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Effects of forest management on the provisioning of ecosystem services under climate change in a mountain forest landscape

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"The clearest way into the Universe is through a forest wilderness."

John Muir

Abstract

Humans depend on forests for a multitude of ecosystem services, and often require landscapes to fulfil several different services simultaneously. Recent investigations predicted severe, mostly negative impacts of climate change on the future provisioning of forest ecosystem services. Forest management is thus faced with the challenge to ensure a stable provisioning of ecosystem services under changing environmental conditions while also meeting the increasing demands on forests and the services they provide. To date, there is still considerable uncertainty regarding the utility of different management approaches in addressing these future challenges.

The objective of this thesis was to investigate the ability of contrasting management strategies to support a variety of different ecosystem services, including timber provisioning, climate regulation, site protection, and biodiversity conservation. To this end, I determined the performance of the strategies under historic baseline conditions, and analysed the stability of ecosystem service provisioning in each strategy under climate change.

The investigated strategies ranged from the Norway spruce focused management of the past to a future-oriented strategy with increased tree diversity. The intermediate strategies represent the current management and silvicultural recommendations in the area, and were designed together with local stakeholders.

The individual-based forest landscape and disturbance model (iLand) was used to simulate a forest landscape in the Northern Front Range of the Alps in Austria (Weissenbachtal, Upper Austria). iLand includes processes from the individual tree to the landscape scale, and dynamically simulates interactions between vegetation, climate and disturbances. A recently developed agent-based forest management submodel (ABE) was used to implement the four alternative management strategies. Each management strategy was projected under seven different climate scenarios (one baseline scenario and six scenarios of changing future conditions), and replicated 20 times to account for the stochasticity in the simulations. The analyses were performed for a period of 200 years, starting in 2013. For each of the four ecosystem services two indicators were analysed.

Management had a distinct effect on forest structure and composition, and consequently also on the susceptibility to climate change and disturbances. The response of the four ecosystem services to climate change was highly variable. Timber production and climate regulation were generally negatively impacted by climate change, while site protection showed only small responses and biodiversity was clearly positively affected. Strategies which were focused on Norway spruce showed higher performance especially for timber production and, to a lesser extent, also for climate regulation. However, they were also highly prone to disturbances, resulting in a decreasing stability of service provisioning under climate

change for these services. Strategies increasing the tree species richness had generally lower levels of timber production and climate regulation under baseline climate, but were more robust under climate change. These strategies also had the highest levels of biodiversity, yet changing climate and disturbance regimes also increased diversity in the other strategies.

No management strategy was found to be clearly superior in providing all the services investigated. However strategies actively adapting to climate change via reducing the rotation period and fostering tree species better adapted to warming conditions generally showed a more robust provisioning of ecosystem services under changing conditions.

Zusammenfassung

Wälder stellen eine Vielzahl von Ökosystemleistungen zur Verfügung, auf welche die Gesellschaft angewiesen ist. In vielen Fällen sollen Wälder sogar mehrere gesellschaftlich nachgefragte Leistungen zeitgleich auf derselben Fläche erfüllen. Jüngste Analysen deuten auf beträchtliche, meist negative, Auswirkungen des Klimawandels auf die Bereitstellung von Ökosystemleistungen aus Wäldern hin. Die Waldbewirtschaftung steht also vor der großen Herausforderung, nicht nur die Leistungsfähigkeit von Wäldern unter sich ändernden Umweltbedingungen zu erhalten, sondern auch die steigenden Ansprüche der Gesellschaft an Wälder zu erfüllen.

Das Ziel dieser Masterarbeit war es, die Fähigkeit von kontrastierenden Bewirtschaftungsstrategien zu untersuchen, Ökosystemleistungen wie Holzproduktion, Klimaregulation, Standortschutz und Biodiversität bereitzustellen. Hierzu wurden sowohl die Leistungsfähigkeit der Alternativen in Bezug auf Ökosystemleistungen unter historischem Klima als auch die Stabilität der Bereitstellung im Klimawandel analysiert.

