0.21
Mean daily VPD in Summer [kPa]	0.65	0.46	0.49
Mean daily VPD in Autumn [kPa]	0.28	0.23	0.23

3.5 Climate change scenarios

For the assessment of thinning effects under potential future climate conditions I used results from 3 different regional climate models based on two different global climate models (GCM) under the A1B emissions scenario (IPCC, 2000). To cover a wide range of changing conditions I choose two periods from within these scenarios, the first one in the middle of the 21th century (2040 – 2060) and the second period at the end of the 21th century (2080 – 2100). From each of the thus derived six climate scenarios (1 emission scenario x 3 climate model combinations x 2 time slices) years were randomly sampled for the study period to construct the climate time series for simulation.

3.5.1 Global climate models

Two different global climate models were used to derive potential future climate data, ECHAM 5 and the global climate Model ARPEGE. The ECHAM 5 is a general circulation model, which was developed by the European Centre for Medium-Range Weather Forecasts (ECMWF) and the Max Planck Institute for Meteorology. This climate model was developed in 2003 and it's the fifth generation of the ECHAM model family (Roeckner et. al., 2003). ARPEGE was developed by the Météo France and the European Centre for Medium-Range Weather Forecasts (ECMWF) (Deque et al., 1994).

3.5.2 Regional climate models

To simulate the impact of future climate conditions at the three study locations, there is a need for applying regional climate scenarios, which have a much finer spatial resolution and are therefore able to better represent local conditions. GCM scenarios were thus downscaled to a 25 km x 25 km grid using regional climate models and further downscaled to a 1 km x 1 km grid using statistical downscaling.

Three different regional climate models from three different institutions were used here, the CNRM-FM 4.5 (Radu et al., 2008), MPI-REMO (Jacob, 2001) and ICTP-RegCM3 (Pal et al., 2007).

Table 10: The annual changes in the two time periods in the Temperature (in Degrees Celsius), in the Precipitation (in %), in the radiation (in %) and in the VPD (in %) in the three thinning trials and the various climate scenarios. All the annual changes are regarding to the baseline climate.

	Temperature [°C]			Precipitation [%]			Radiation [%]			VPD [%]		
	Eibiswald	Karlstift	Ottenstein	Eibiswald	Karlstift	Ottenstein	Eibiswald	Karlstift	Ottenstein	Eibiswald	Karlstift	Ottenstein
Arpege 40-60	1.65	1.59	1.57	3.3	0.3	2.3	3.7	5.4	3.4	30.7	37.5	27.3
Arpege 80-100	3.20	3.15	3.16	-7.6	-8.0	-8.3	6.2	7.8	5.3	80.7	91.7	75.8
Ictp 40-60	1.38	1.31	1.42	2.2	-7.9	-7.2	-17.3	-34.5	3.4	11.5	16.7	15.2
Ictp 80-100	2.98	2.88	2.96	9.5	4.6	6.5	-16.3	-32.4	4.1	34.6	37.5	33.3
Remo 40-60	1.65	1.35	1.47	-3.9	-6.5	-6.8	1.2	1.5	0.0	80.8	58.3	48.5
Remo 80-100	3.29	2.92	2.99	1.7	3.0	6.9	0.0	0.6	-1.2	215.0	83.3	72.3

The regional climate model CNRM-FM 4.5 was driven by the global climate model ARPEGE. This scenario is subsequently referred to as “ARPEGE”. The regional climate models MPI-REMO and ICTP-RegCM3 were driven by the global climate model ECHAM 5. These scenarios are subsequently referred to as REMO and ICTP, respectively.

Table 10 gives an overview of the annual changes of the climate scenarios in the various thinning trials regarding to the baseline climate. The temperature increase in all scenarios, with a slightly increase in the first period and a stronger increase in the second period. Regarding the precipitation there is no clear trend observable between the climate scenarios, similar to the changes in the radiation.

3.6 Analysis

3.6.1 Evaluation

To evaluate iLand, I compared the observed results of the thinning trials with the results of the simulations. I analysed results with the statistical software R Version 3.1.1 (R Core team, 2014), using linear regression. To study the strength of the relationship between the observed and the simulated data I studied the slope of the regression, the R^2 and the mean absolute bias of the simulation. The mean bias is a good measure of the precision of a model and describes the mean difference between the observed and the simulated results (Pretzsch, 2009).

To address the main research question for the evaluation, i.e. if iLand is able to reproduce the observed thinning response, the following parameters were assessed:

- Mean diameter at breast height (Dbh)
- Dominant height, which is defined as the mean height of the 100 largest trees per hectare (Pretzsch, 2009).

The stands without treatment at Karlstift were not considered in the calculation of dominant height because of unrepresentative results, caused by snow breakages in the years 1980 and 1993.

3.6.2 Thinning response under different climate scenarios

For the second part of my analysis the goal was to compare thinning effects across various climate change scenarios. I used relative values for the analysis, which relate the climate change scenario to the baseline scenario. These relative effects allowed me to investigate how thinning responses changed under changing climate conditions.

The following parameters were studied to assess the impacts of climate scenarios and the effects of thinning:

- Net primary production (NPP),which is the gross primary production of a plant minus the autotropic respiration
- Mean annual increment (MAI), which is defined as the mean annual stemwood increment over a period of time
- Mean annual increment in tree diameter at breast height (Dbh increment)
- Stress Index, a scalar indicator [0,1] for the individual stress level of a tree

The first two indicators are indicators at the stand level and the second two indicators at the individual tree level. For the comparison between the thinning responses, the mean annual removal percentage were used, which is a common indicator of thinning strength, integrating over thinning frequency and intensity (see section 3.2 above for details). To determine the changes of the indicators with every mean annual removal percentage I used the slopes and the related p-values from linear regression analysis.

4 Results

4.1 Evaluation of the iLand model

The main goal of this part is to test whether iLand is able to reproduce the observed thinning responses at the three thinning trials.

4.1.1 Diameter breast height (dbh)

Diameter at breast height is generally very sensitive to a changing stand density. In Figure 13 the linear relationship between simulated and observed dbhs are shown for the three thinning trials: Eibiswald, Karlstift and Ottenstein.

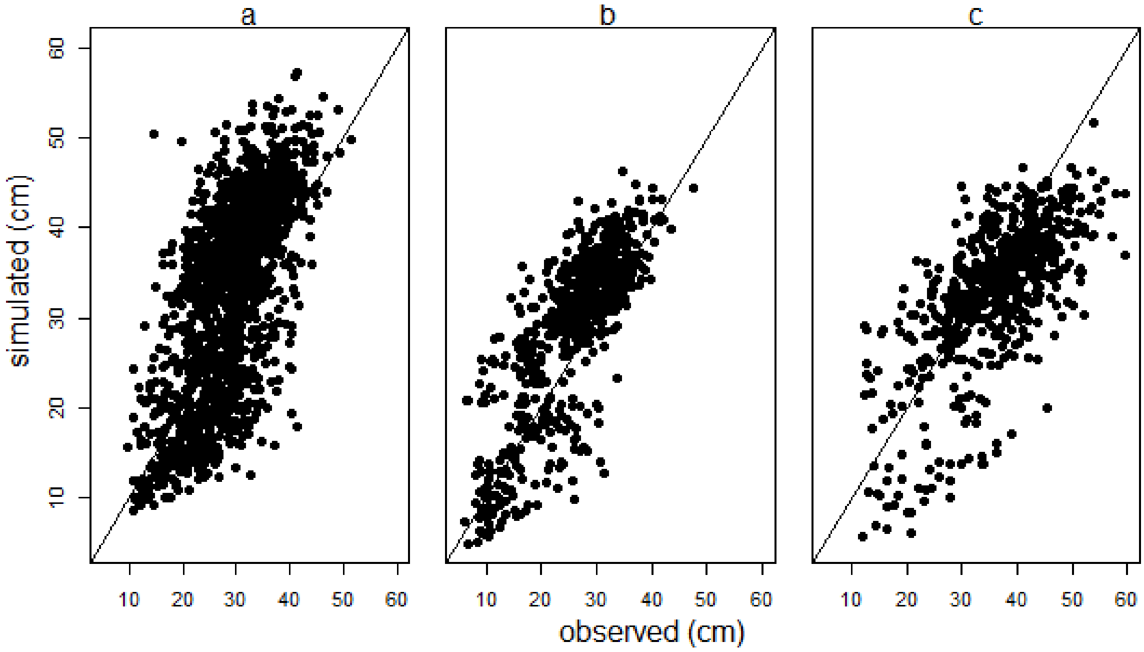

Figure 13: Simulated and observed dbh in centimeters at the end of the study period for individual trees in the three thinning trials: Eibiswald (a), Karlstift (b) and Ottenstein (c). This results are at the end of the study period, which ended after 46 years in Eibiswald, 36 years in Karlstift and 44 years in Ottenstein.

The slope of the linear regression between the observed and the simulated dbhs was in all thinning trials significant different from a slope of 0. In Ottenstein (0.579) and Karlstift (0,894) the slope differ significantly from a slope of 1 (α=0.05).

For the thinning trial Eibiswald, the left panel in Figure 13, the relation between the observed and the simulated dbh is the lowest among the three study sites, with a R^2 of 0,436. The results for Ottenstein, the right panel of the Figure 13, show a similar goodness of fit of iLand at the end of the 46 year study period with a R^2 of 0,452. That means that in Eibiswald and Ottenstein iLand is able to explain nearly the half of the variation in tree dbh within the respective thinning trials. For the thinning trial Karlstift, the centre panel of Figure 13, the goodness of fit is significantly higher as in the other two thinning trials, with a R^2 of 0,621. Here iLand explains nearly two third of the variation of the dbh at the end of the study period. At the stand level the R^2 for the three trials were 0.894 in Eibiswald, 0.959 in Karlstift and 0.760 in Ottenstein (see Appendix A).

The mean dbh over all simulated trees at Eibiswald amounts 32.3 cm comparing to the observed mean dbh of 28.7 cm. This means that the model overestimates the mean dbh with 11.5 %. At Karlstift I found nearly the same result, here the model overestimated the mean dbh of the observed trees, which is 25.62 cm, by 11.1 % (simulated mean dbh of 28.79 cm). At Ottenstein the mean deviation differs though. Here the model underestimated the observed mean dbh of 36.01 cm by 9.7 % simulating a mean dbh of 32.82 centimetre. Overall the average simulated dbh of the three thinning trials at the end of the study period is within the range of – 10% to +11.5% (or -3 cm or +4 cm). Dbhs are slightly underestimated at the site with the harshest growing conditions (Ottenstein) and are slightly overestimated at the site with the most favourable growing conditions for Norway spruce (Eibiswald).

The mean absolute bias between the observed and the simulated dbhs was very low at Eibiswald with 0.005 cm at Eibiswald, followed by 0.039 cm at Karlstift and 0.096 cm at Ottenstein. With this results it can be assumed that the differences between the observed and the simulated dbhs was very low.

4.1.2 Dominant height

For the evaluation dominant height was calculated for every stand within in each thinning trial and compared to iLand simulations (Figure 14).

In the linear regression between the observed and the simulated top height the slope of the thinning trials Eibiswald and Ottenstein were significant different from a slope of 0, and in Ottenstein (0.465) and Karlstift (0.143) the slope differ significantly from a slope of 1 ($\alpha=0.05$).