Die analysierten Bewirtschaftungsalternativen reichten von einem den vergangenen Bedingungen entsprechendem Fokus auf Fichte bis zu einer auf zukünftige Verhältnisse ausgerichteten, baumartenreichen Strategie. Zwei zwischen diesen Extremen liegenden Strategien wurden in Zusammenarbeit mit lokalen Stakeholdern erarbeitet und repräsentieren die derzeitige Bewirtschaftung beziehungsweise aktuelle Empfehlungen. Das Landschaftsmodell iLand (the individual-based forest landscape and disturbance model) wurde verwendet um die vier Bewirtschaftungsalternativen für eine Waldlandschaft in den nördlichen Kalkalpen Österreichs (Weißenbachtal, Oberösterreich) zu simulieren. iLand berücksichtigt Prozesse von der Einzelbaum- bis zur Landschaftsebene und simuliert die Interaktionen zwischen Vegetation, Klima und Störungen dynamisch. Die Bewirtschaftung wurde mit dem kürzlich entwickelten agenten-basierten Bewirtschaftungs-Submodell ABE (agent-based model of forest management) simuliert. Jede Bewirtschaftungsstrategie wurde unter sieben verschiedenen Klimaszenarien (ein dem vergangenen Klima entsprechendes Basisszenario und sechs verschiedene zukünftige Klimawandelszenarien) simuliert, wobei 20 Wiederholungen durchgeführt wurden, um die Stochastizität der Simulationen zu berücksichtigen. Die Analysen wurden für einen Zeitraum von 200 Jahren, beginnend im Jahr 2013, durchgeführt. Für jede der vier Ökosystemleistungen wurden zwei Indikatoren analysiert.

Die Bewirtschaftung zeigte einen klaren Einfluss auf die Struktur und Zusammensetzung der Waldlandschaft. Dadurch unterschieden sich die Bewirtschaftungsalternativen stark in ihrer Anfälligkeit auf Störungen und klimatische Veränderungen. Die verschiedenen Ökosystemleistungen reagierten sehr unterschiedlich auf Bewirtschaftung und Klimawandel.

Holzproduktion und Klimaregulation nahmen im Klimawandel ab, während der Standortschutz sich nur wenig veränderte und Biodiversität stark positiv reagierte. Die Strategien mit höherem Nadelholzanteil produzierten mehr Holz und erbrachten in geringerem Maße auch bessere Leistungen in der Klimaregulation. Sie waren jedoch auch deutlich stärker von Störungen betroffen, was zu verringerter Stabilität der Leistungsbereitstellung im Klimawandel führte. Die artenreicheren Strategien zeigten zwar im Basisszenario eine geringere Leistung für diese Services, erreichten aber ein höheres Maß an Stabilität im Klimawandel. Diese Strategien erzielten erwartungsgemäß auch die höchste Biodiversität, wobei jedoch Klimawandel und Störungen die Diversität auch in den anderen Strategien positiv beeinflussten.
Keine der untersuchten Bewirtschaftungsstrategien zeigte sich im Gesamtbild als klar überlegen, jedoch erwiesen sich zukunftsorientierte Strategien mit kürzeren Umtriebszeiten und einer höheren Baumartendiversität als robuster in ihrer Leistungsbereitstellung im Klimawandel.

Content

1 Introduction

Forests make a considerable contribution to human well-being by providing ecosystem services, often having to fulfil demands for several, even opposing services at once (Thorsen et al., 2014). Ecosystem services provided by forests cover the full range of services defined by the Millennium Ecosystem Assessment (MEA, 2005), from provisioning (e.g. fibre, fuel, food, drinking water), and regulating (e.g. natural hazards, air and water quality) to cultural (e.g. recreation and tourism, spiritual services) and supporting services (e.g. primary production, soil formation). Additionally, forests are extremely diverse ecosystems, providing habitat for an estimated two thirds of all known terrestrial species. This biological diversity harboured by forests not only has an intrinsic value but is also crucial for ecosystem functioning (Thompson et al., 2009). However, climate change impacts threaten the ability of forests to provide all these ecosystem services. Climate change is expected to significantly affect the provisioning of ecosystem services across all types of ecosystems, with an overall negative impact being hypothesized on most services (MEA, 2005). Also biodiversity is expected to be negatively impacted by climate change (MEA, 2005).