At Karlstift the R^2 was the lowest one ($R^2=0.185$), which means that the goodness of fit between the simulated and observed dominant heights was poor at this trial. Another result was found at the other two trials, where the goodness of fit was considerably higher at Ottenstein ($R^2=0.383$) and at Eibiswald ($R^2=0.503$).

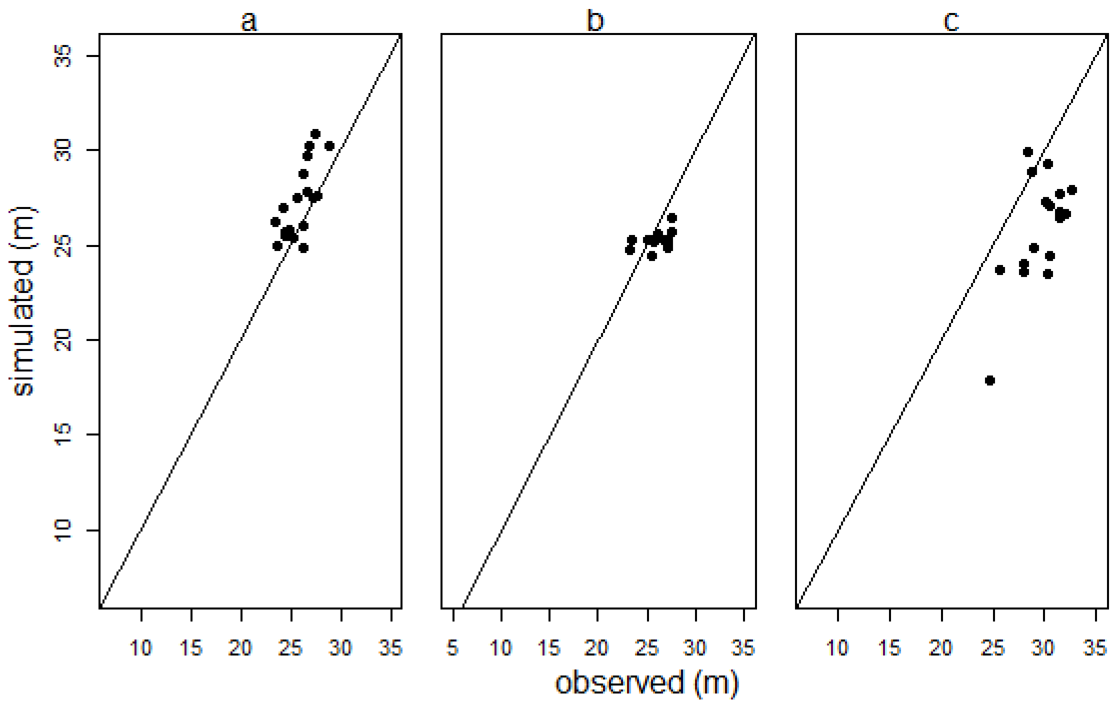

Figure 14: Simulated and observed dominant height in metre for each parcel for Eibiswald (a), Karlstift (b) and Ottenstein (c). This results are at the end of the study period, which ended after 46 years in Eibiswald, 36 years in Karlstift and 44 years in Ottenstein.

The evaluation of the simulated dominant heights yielded similar results as the analysis for dbh, just that the relative differences between simulated and observed values are somewhat lower. The simulated mean dominant height over all stands at Eibiswald is 27.31 meters at the end of the study period, while the observed mean dominant height is 25.93 meters, i.e. the model has overestimated the mean dominant height by 5.1 % at Eibiswald. At Karlstift the observed dominant height (26.01 m) was underestimated slightly by the model (25.27 m) by 2.9 % on average over all stands. In Ottenstein I found the largest differences between observed and simulated dominant height. Here iLand underestimated the observed top height by 14.5 % (observed: 29.62 m, simulated: 25.87 m). Similar to the results for the dbh, dominant height was underestimated at the thinning trial with the harshest growth conditions for Norway spruce while it was overestimated at the most favourable site.

At Eibiswald, the mean absolute bias for the dominant height was the lowest one with 0.088 m, which means that at this trial the average difference between the simulated and the observed dominant heights was very low. At Ottenstein (0.232 m) and Karlstift (0.114 m) the mean absolute bias was slightly higher.

4.2 Climate effect

In this chapter I will present climate impacts on the different thinning response variables in the three climate scenarios (Arpege, Ictp and Remo) and two time periods. The values presented in this chapter are all relative to baseline climate and address to the following variables: net primary production (NPP), mean annual increment (MAI), mean annual DBH increment (D.inc) and Stress Index.

4.2.1 Net primary production (NPP)

The first climate scenario is Arpege shown on Figure 15. Here we can see that in all three thinning trials, the average NPP over the trial period increased under the projected climate for 2040-2060 regarding to the baseline climate. Ottenstein showed the highest increase with 10.9 %, followed by 5.2 % in Eibiswald and 1.6 % in Karlstift. In the second time period the increases are not that high and in Karlstift the NPP decreased by 1.1% relative to baseline climate.

The Ictp scenario resulted in an increase in NPP relative to baseline climate, regardless of thinning trial and time period. Eibiswald shows the highest NPP gain of all scenarios with 13.4%, followed by Ottenstein with 11.8 % both for a climate representing the period 2080-2100. Overall the ICTP scenario resulted in an averaged increase in NPP of 8.2 %.

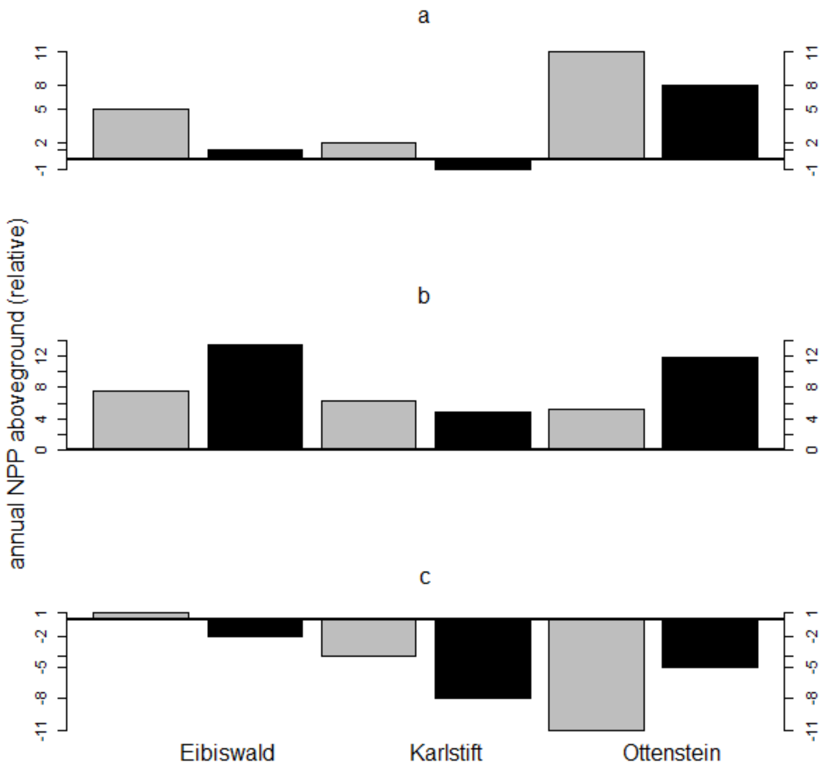

Figure 15: The percentage change of mean annual aboveground net primary production for each thinning trial (relative to baseline climate). Results are shown for: Arpege (a), Ictp (b) and Remo (c) and the climate representative for two time periods (grey bars = 2040-2060, black bars = 2060-2080).

The results from the Remo scenario are different as all thinning trials (except in Eibiswald in the first period), show decreasing NPP compared to baseline climate. The decrease in the NPP was especially pronounced in Ottenstein under the climate representing 2040-2060 conditions, with a reduction of 11.5%. This reduction could be explained with increasing temperatures and decreasing precipitations in the projected climate 2040-2060, while the climate representative for the period 2080-2100 actually shows and increase in precipitation.

Overall this scenario led to an averaged decrease in the net primary production of 6% over all thinning trials relative to baseline climate.

Figure B 1 in Appendix B illustrate absolute values for baseline climate and the three climate scenarios and two representative time periods.

4.2.2 Mean annual increment (MAI)

The results for MAI (Figure 16) are very similar to the results for NPP (Figure 15). Under the Arpege scenario, with the exception of the second period at the Karlstift location, the mean annual increment was higher than in the baseline scenario, ranging from +2.7% to 13.7 %. Overall in Arpege scenario stemwood increment was higher in the first period with an average increase of 8.4% compared to second period (5.6%).

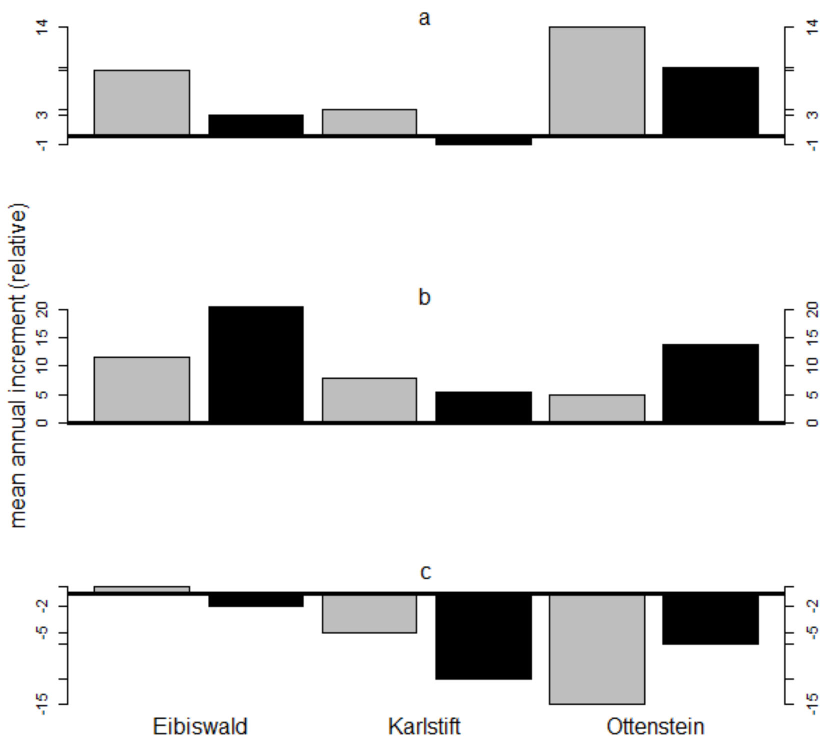

Figure 16: The percentage change of mean annual increment for each thinning trial (relative to baseline climate). Results are shown for three climate scenarios: Arpege (a), Ictp (b) and Remo (c) and the climate representative for two time periods (grey bar = 2040-2060, black bar = 2060-2080).

Under the Ictp scenario the mean annual increment in every thinning trial and period was higher than in the baseline scenario ranging from +5.5 % to +20.4 %. These numbers illustrate that the Ictp scenario has the most positive influence on the MAI.

The results of the Remo scenario, on the other hand, showed the same negative trend as for NPP. With the exception of the first period at Eibiswald, every trial and period showed decreasing MAI in REMO relative to the baseline scenario. The increment reduction was an average of -10.1 % in the first periods and -6.6%. For reference Figure B1 in Appendix B reports the absolute values of MAI in all scenarios and time periods.

4.2.3 Annual DBH increment (D.inc)

For the annual DBH increment which is an individual tree level indicator, the negative and positive impacts from the different climate scenarios were not as big as for NPP (Fig. 15) and the MAI (Fig. 16).

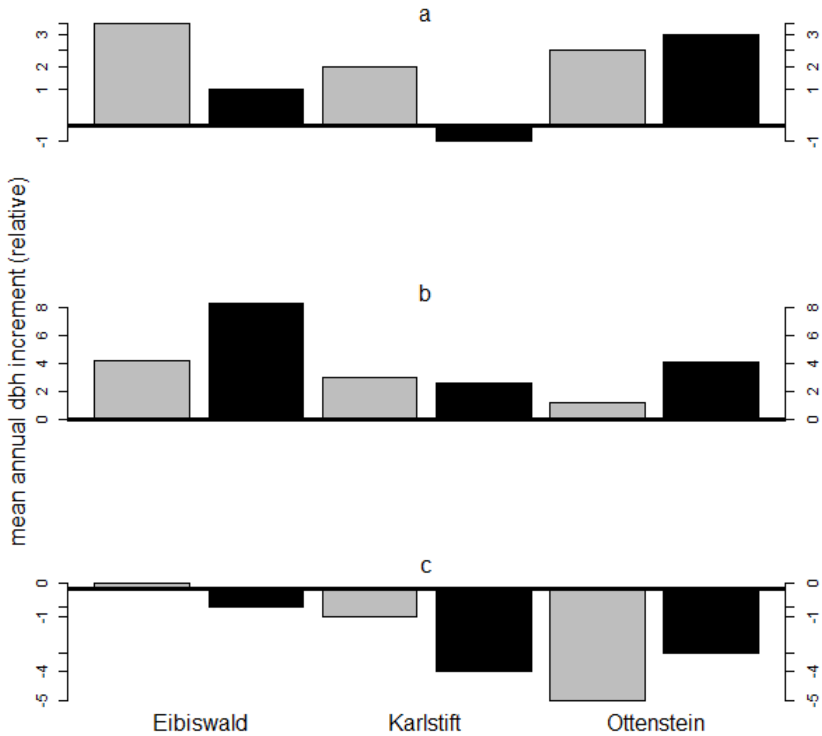

Figure 17: The percentage change of mean annual individual DBH increment for each thinning trial (relative to baseline climate). Results are shown for three climate scenarios: Arpege (a), Ictp (b) and Remo (c) and the climate representative for two time periods (grey bars = 2040-2060, black bars = 2060-2080).

However the pattern of the stand level indicators is also retained for annual DBH increment at tree level, with declines under the Remo scenario and increases under the Arpege and the Ictp scenarios. In the Arpege scenario (Figure 17), the averaged increase in D.inc is +2.7 % over all thinning trials, and very similar to in the effect of the Ictp scenario (+ 3.8 %). However there is no clear trend between the climate representing first and the second period. Under the Remo scenario Eibiswald nearly remains unchanged relative to baseline climate. In Karlstift the mean annual DBH increment declined by -3.5 % and in Ottenstein for -5.5 %. Absolute values of D.inc in all climate scenarios are presented in Figure B 3 (Appendix B).

4.2.4 Stress Index

Like the DBH increment the stress index is also an individual tree level indicator. However contrary to the previously discussed parameters a relative increase of the stress index relative to baseline means a negative climate change impact and vice versa. The results in Figure 18 demonstrate there is a large variation in climate effects on stress index between the thinning trials and climate scenarios. Particularly strong are the impacts at Ottenstein, where an average increase in stress in the first time period under the Arpege and Ictp scenarios is +28.6% and +25.8 % respectively. In the Remo scenario on the other hand, the stress index at Ottenstein declined by -25.0 % in the first and by -5 % in the second period.

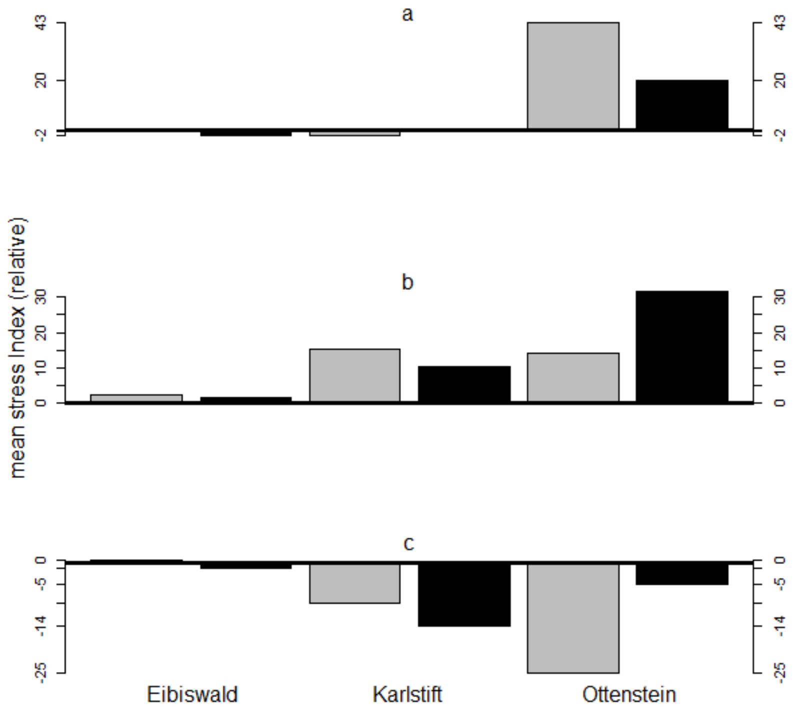

Figure 18: The percentage change of mean annual stress index for each thinning trial (relative to the baseline climate). Results are shown for three climate scenarios: Arpege (a), Ictp (b) and Remo (c) and the climate representative for two time periods (grey bar = 2040-2060, black bar = 2060-2080).

At Karlstift the impacts of a changing climate vary strongly with scenario and no a clear trend can be observed. At Eibiswald the climate scenarios have almost no impact on the individual stress index. All climate responses were within +/- 2% of the baseline scenario at Eibiswald.

The absolute values for the stress index are given in Figure B 4, Appendix B.

4.3 Thinning effects under climate change

Table 11 gives an overview of the minimum, the mean and the maximum annual removal percentage of volume over all stands within the three thinning trials. Clearly, thinning intensity differed strongly between the thinning trials. Especially at Ottenstein thinning intensity was high.

Table 11: Minimum, mean and the maximum annual removal percentage of volume in the three thinning trials.

Removal %	Eibiswald	Karlstift	Ottenstein
minimunm	0.6	2.2	1.8
mean	1.2	3.4	4.4
maximum	1.7	5.2	9.9

4.3.1 Net primary production (NPP)

I used linear regression to determine the change in NPP response under climate change with removal percentage (Table 12).

Table 12: Overview of the slopes of net primary production change with every removal percentage and the respective P-values, determined from linear regression analysis. The results are the relative decrease or increase in NPP over removal percentage in the respective climate scenarios relative to baseline climate. (Significance level: * <0.001, ** <0.01, * <0.05)**

Scenarios	Eibiswald (%)	P-values	Karlstift (%)	P-values	Ottenstein (%)	P-values
Arpege 40-60	-0.13	0.288	-0.01	0.809	0.34	0.002 (***)
Arpege 80-100	0.26	0.374	-0.02	0.104	-0.07	0.099
Ictp 40-60	0.99	0.0143 (*)	0.06	0.442	0.18	0.0002 (***)
Ictp 80-100	1.65	0.172 (*)	0.08	0.273	0.01	0.892
Remo 40-60	-0.98	0.067	-0.10	0.121	0.28	0.001 (**)
Remo 80-100	-0.02	0.398	-0.18	0.004 (**)	0.11	0.022 (*)

Especially the Ictp scenario had a big influence on the thinning response of NPP at Eibiswald, with NPP increasing significantly by 1% and 1.65 % with every additional percent of volume removed by thinning. The NPP at Karlstift showed generally small and not significant decreases in productivity with thinning intensity for the Arpege and Ictp scenarios. Just the Remo scenario lead to a significant decreases in NPP of 0.18 % (α=0.01) in the second period.

A clearer pattern emerged for the thinning trial Ottenstein. In all but one climate scenario increasing removal though thinning lead to a significant increase of NPP under climate change compared to baseline climate, from 0.18% (P-value= 0.0002, α=0.001) in the Ictp scenario to 0.34% (P-value=0.002, α=0.001) in the Remo scenario. The Figure 19 shows increasing annual NPP with an increasing annual removal percentage at Ottenstein under the Remo scenario and thus illustrates how thinning reduces climate-induced NPP losses at this study site.

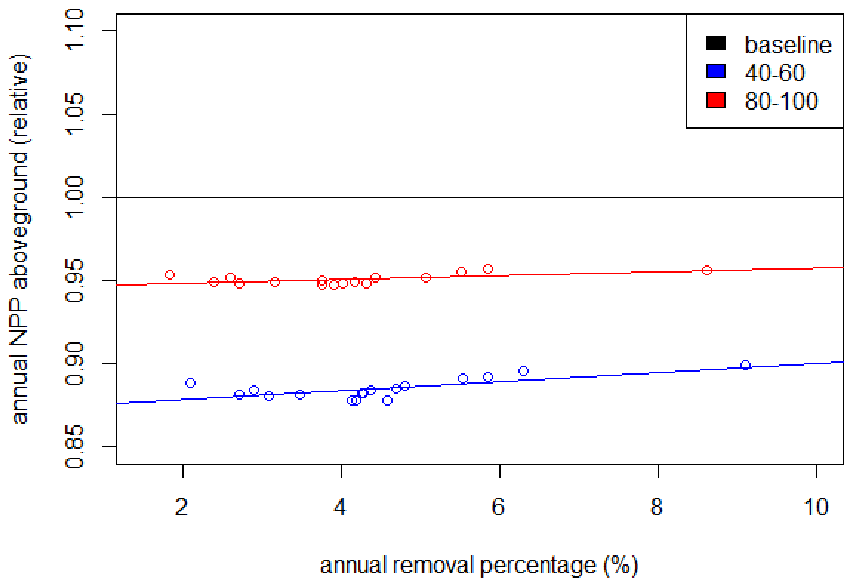

Figure 19: The annual percent changes in NPP at Ottenstein under the Remo scenario and two representative climate periods, relative to baseline climate. Lines show linear regressions of the change of the climate impact with thinning intensity.

4.3.2 Mean annual increment (MAI)

For the thinning trial Eibiswald there is only one significant scenario combination with regard to how thinning modulates the climate impact, i.e. a significant decrease of MAI by 0.64% (α=0.01) with every percent of volume removed by thinning in the first time period of the Ictp scenario. The other changes at both Eibiswald and Karlstift are small and not statistically significant.