In many ways, forests are especially susceptible to changes in the environment. Trees, the defining organisms in forest ecosystems, are immobile and long-lived compared to other types of vegetation and therefore can adapt only slowly. This relatively slow pace of adaptation puts forests at risk of becoming increasingly mal-adapted in the face of rapidly changing environmental conditions (Lucier et al., 2009; Thom et al., 2016b). Climate change impacts on mountain forests are of particular interest in this regard. Mountains have not only been shown to be especially vulnerable to and more heterogeneously affected by climate change impacts than other regions but also play an essential role in ecosystem provisioning in many parts of the world (Beniston, 2003; Gobiet et al., 2014; Haida et al., 2015).

There is still a considerable level of uncertainty regarding potential impacts of climate change on forests, especially taking into account the effect of disturbances, which are expected to increase under climate change (Lindner et al., 2014). The effect of a changing environment on disturbance regimes is of special interest as not only an increase in historically occurring disturbance agents (e.g. wind and bark beetles in the forests of Central Europe) is likely in the future (Seidl et al., 2014c), but also previously unknown disturbances such as invasive pests and diseases can occur (Ramsfield et al., 2016). Furthermore, interactions between different disturbance agents can be intensified by climate change (Seidl and Rammer, 2016), contributing to unprecedented levels of disturbances in the future, and resulting in potentially rapid changes in ecosystem structure and functioning.

Findings so far suggest variable yet generally negative impacts of climate change (Breshears et al., 2011; Maroschek et al., 2009) and disturbances (Thom and Seidl, 2016) on forests and their ability to provide ecosystem services. However, positive impacts have also been reported for certain ecosystem services, and especially biodiversity could also benefit from some of the changes expected for the future (Silva Pedro et al., 2016; Thom et al., 2016a).

It is important to note that not only the ability of forests to provide ecosystem services may change as a result of environmental changes, but that also the demands of society on forests may very well be different in the future. As one example among many, the potential role of forests in climate change mitigation has received increasing attention recently. On the one hand, the potential contribution of forests to climate regulation through carbon sequestration and storage in situ is emphasized. On the other hand demands for renewable resources from forests are steadily increasing, calling for an intensified utilization of forest resources (Fahey et al., 2010; Hetemäki, 2014).

Forest management can play an important role in ensuring that forests continuously provide ecosystem services to society. However, the previously mentioned developments related to climate change lead to increasing uncertainty in management. In Central Europe, forest management has shifted to incorporate multifunctionality as a central management paradigm, widely replacing the single-objective, timber-oriented management approaches of the past (c.f. Schoene and Bernier, 2012). For example, multifunctional forest management is explicitly mentioned in the Austrian Forest Act (Anonymous, 1975), along with the four forest functions production, protection, welfare and recreation. Forest managers are thus increasingly used to managing for several ecosystem functions or services simultaneously, and designing silvicultural strategies accordingly. The challenges imposed by changing environmental conditions, however, raise the question if current management strategies will still be appropriate in the future, or whether new approaches need to be found in order to maintain the ability of forests to simultaneously fulfil a wide range of human demands (see Innes et al., 2009; Keenan, 2015 for an overview on the adaptation of forest management to climate change). Using a variety of methods, previous research has therefore assessed the performance of current management strategies under a changing climate (e.g. Irauschek et al., 2015; Pardos et al., 2016; Seidl et al., 2011), identified factors influencing ecosystem services provisioning under climate change, and provided recommendations of how to adapt to future conditions (Diaz-Balteiro et al., 2017; Härtl et al., 2015; Mina et al., 2016; Rasche et al., 2013; Temperli and Elkin, 2012), However, considerable uncertainty remains, not least because major drivers, such as increased disturbance activity, have rarely been considered explicitly in previous analyses.