Table 13: Overview of the slopes of mean annual increment change with every removal percentage and the respective P-values determined from linear regression analysis. The results are the relative decrease or increase of MAI over removal percentage in the respective climate scenarios relative to baseline scenario. (Significance level: * <0.001, ** <0.01, * <0.05)**

Scenarios	Eibiswald (%)	P-values	Karlstift (%)	P-values	Ottenstein (%)	P-values
Arpege 40-60	0.00	0.990	-0.11	0.485	0.26	0.00036 (***)
Arpege 80-100	0.18	0.653	-0.05	0.707	-0.3	0.0012 (**)
Ictp 40-60	-0.64	0.0018 (**)	-0.05	0.809	0.14	0.0026 (**)
Ictp 80-100	-0.79	0.101	0.10	0.512	-0.34	0.0019 (**)
Remo 40-60	1.36	0.061	0.01	0.980	0.72	0.00005 (***)
Remo 80-100	0.73	0.150	0.01	0.989	0.30	0.0003 (***)

The results from the simulations demonstrate the huge influence of the climate scenarios and the thinning intensity in the thinning trial Ottenstein, which can compared with the results of the NPP, demonstrated in the Table 13. The results demonstrate also here that in the first period of every climate scenario the respective thinning treatment lead to a significant increase of the MAI from 0.14 % (α=0.01) in the Ictp scenario to 0.72 % (α=0.001) in the Remo scenario. The results of the second period of the Arpege and the Ictp scenario are very similar with a significant decrease of 0.30% with every removal percentage (α=0.01).

As demonstrated the results of the NPP also the results in the MAI demonstrate that the Remo scenario had the biggest influence in the thinning trial, with highly significant increases in both periods (α=0.001). In the second period there are a high significant decrease in the Arpege and in the Ictp scenario and a highly increase in the Remo scenario (Figure 20).

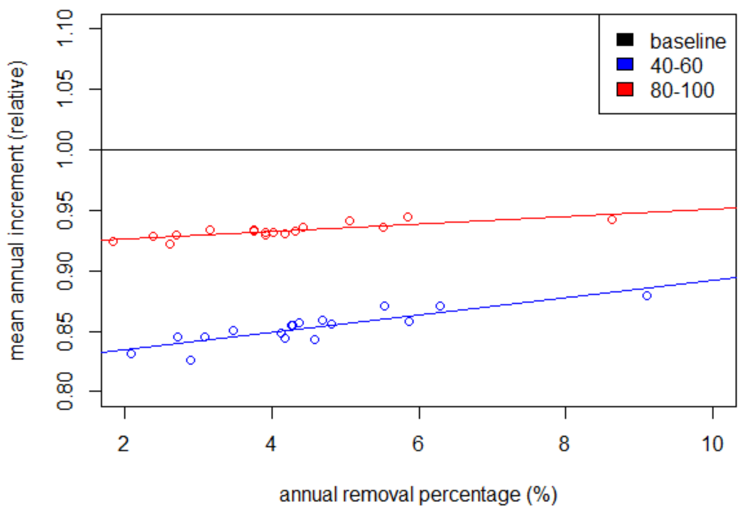

Figure 20: The annual percent changes in MAI at Ottenstein under the Remo scenario and two representative climate periods, relative to baseline climate. Lines show linear regressions of the change of the climate impact with thinning intensity.

4.3.3 Annual dbh increment (D.inc)

At Eibiswald there are strong significant reductions in D.inc with increasing removal strength in the first time period, both under the Arpege (-1.72%, (α=0.001)) and Remo scenarios (-3.71%, (α=0.05)). The results from the other climate scenaris lead to non significant smaller increases from 0.08 to 0.77 %, except in the second period of the Remo scenario there is an annual decrease of 0.74%.

Table 14: Overview of the slopes of DBH increment change with removal percentage and the respective P-values determined from linear regression analysis. The results are the relative decrease or increase in D.inc over removal percentage in the respective climate scenario relative to baseline climate. (Significance level: * <0.001, ** <0.01, * <0.05)**

Scenarios	Eibiswald (%)	P-values	Karlstift (%)	P-values	Ottenstein (%)	P-values
Arpege 40-60	-1.72	0.00055 (***)	-0.13	0.303	0.05	0.712
Arpege 80-100	0.08	0.740	-0.17	0.068	-0.14	0.147
Ictp 40-60	0.39	0.727	-0.15	0.364	0.22	0.161
Ictp 80-100	0.77	0.667	-0.43	0.0049 (**)	-0.17	0.333
Remo 40-60	-3.71	0.033 (*)	-0.20	0.250	0.66	0.00003 (***)
Remo 80-100	-0.74	0.195	-0.08	0.647	0.28	0.00097 (***)

At Karlstift the mean annual increment decreases in both periods of all climate scenarios, but only one scenario resulted in statistically significant results (-0.43 % for Ictp scenario (α=0,01)).

Also at Ottenstein the influence of thinning treatments on the climate response of D.inc is not as pronounced as for NPP (Table 12) and MAI (Table 13). In Arpege and Ictp scenario the results from the simulations were marginal percent changes.

For the Remo scenario, the most extreme of the three sudied scenarios, thinning effects on climate impacts are highly significant, as seen before also for NPP and the MAI, (α=0,001). Increases range from 0.66 % in the first period to 0.28 % in the second period. The significant increases in both time period are illustrated below in the Figure 21, showing that thinning reduces the climate-incuced reduction in D.inc at Ottenstein under the REMO scenario.

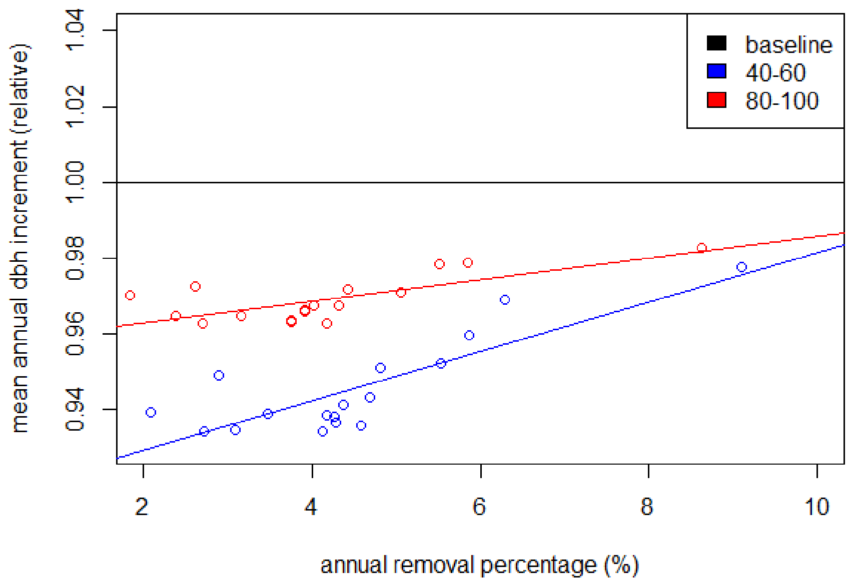

Figure 21: The annual percent changes in DBH increment at Ottenstein in the two representative climate periods under the Remo scenario, relative to baseline climate. Lines show linear regressions of the change of the climate impact with thinning intensity.

4.3.4 Stress Index

The results in Table 15 shows that at Eibiswald the stress index increased with increasing thinning in every climate scenario and in both time periods, up to a value of 7.84 % with every additional removal percent. Also at Karlstift the stress index increased in both time periods from 1.64 % in the second period of the Arpege scenario and up to 6.52 % in the Ictp scenario. For the Remo scenario, the stress index decreased in both time periods from 0.06 to 2.00% with every additional percent of volume removed by thinning.

Table 15: Overview of the slopes of stress index change with removal percentage and the respective P-values determined from linear regression analysis. The results are the relative decrease or increase in NPP over removal percentage in the respective climate scenario relative to baseline climate. (Significance level: * <0.001, ** <0.01, * <0.05)**

Scenarios	Eibiswald (%)	P-values	Karlstift (%)	P-values	Ottenstein (%)	P-values
Arpege 40-60	1.44	0.688	3.84	0.193	-1.77	0.741
Arpege 80-100	0.05	0.963	1.64	0.494	-3.19	0.298
Ictp 40-60	2.55	0.675	6.52	0.231	-1.38	0.736
Ictp 80-100	7.84	0.390	1.60	0.695	-0.21	0.962
Remo 40-60	1.15	0.439	-2.00	0.603	-3.22	0.144
Remo 80-100	0.27	0.879	-0.06	0.988	0.06	0.976

At Ottenstein results are again different from the other two thinning trials. At Ottenstein the thinning treatment generally had a positive influence to the individual stress index of a tree, decreasing stress with increasing removal percentage. Especially in the Arpege scenario is a clearly decrease from -1.77% up to -3.19%, which is pictured below in the Figure 22.

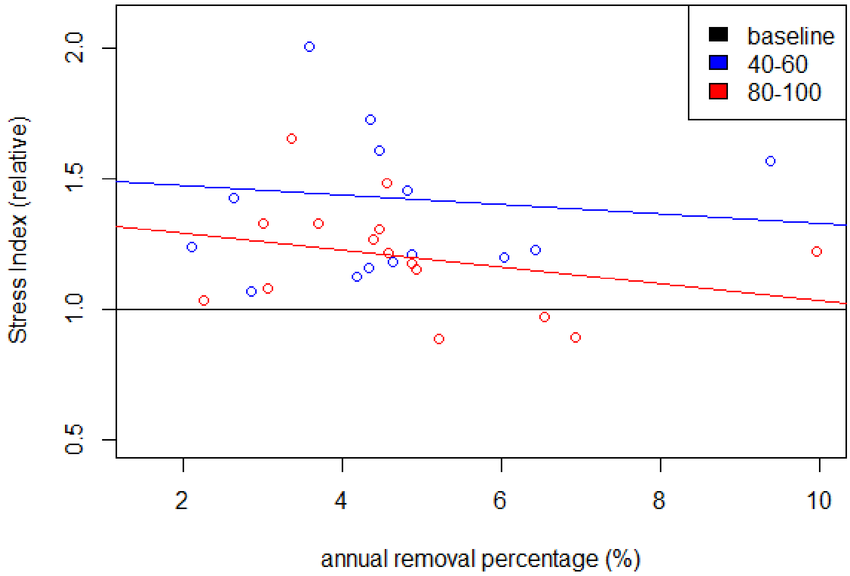

Figure 22: The annual percent changes in Stress Index at Ottenstein under the Arpege scenario and two representative climate periods, relative to baseline climate. Lines show linear regressions of the change of the climate impact with thinning intensity.

For a better overview how large the differences between the baseline climate and the climate scenarios are really, the absolute values of the four parameters are illustrated in the Appendix part B.

5 Discussion

5.1 Evaluation of the model iLand

The aim of models is to capture the environment and its effect on ecosystem processes as realistically as possible, and they help to understand the basic processes and the functioning of the forest ecosystem (Jarvis et al., 1998). However, as Box and Draper (1987) stated: “A much safer approach is to assume that all models are wrong and only a few might actually be useful” (cited from Weiskittel et al., 2011). With this statement they want to express that models can never reproduce reality 100 %, but rather are by definition a simplified approximation of reality. This is the reason why model testing and evaluation is of critical importance. Every model can be evaluated in different ways and with various approaches. Generally the model evaluation is an important tool to demonstrate the ability of a model to reproduce the dynamic processes within a forest ecosystem. Evaluation is an integral part of the modelling process, not least because imprecise and wrong predictions can lead to unfavourable decisions. Testing the suitability of a model to a given purpose should be the first step in an evaluation framework (Pretzsch, 2009). Within model evaluation, model benchmarking is a good choice to evaluate a model, provided that independent data are available for comparison (Weiskittel et al., 2011). iLand already demonstrated in previous simulation studies the ability to reproduce forest ecosystem dynamics (Seidl et al. 2012 a, Seidl et al. 2012b). However, the forest management response of iLand has not been tested in detail previously.

With this work I showed that iLand is also able to reproduce different silvicultural management effects with regard to thinning responses, by comparing model simulations against long-term, independent data from the three thinning trials. iLand is, for instance, able to reproduce the observed dbh responses of individual trees to thinning, and therefore can be assumed to be suitable to reproduce different thinning treatments across a range of locations and growing conditions.

In comparison with previous evaluation results of iLand, the R^2 values for regression of observed versus predicted basal area were found to be in the range of between 0.375 to 0.521 (Seidl et al. 2012a). In this study the R^2 values for dbh projections were between 0.436 and 0.621 (Figure 13), i.e. even slightly higher than in Seidl et al. (2012a). This results are in line with findings from other models, which were tested against independent forest inventory data, i.e. with the single-tree model Silva tested along an elevation gradient (R^2 values for regression of diameter increment between 0.031 and 0,621; Schmid et al., 2006) or with the growth model PBRAVO simulating forest management (R^2 value for regression of basal area 0.17; Soares et al., 1995).

Compared to the simulation of dbh increment- the simulation of height increment is more difficult because of- a lower number of remeasurements, a higher within-stand variability and a greater dependence on environmental than on stand-level conditions (Weiskittel et al. 2011).

The results regarding the simulated dominant height at the three thinning trials, shows that dominant height in iLand is less sensitive to thinning than the individual dbh of the trees, which is in line with the previous findings (Weiskittel et al. 2011). The R^2 values for dominant height projections were between 0.185 and 0.503, with an average R^2 over all thinning trials of 0.357 which is slightly lower than the average R^2 over all thinning trials for dbh projections (R^2=0.504). A previous simulation experiment with iLand in the eastern Alps found an R^2 of 0,831, for dominant height at age 100 (Seidl et al. 2012 a), yet tested simulated heights over a wide environmental gradient rather than for different management regimes at the same site. Compared with the results from the growth model PBRAVO (R^2=0.21 for regression of dominant height; Soares et al., 1995) the result of this study is very satisfactorily. Also in comparison with the mixed-wood-growth model MGM in mature stands (Efficiency between 0.16-0.66 regarding the dominant height, which is nearly similar to the R^2; Bokalo et al., 2013) the results of iLand are satisfactorily.

Another parameter to define the precision of a model is the bias (Pretzsch, 2009). Both mean absolute bias in this study were very low (Dbh=0.046 cm and dominant height=0.145 m) regarding to other studies (Harkönen et al., 2010; Seidl et al. 2012 a).

At the two thinning trials Eibiswald and Karlstift dbh and dominant height (except a slightly underestimation at Karlstift) were overestimated by between 5 and 13 %, whereas at Ottenstein the observations were underestimated by between 10 and 15 % by iLand. The reason could be that growing conditions are considerably more harsh for Norway spruce in Ottenstein compared to the two other sites, as Ottenstein features a higher mean annual temperature (Table 6), a lower annual precipitation sum (Table 7) and a lower effective soil depth (Table 4) compared with the other two thinning trials. It thus appears that iLand overestimated stands under favourable growing conditions and underestimated stands under harsher growing conditions. In other words, the sensitivity of the model to the environment appears to be somewhat too high. This observations should be tested in future studies conducted over a larger environmental gradient.

Another reason for the specific over- and underestimation found here could be tree age. At Eibiswald the mean tree age at the end of the thinning trial is 85 years, and 62 at Karlstift, whereas Ottenstein features younger trees of only 56 years at the end of the trial. It could thus also hypothesized that iLand overestimates the growth of older trees and underestimates younger trees.

Overall, the results from the evaluation showed that iLand is able to reproduce the observed thinning responses across different sites and therefore the hypothesis can be confirmed. I thus conclude that the model can be used to assess forest ecosystem responses to thinning, and to answer the main questions of this study.

5.2 The climate effect

Changing climate conditions are expected to affect forest ecosystems in the European mountainous regions, like the Alps (Lindner et al., 2010). Whether these changes will be negative or positive depends strongly on the location, the exposure, and on the species composition of the forest ecosystem. Besides the changes in distribution and annual precipitation amount European mountainous regions are exposed to an increasing temperature (Lindner et al., 2010). Consequently, there is a great demand to study the impacts of climate scenarios on forest ecosystems.

The results in this study demonstrate that Norway spruce forests in Austria are sensitive to different climate scenarios. The three climate scenarios have a distinct influence on the net primary production (from -11.5% to +13.4% regarding to the baseline climate), the mean annual increment (from -14.8% to + 20.4%), the dbh increment (from -5.5% to +8.3%) and the stress level (-25.0% to +42.9%) of the forest stands. Especially the harshest climate scenario Remo (see Table 10) has a negative impact at all three thinning trials and all investigated variables. Particularly a decreasing precipitation and an increasing temperature iLand predict a decrease of the investigated variables, which is particularly clear at the harshest thinning trial (Ottenstein) under the harshest climate scenario (Remo).

Recent studies demonstrated that Norway spruce can show higher net primary production and increased tree growth with increasing temperature and atmospheric CO_2 content (Eastaugh et al., 2011; Ge et al., 2013; Lindner et al., 2014). However, an increase in temperature could also lead to an increasing drought risk for the tree species, which could decrease forest growth (Alam et al., 2008). Apart from the temperature, the precipitation is really important for the growth of a tree. Especially in the temperate continental zone the most important limitation in the future is likely going to be water availability (Lindner et al., 2010).

My results are generally in line with these expectations and previous findings, and show that NPP increases with increasing temperature and precipitation, and decreases with an increasing temperature and a decreasing precipitation. This results are in line with the findings of Lindner et al. (2014), which suggest that the forest production in the future could be negative on sites which are water limited. Besides net primary production also the mean annual increment (chapter 4.2.2) and DBH increment (chapter 4.2.3) shows the same trend. In other words simulated allocation of carbohydrates within trees did not change significantly.

Particularly at Ottenstein, which is situated at a lower altitude (540 meters, sub montane altitudinal zone) than the other two thinning trials, significant decreases in NPP, MAI, DBH increment were found under the warmer and drier REMO scenario. I.e. where water availability is already limiting for Norway spruce and is further intensified by a changing climate, ecosystem processes are affected more strongly. This is congruent with the findings of Eastaugh et al. (2011), who assessed the future growing conditions of Norway spruce in Austria, and found the strongest climate effect for "climate change zones" with an increasing temperature and a decreasing precipitation. In this study a precipitation reduction of 7% lead to a decrease in NPP of 12% under the Remo scenario at Ottenstein. In such areas it can be assumed that the Norway spruce is no longer suitable under changing climate conditions, which is in line with the findings of Gebert (2013) and Lexer et al. (2001). In such areas it's thus important to adapt forest management to the changing environmental conditions.

In this context an interesting result was found for stress index, which showed a positive reaction (i.e., decreased stress) under the harshest climate scenario REMO (e.g. at Ottenstein). This somewhat counter-intuitive response can be explained through the fact that stress in pole- and early timber-stage stands first and foremost depends on the density in a forest stand, and relates to stress from competition through neighbours. A reduction in growth in response to climate change also alleviates competitive pressure (particularly with regard to competition for light), and thus reduces stress in the simulations conducted here.

5.3 The thinning effect

Thinning is one of the well-developed silvicultural management strategies and the long-term thinning effect on Norway spruce was studied and discussed in a large number of previous studies (Eriksson, 2006; Pretzsch, 2005; Misson et al., 2003; Gebhardt et al., 2014).

More recently, thinnings have also been discussed in the context of climate change. Here thinnings are seen as an important short-term adaption measure to reduce climate change vulnerability in forest stands. (Bolte et al., 2009; Ge et al., 2013). In the context of climate-change adaption, thinnings can provide numerous functions, for example stimulating crown development and increasing the fruiting of seed trees, reducing drought stress and increasing growth (Ogden and Innes (2007); Kohler et al., (2010); Amato et al. (2013)).

The first hypothesis of this study, i.e. that there is a significant difference between the effects of thinning under different climate scenarios, can be confirmed. My results demonstrate clearly that the thinning responses differed between significant the chosen climate scenarios and sites (Table 13 – 16). So overall no clear pattern of thinning effects under climate change was found.

The two growth parameters NPP and MAI show statistically significant results (see chapter.4.3.1 and chapter 4.3.2). At Ottenstein, in every scenario and period, but one, thinnings effects under climate change varied significantly with removal percentage. Thinning under climate change significant increased the net primary production compared to the baseline, with the exception of a single scenario. Especially for Ottenstein, the potential role of thinnings under climate change could be demonstrated. At the other two sites, however, either no significant thinning effects under climate change or varying thinning responses were found, and no clear pattern emerged from the analysis. Therefore the second hypothesis of this work, i.e. that there is a significant change of the stand parameters through thinning, can just confirmed at Ottenstein.

A result from previous long-term thinning-trials was, that through the reduction in the tree density the water availability for remaining trees increased, a thinning effect which is particularly important for forest stands which are water limited (Misson et al., 2003). This finding is confirmed by this study, e.g. with regard to individual tree stress (see Table 16). In the two thinning trials Eibiswald and Karlstift, which are not water limited, thinnings did not significantly improve the individual stress level of trees under climate change.

At Ottenstein, which has a harsher climate and is more water limited (see Figure 9 and Figure 10) than the other two thinning trials, the variation of individual tree stress level with removal percentage indicated a slight yet not significant decrease in stress with increasing thinning. (see Figure 22 as example). Here it can be assumed that in the future the water availability will be improved and the drought risk can be mitigated through thinning treatments. This general finding is in line with Amato et al. (2013), which predicate that reducing the tree density can reduce the drought vulnerability in predisposed Norway spruce stands. The same result was found by Kohler et al. (2010), who analysed three different thinning regimes, finding that thinnings can increase the individual drought tolerance of a tree and therefore also decrease the vulnerability to secondary pathogens or pest species (i.e. bark beetle) can be reduced.

Also Gebhardt et al. (2014) found that, due to the improvement of the water availability through thinnings, the drought risk can be mitigated. However, also other factors besides thinning can influence the non-structural carbohydrates available for a tree (which are trees C reserves, and thus negatively related to stress): An increase in the atmospheric CO_2 concentration, for instance, can improve a trees C balance and thus decrease stress (Jarvis et al., 1998). On the other hand increasing growth from CO_2 fertilization can also lead to increasing competition and thus increasing tree stress.

As a result of these competing factors, the hypothesis that a stronger reduction in the tree density decreases the individual tree stress level, was only indicated at Ottenstein and was not significant at any of the three study sites. This knowledge could help to mitigate changing climate conditions, underlining that thinnings are an important measure to reduce the possible negative impacts of the climate change (Bolte et al., 2009; Ge et al., 2013).

A similar result as for the Stress Index could be found for dbh increment. Also here the hypothesis that a stronger reduction in the tree density increase the individual dbh increment under climate change relative to baseline could just confirmed at Ottenstein under the Remo scenario (see Figure 21) some climate-site combinations, such as at Karlstift under the Arpege and the Ictp scenario in the second period, more heavily thinned stands even performed a bit poorer compared to dense stands under climate change (see Table 15). Overall, my results show that the more extreme the stand conditions are and the more extreme climate change is, the stronger is the thinning response compared to baseline climate.

Within the toolbox silvicultural adaption measures thinnings are thus a main tool to reduce the risk from a changing climate, especially in lower elevation areas (Seidl et al., 2011). With regard to growth and productivity however, climate change is not only a challenge but also provide an opportunity for increases particularly in high elevation areas (Eastaugh et al., 2011). However the exact and long term influences of a rising atmospheric CO_2 content, remain difficult to determine (Reyer et al. 2014). Yet, the short term growth responses for several tree species to an elevated CO2 content suggest that increasing growth might be possible in the future (Jarvis et al., 1998). In this context thinnings are an indispensable adaption tool to take advantage of the positive climate effects, like an increasing tree growth, and not just to reduce the negative climate effects.