Due to the inherent uncertainty in predictions of future climate conditions and their impacts on forest ecosystems, scenario analyses, are needed, assessing possible outcomes for a range of plausible future conditions. Considering the fact that forest management planning extends over time horizons of decades to centuries, and drivers such as climate change and adaptation decisions often show observable impacts only after an extended period of time, a relatively long period of investigation is needed in order to deduce their influence. Additionally, as spatial configuration and landscape scale processes often play an important role in the provisioning of ecosystem services, an analysis at scales beyond the stand scale is important to quantify forest ecosystem functions and services. Modelling approaches have been shown to be well suited as scaling tools in this regard (Seidl et al., 2013). Models such as gaps model and forest landscape models are therefore widely used in the assessment of the impacts of forest management and climate change on forest ecosystem services (c.f. Irauschek et al., 2015; Mina et al., 2016; Pardos et al., 2016; Rasche et al., 2013, 2011; Temperli and Elkin, 2012; Thom et al., 2016a; Zlatanov et al., 2015).

2 Objectives

To further contribute to the understanding of the impacts of climate change on the ability of forest ecosystems to provide ecosystem services, and to assess the role of forest management in ensuring continued provisioning under changing conditions, the individual-based forest landscape and disturbance model iLand (Seidl et al., 2012a) is used in this thesis to assess the impacts of different management strategies and climate change (including a changing disturbance regime) on an mountain forest landscape in Austria.

The specific aim of this thesis was to improve the understanding of the impacts of climate change and forest management on the ability of forest landscapes to provide ecosystem services. In order to tackle this objective, four alternative management strategies were designed based on a stakeholder process, implemented within the process-based forest landscape model iLand, and simulated over a period of 200 years under different climate scenarios. My specific aims were to

(i) evaluate the model's suitability for comparing different management strategies,

(ii) assess the effects of forest management on forest composition under varying environmental conditions,

(iii) analyse the performance of alternative management strategies regarding four selected ecosystem services, defined by eight indicators, under stable climate conditions,

(iv) quantify the change in performance under climate change for each strategy and ecosystem service indicator, assessing the stability of ecosystem service provisioning under six different future climate scenarios.

3 Materials and methods

3.1 Study area

The study area "Weissenbachtal" is a valley in the northern frontrange of the Alps in the Austrian Province of Upper Austria, connecting the Traun valley with lake Attersee (N 47.78°, E 13.59°). I here focus on the management district Mitterweissenbach, which is part of the forest enterprise Inneres Salzkammergut and under the stewardship of the Austrian Federal Forests (Österreichische Bundesforste AG, 2016). The management district covers approximately 6,500 ha. The extent of the simulated landscape is 5716 ha of stockable forest area and covers an elevational gradient from 500 m to 1400 m. The geology of the region is dominated by limestone and dolomite (Krenmayr et al., 2006). Common soil types are Chromic Cambisols and and Rendzic Leptosols associated with the humus types Moder and Tangel (Matthews et al., 2017). The mean annual precipitation on the landscape is 1503 mm (1207 – 2071 mm, increasing with elevation) and the mean annual temperature is 7.5°C (5.5 – 9.6°C, decreasing with elevation).