Demonstrated with the significant changes of the two variables NPP and MAI at Ottenstein it can be assumed, that the stronger the actual growth conditions are in the baseline climate the more important is the role of thinnings as an adaption measure in the future. My findings thus suggest that thinnings should be considered more strongly in climate-change adaption strategies for water limited sites.

6 Conclusion

Climate change has affected forest ecosystems in the past, and will likely affect them also in the future. An important question for forest management is, what impacts we need to expect for the future?

To answer this question I here conducted a simulation study, showing that climate change strongly influences forest growth characteristics. One outcome of my analysis is that changing climate conditions do not necessarily lead to a worsening of growing conditions everywhere, but can also improve forest growth in some cases. Generally, the more we know about the climate change impacts, the better we can adapt planning and management strategies, and thus make forests better suited for future environmental conditions.

Several strategies and approaches to address future climate change in forestry have been discussed previously, including a silvicultural “evergreen”: thinning. Here I focused on this specific silvicultural measure, and demonstrated that the model ILand is sensitive to forest management interventions, and able to mimic a wide range of thinning effects in forest ecosystems. These findings thus suggest that iLand can be used as a research tool to simulate and analyze the effect of a wide range of tree-level management interventions.

Subsequently, I tested thinning responses under climate change, i.e. as to whether thinnings can alleviate negative climate effects or enhance positive climate effects. Between sites the thinning responses under climate change were very different: the more limited sites conditions were, the greater the positive effect of thinnings. Therefore, I conclude that particularly on poor water-limited sites thinning could be an important climate change adaption measure.

Yet, on better sites responding mostly positive to climate change, I could not find any further improvement of growing conditions through thinning. This highlights that adapting forests to climate change needs a mix of different strategies and measures rather than a one-size-fits-all solution, and depends strongly on the particular site conditions.

In the future there is a strong need for further studies to learn more about the climate change impacts and adaption in general, and the role of thinnings for mitigating climate change effects in particular, and to help future forest managers address the positive and negative impacts of a changing climate.

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8 Appendix

A – Evaluation of the model iLand

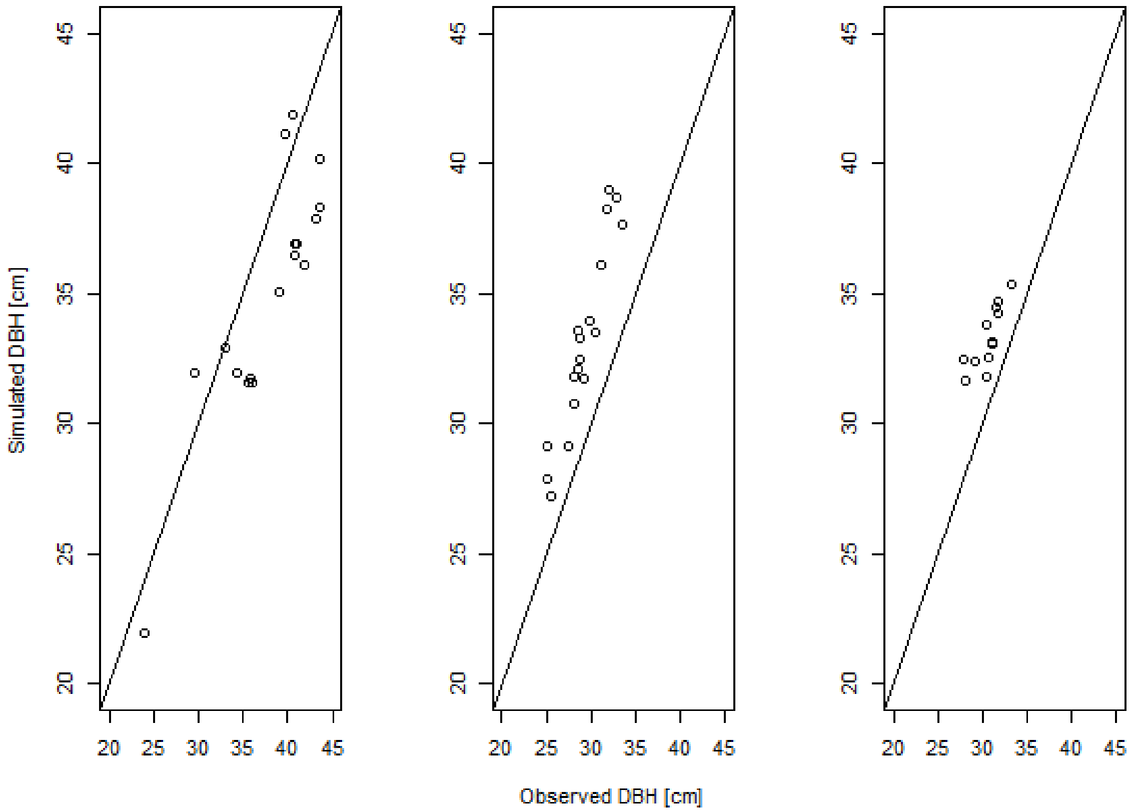

Figure A 1: This Figure shows the linear relationship between the simulated and the observed averaged dbh for each stand within the trials. The left panel are the results for the thinning trial Eibiswald, in the middle for Karlstift and the right panel for Ottenstein.

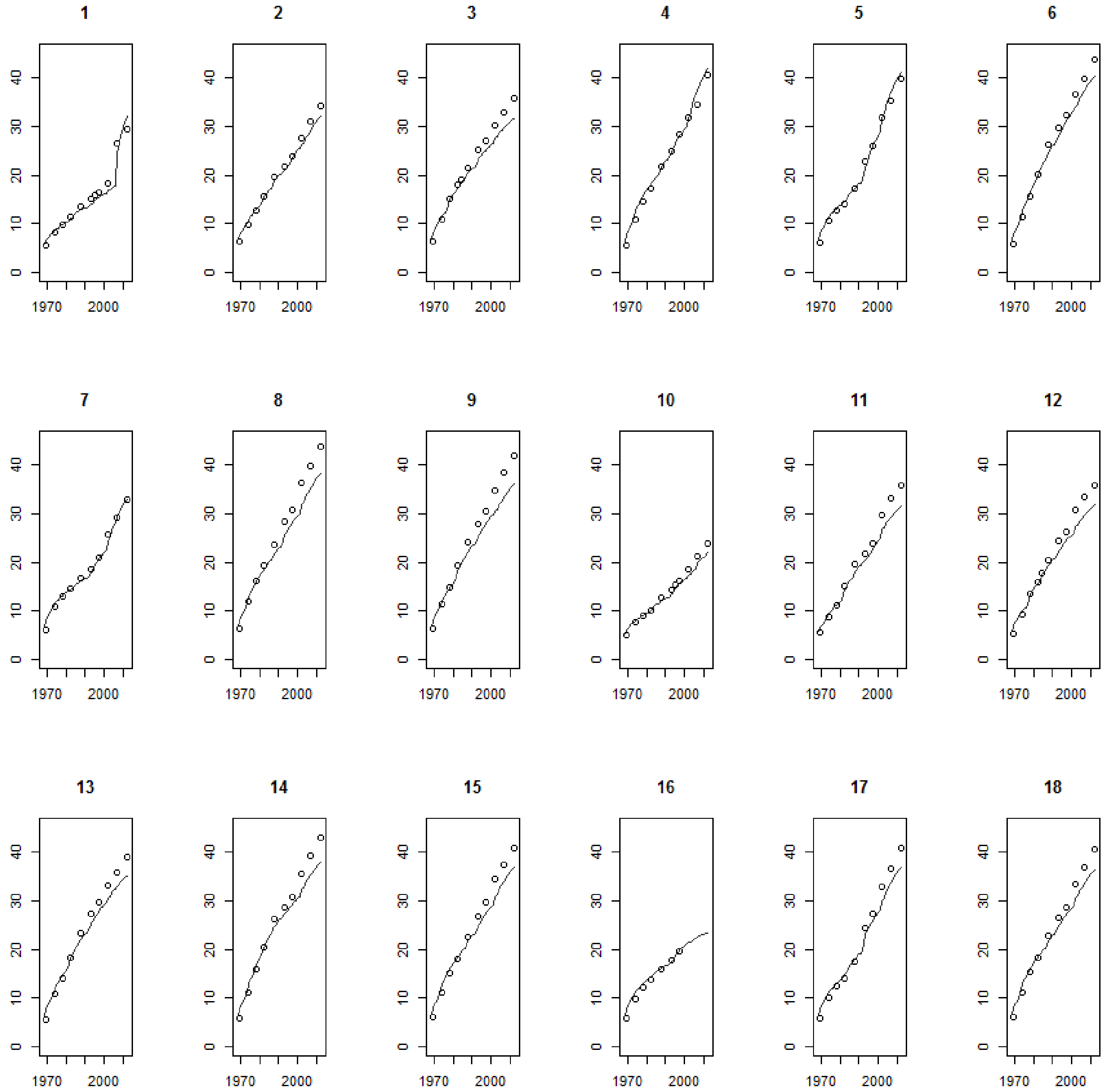

Figure A 2: This graphic demonstrate the reproduce of the observed averaged dbh from the model iLand of every stand from the thinning trial Ottenstein after the 44 year study period. The circles are the observed averaged dbh in centimetre of a stand and the line are the simulated results from the model iLand. The y-axis represents the mean dbh in centimetre and the x-axis the year.