The potential natural vegetation (PNV) under current climate is dominated by Norway spruce [*Picea abies* (L.) Karst], European beech [*Fagus sylvatica* (L.)] and silver fir [*Abies alba* (Mill.)] with Adenostylo glabrae-Abieti-Fagetum as the dominating vegetation type. In the lower elevations (500 – 800 m a.s.l), the PNV is dominated by beech, with spruce and fir only present in small shares. In middle montane elevations (800 – 1000 m a.s.l), higher shares of spruce and fir are present but beech remains the main species. Above 1000 m a.s.l, the PNV is characterised as a typical Spruce-Fir-Beech forest (A. F. F. typicum) with either spruce or beech as the dominating tree species, depending on the site (Frank, 1992). The present actual vegetation is dominated by spruce (48.9 % of the volume), beech (45.0) and European larch [*Larix decidua* [Mill.)] which represents 3.0 % of the volume. Silver fir is currently present only with 2.2 % of the volume. Most stands are mixed stands, mainly of spruce and beech, with only a few stands either pure spruce or pure beech (Figure 1). Especially in the higher elevations, stand ages are high (age classes VII, 121-140 years and VIII, < 140, see also Figure 2) as these stands are harder to access for harvesting. In the lower elevations, stands are younger, with the age classes I-IV (21-80) being most prevalent. On average the stocking volume per ha is 213 m³.

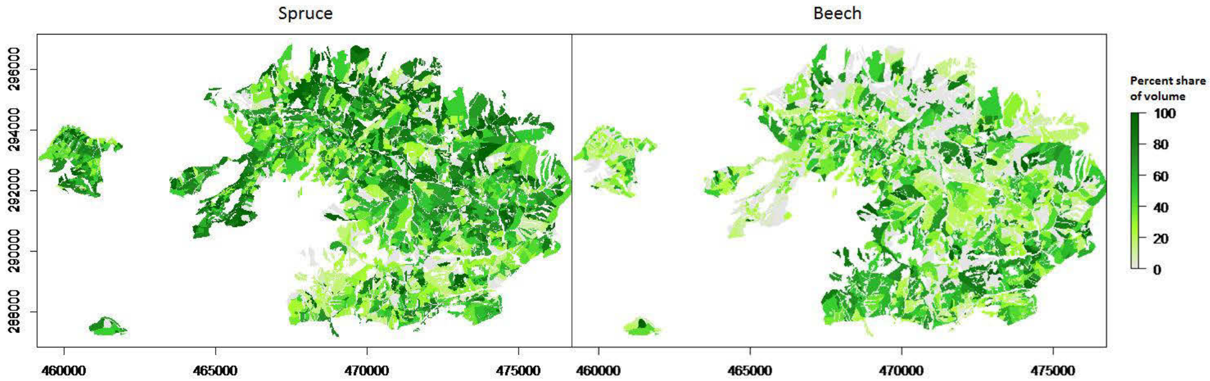

Figure 1: Species shares (on total standing volume) for beach and spruce in each stand at the time of model initialisation

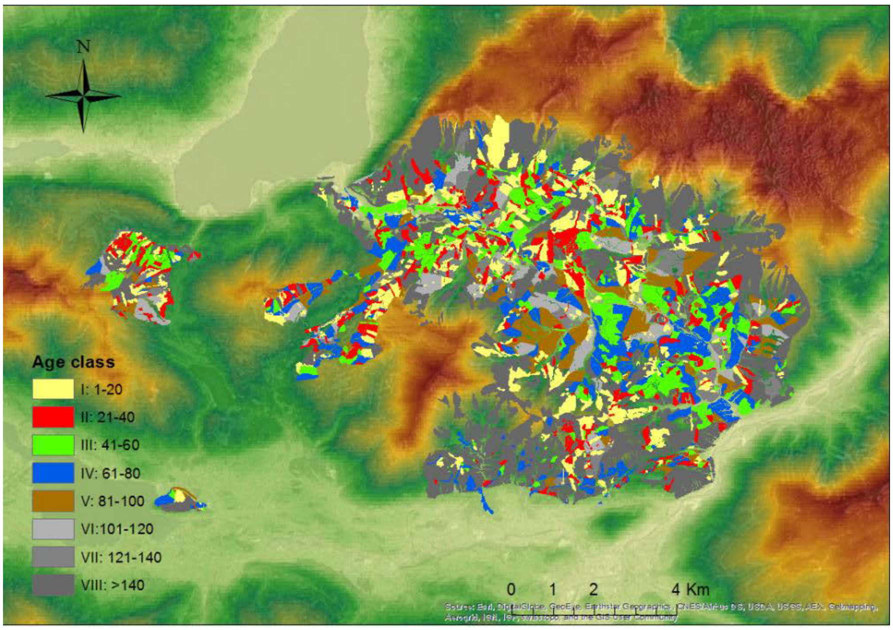

Figure 2: Age class distribution (according to the management plans of the Austrian Federal Forests) on the landscape. Ages are presented at the level of individual stands

Historically, the area was managed to provide fuel wood for the salt production in the area, leading to a higher than natural share of spruce (Kleine, 1980). It was also a popular hunting ground for the Austrian imperial family, especially Emperor Franz Joseph I, and accordingly game populations were kept high in the past (Wallentin and Wallentin, 2010). Currently, the dominating forest functions (sensu Austrian Forest Act) in the landscape are protection and timber production (Figure 3).

Due to shallow soils, the area is highly prone to erosion and degradation after disturbance, which underlines the site protection function of the forest (Reger et al., 2015).

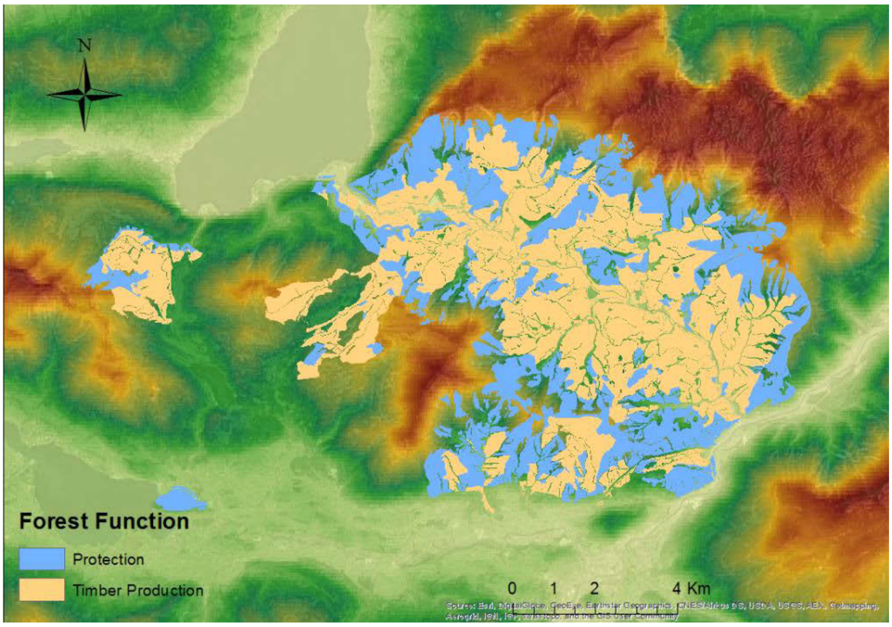

Figure 3: Current dominating forest functions (sensu Austrian Forest Act) on the landscape (according to the management plan of the Austrian Federal Forests)

3.2 Simulation model: iLand

The invididual-based forest Landscape and disturbance model iLand (Seidl et al., 2012a) was used to investigate the effect of different management strategies and climate change scenarios on the provisioning of ecosystem services in this study.

iLand combines processes at several levels (i.e. individual tree, stand, landscape) to model interactions between forest vegetation, environmental drivers, disturbances, and forest management. Different hierarchical scales interact dynamically, with processes on lower levels producing emerging dynamics which influences processes on higher levels. These, in turn, can constrain processes on lower levels.

Trees are modelled as individual, adaptive agents in iLand. Using an approach based on ecological field theory, competition is modelled spatially explicit by generating a continuous field of light availability across the landscape based on physical traits (height, crown shape, opacity) of the individual trees. A tree's position within this field of light availability defines its relative competitive success.

At stand level, the absorbed photosynthetically active radiation (APAR) is calculated and environmental modifiers (temperature, soil water availability, and vapour pressure deficit) are used to derive the utilizable fraction of APAR on a daily basis. This allows the calculation of gross primary productivity (GPP) via the thus calculated species specific light use efficiency following Landsberg and Waring (1997). Subsequently, NPP is derived as a constant fraction of GPP.