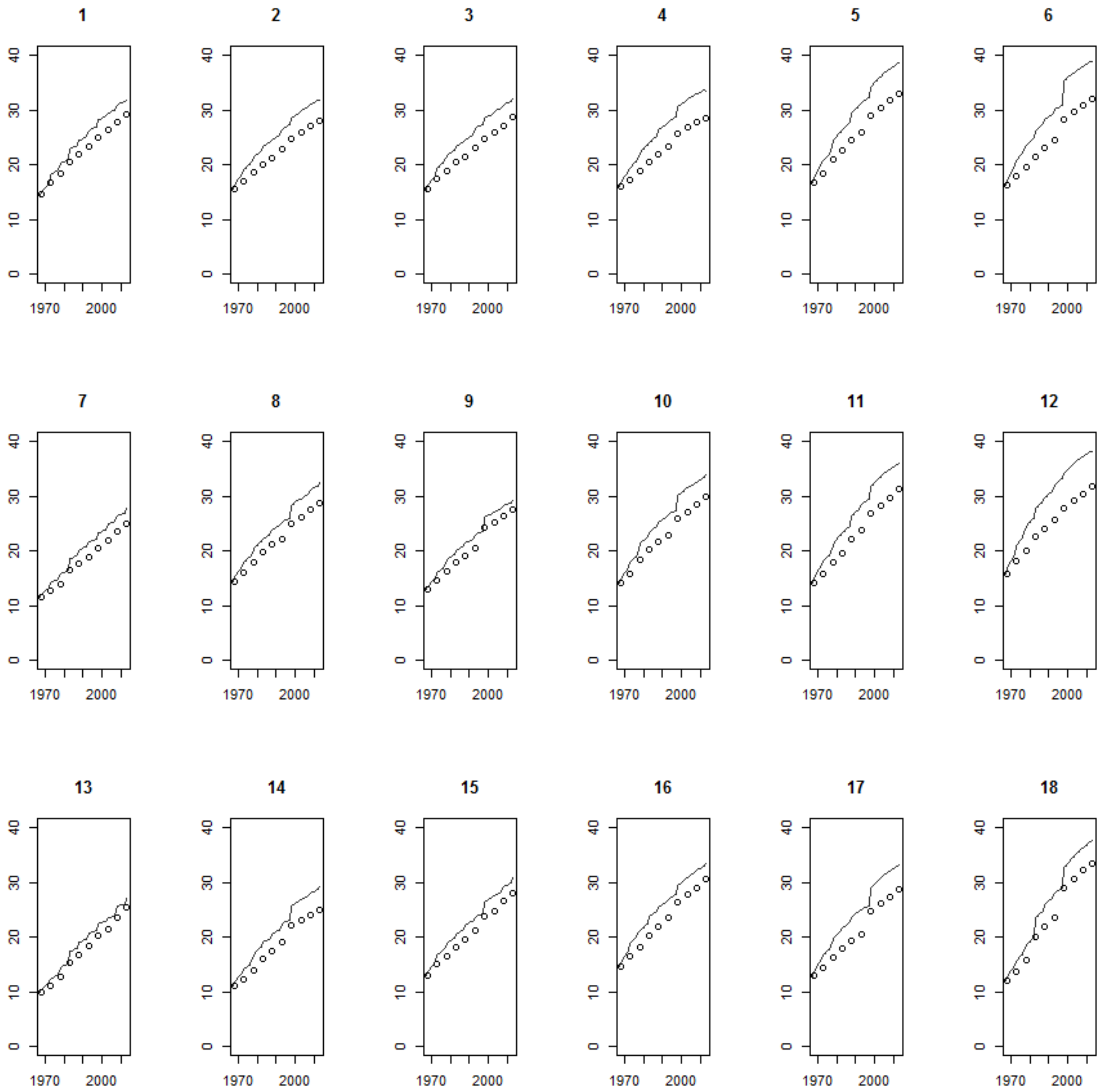

Figure A 3: This graphic demonstrate the reproduce of the observed averaged dbh from the model iLand of every stand from the thinning trial Eibiswald after the 46 year study period. The circles are the observed averaged dbh in centimetre of a stand and the line are the simulated results from the model iLand. The x-axis represents the mean dbh in centimetre and the y-axis the year.

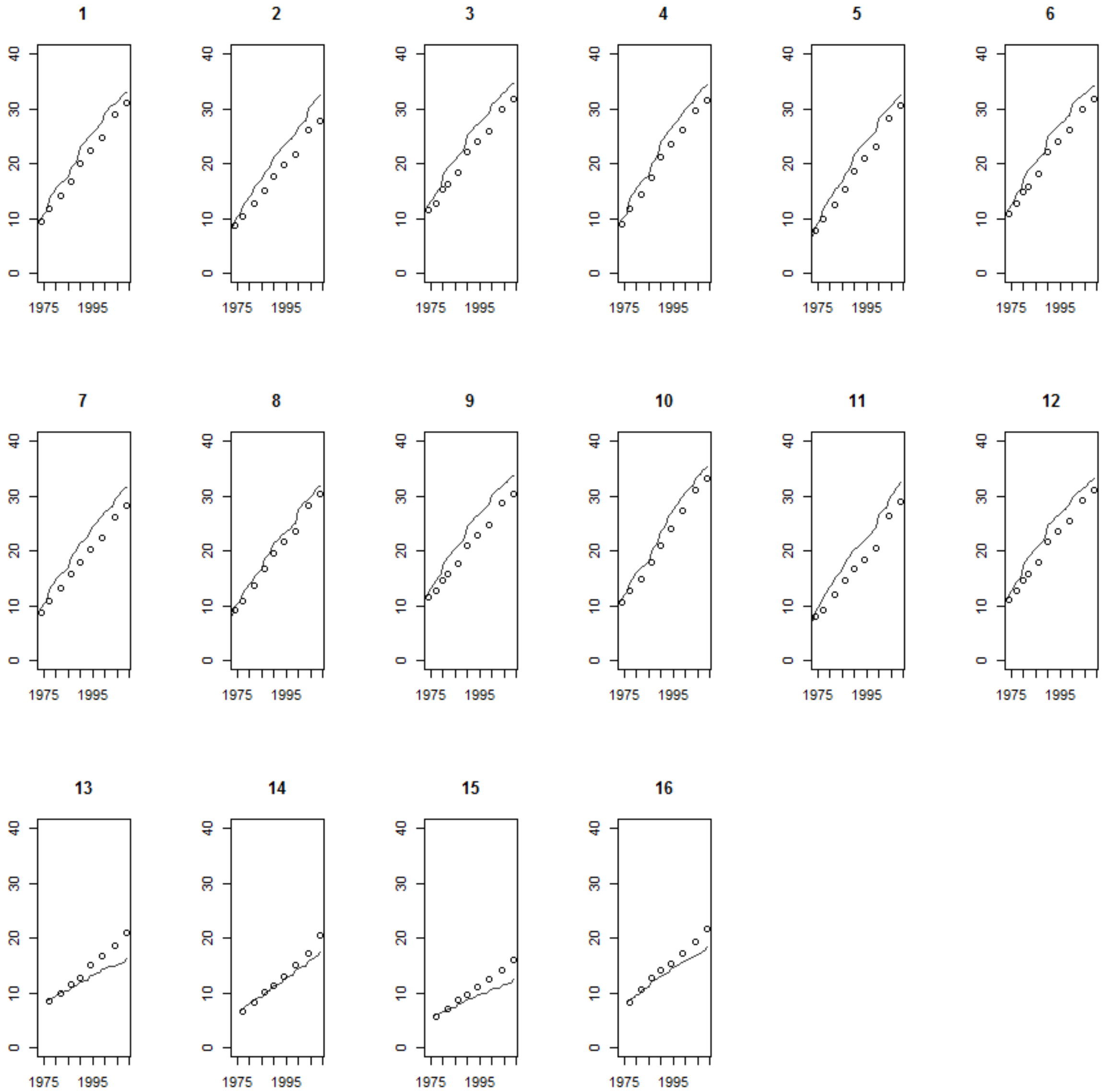

Figure A 4: This graphic demonstrate the reproduce of the observed averaged dbh from the model iLand of every stand from the thinning trial Karlstift after the 36 year study period. The circles are the observed averaged dbh in centimetre of a stand and the line are the simulated results from the model iLand. The x-axis represents the mean dbh in centimetre and the y-axis the year.

B – Climate effect

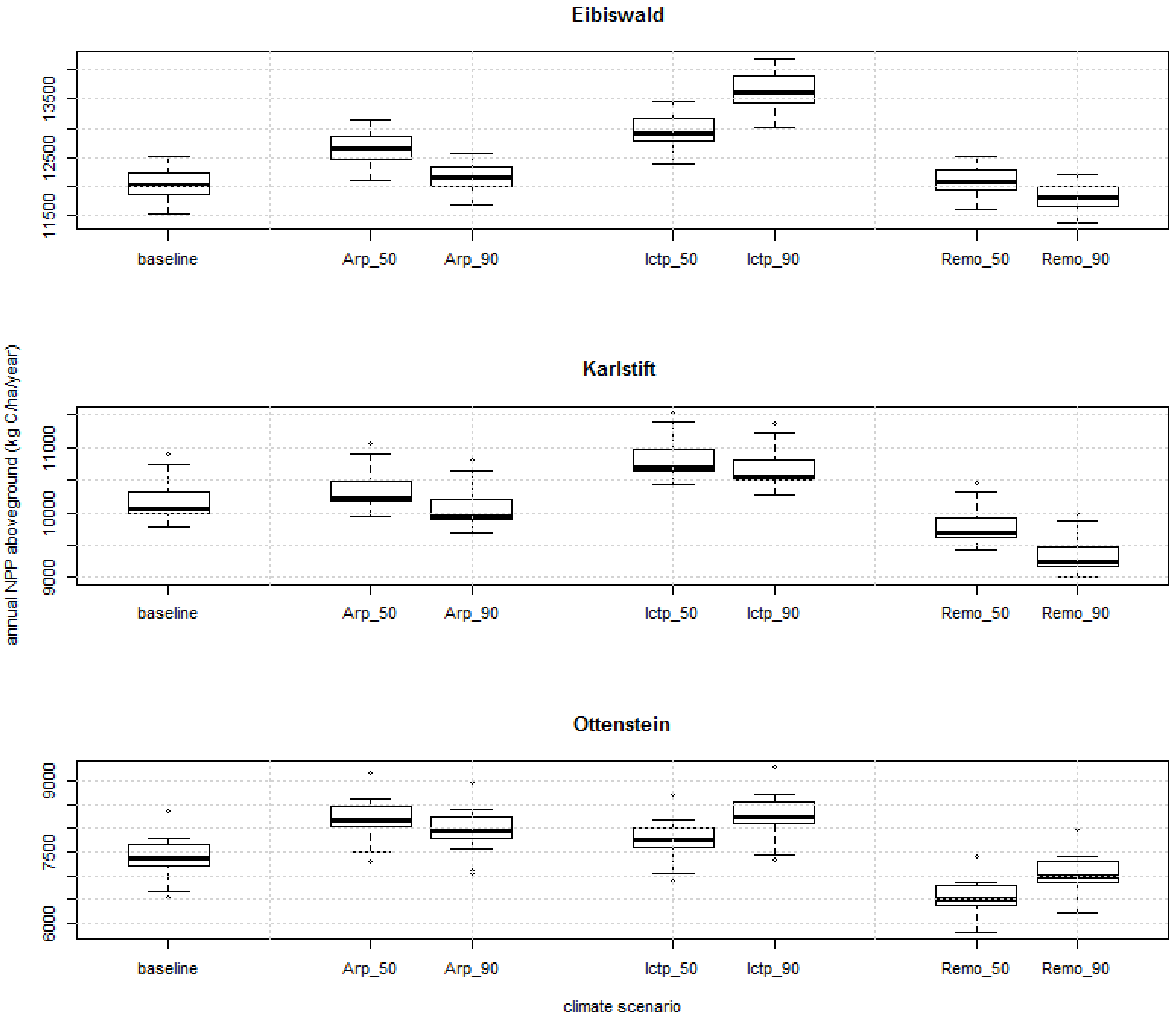

Figure B 1: Annual aboveground net primary production of the three thinning trials in kilogram carbon per hectare. On the left is the NPP of the baseline climate as a comparison with the two periods (50: 2040-2060, 90:2080-2100) of the ARPEGE (Arp), the ICTP and the REMO scenario.

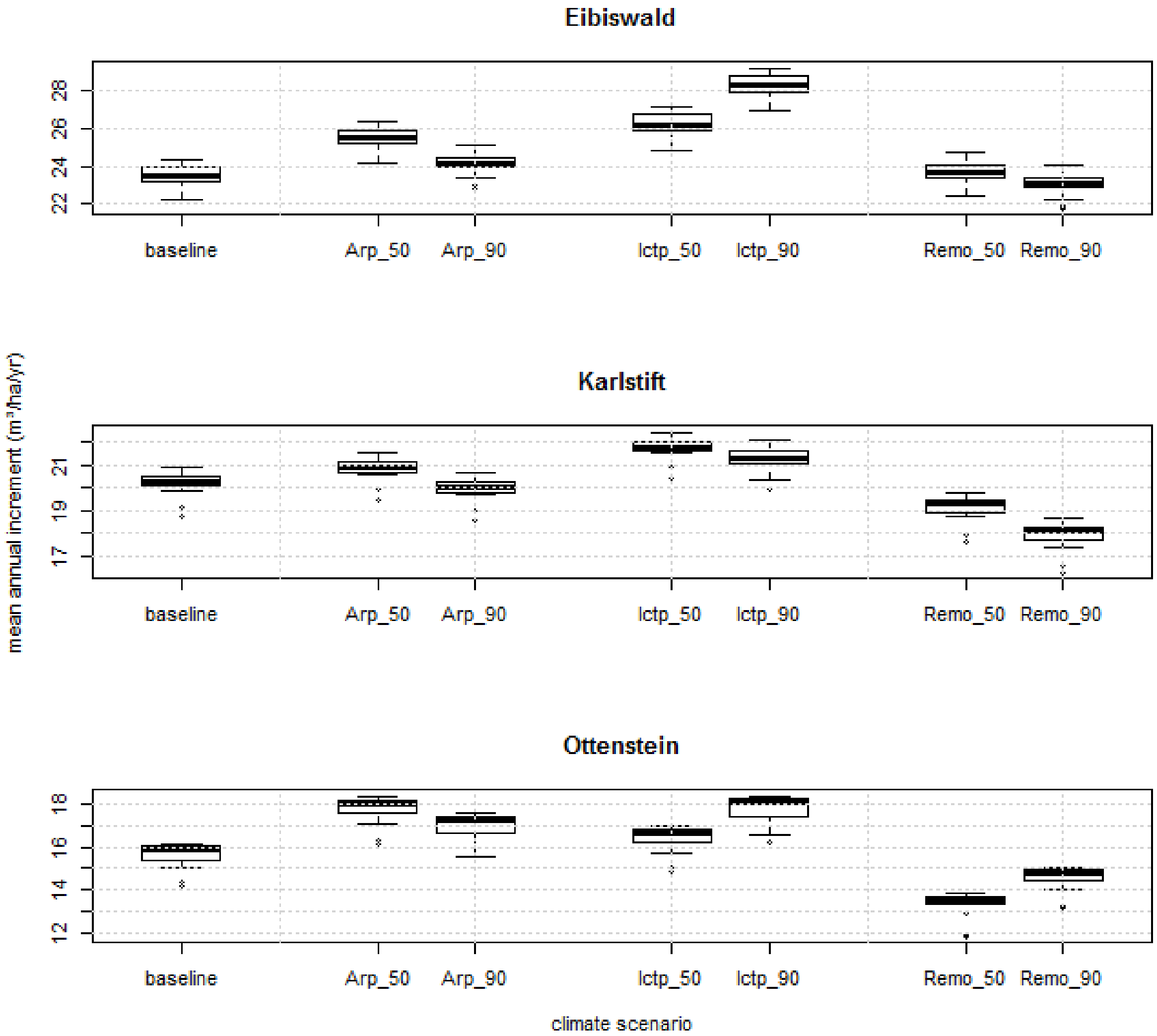

Figure B 2: Average annual increment of the three thinning trials in cubic meter per hectare. On the left is the MAI of the baseline climate as a comparison with the two periods (50: 2040-2060, 90:2080-2100) of the ARPEGE (Arp), the ICTP and the REMO scenario.

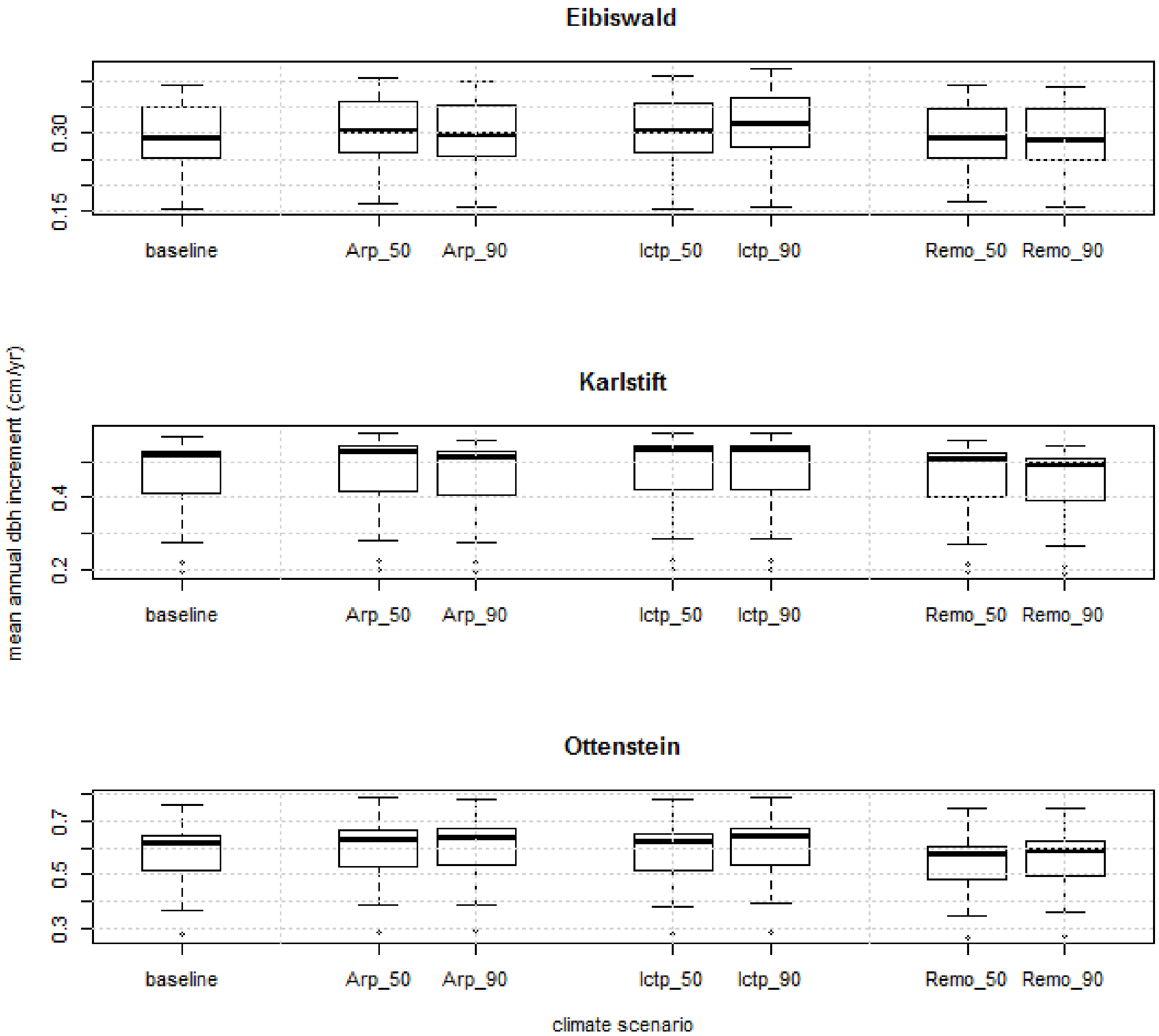

Figure B 3: Average annual dbh increment of the three thinning trials in centimetre. On the left is the dbh increment of the baseline climate as a comparison with the two periods (50: 2040-2060, 90:2080-2100) of the ARPEGE (Arp), the ICTP and the REMO scenario.

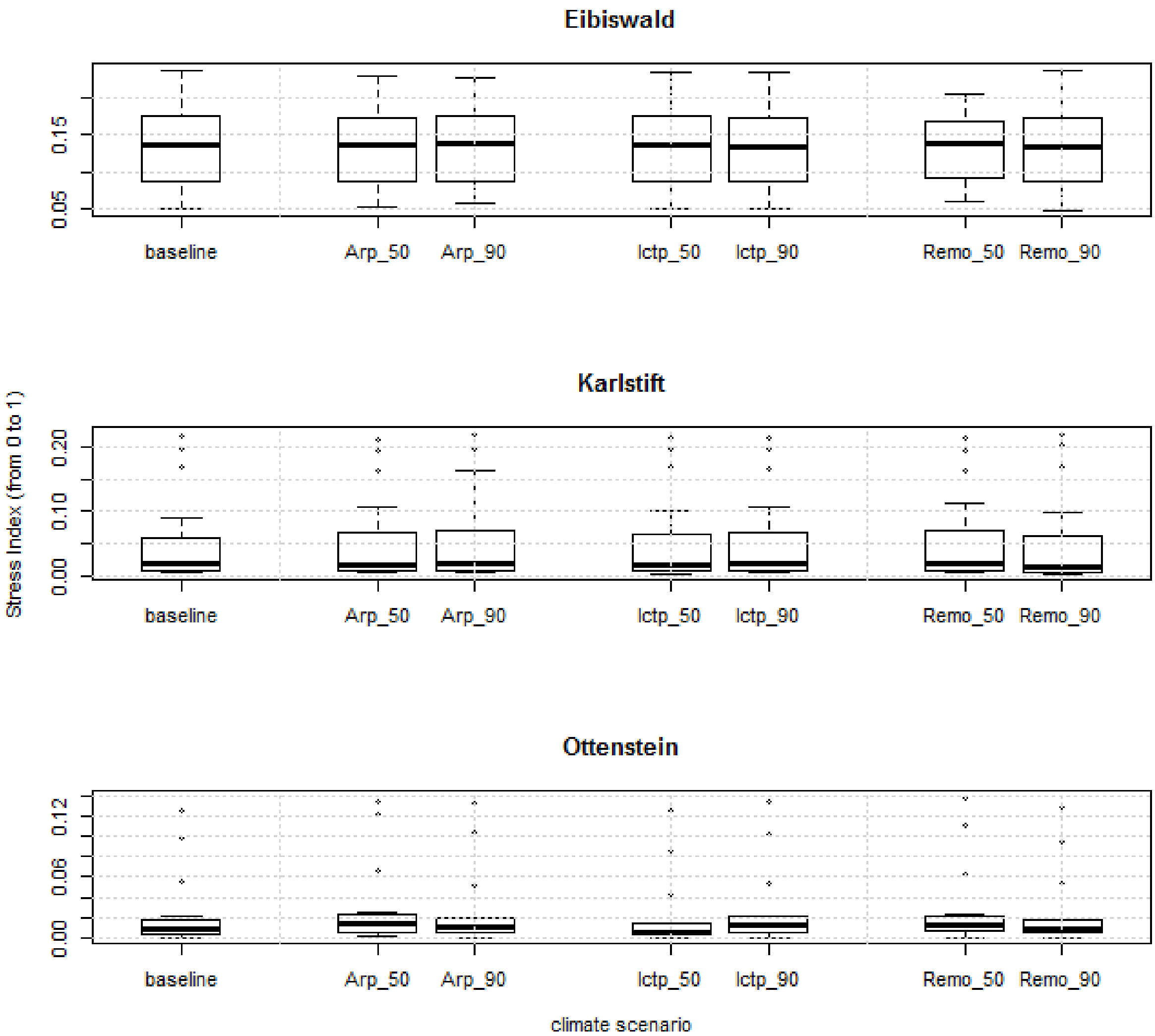

Figure B 4: Average stress index of the three thinning trials in absolute values, which are going from 0 (no stress) to 1 (mortality). On the left is the stress Index of the baseline climate as a comparison with the two periods (50: 2040-2060, 90:2080-2100) of the ARPEGE (Arp), the ICTP and the REMO scenario.