Allocation of carbohydrates is simulated annually and follows a hierarchy from roots and foliage to stem and non-structural carbohydrates reserve pools. A tree adapts its allocation dynamically to its environment (e.g. changed allocation to height and diameter growth depending on competition).

Natural individual-tree mortality (i.e., mortality not caused by disturbances or forest management) can occur via two mechanisms in iLand. Mortality risk increases with age relative to the maximum life-span for its species or because a tree experiences carbon starvation (not enough carbon is available to balance the maintenance costs of the tree, i.e. root and foliage turnover).

iLand also includes a soil module, which tracks organic matter in soil, litter, standing and downed dead wood pools, and allows for the simulation of closed carbon and nitrogen cycles (Seidl et al., 2012b).

Regeneration is modelled spatially explicitly on 2x2 m pixels, with seed dispersal, species specific establishment filters (i.e. climatic limitations) and resource availability as influencing factors. In the sapling stage, competition among individual saplings and the resulting mortality is modelled implicitly, however there is inter-specific competition if more than one species establishes on a pixel. Saplings are treated as individual trees once they reach a height of 4 m (Seidl et al., 2012b).

Disturbances in iLand are simulated spatially explicit on the landscape. Currently, disturbance modules for wind (Seidl et al., 2014a), bark beetles (Seidl and Rammer, 2016) and fire (Seidl et al., 2014b) are available. Here, the modules for wind and bark beetles were used.

Wind impacts are simulated dynamically, taking into account forest characteristics such as edge effects and tree stability. Information on wind events (speed, direction) can be supplied in the form of weather station data, climate modelling data or time series drawn from observed wind events. The model dynamically identifies "edges" in the canopy cover where differences in top-height exceed 10 m and which are particularly exposed to storm damage. Critical wind speeds for uprooting and stem breakage are then calculated, taking into account characteristics of individual trees such as DBH and stand structure such as gaps. If the wind speeds of the current event exceed the critical wind speeds, trees are simulated to be either uprooted or broken. Forest conditions are continuously updated during the wind event, dynamically creating new edges and gaps (Seidl et al., 2014a).

The bark beetle module simulates the interaction of the European spruce bark beetle *Ips typographus L., Coleoptera: Curculionidae*, the main biotic disturbance agent in central European forests, and its primary host tree *P. abies*. Bark beetle dispersal is modelled spatially explicit with beetle cohorts dispersing from brood trees, and targeting potential host trees within a specific search radius. A tree's susceptibility to a bark beetle attack is based on its dynamically simulated physiological condition, i.e. a stressed tree will be more susceptible to attack. Population dynamics of *I. typographus* are also simulated, taking into account the influence of climatic conditions and host availability on bark beetle abundance, the number of beetle generations developing within a year, and beetle mortality (Seidl and Rammer, 2016).

The main focus of this thesis was the implementation and comparison of different forest management strategies on the landscape, for which the agent-based model of forest management (ABE) (Rammer and Seidl, 2015) was used. ABE is fully integrated in iLand and allows the simulation of management strategies which dynamically adapt to the changing conditions in the simulated landscape. The "virtual forester" is able to track changes in the environment such as disturbances and changes in forest growth, and adapt its management accordingly. Management decisions can be made on two levels, i.e., short-term operational decisions which are taken on a stand-level and with a higher frequency (i.e. annually), and long-term strategic decisions which are taken decennially or with even lower frequency. An example for an operational decision of the management agent is the scheduling of a final harvest in a stand, while a strategic decision would be, for example, a change in rotation period, the target species composition or the maximum allowable cut.

Operational management in ABE is implemented through management activities (e.g. thinnings, harvests) which are defined in a stand treatment programme (STP). Several different STPs with different sets of activities can be distinguished, e.g., accounting for differences in site conditions, and all stands need to be assigned to a stand treatment programme in order to be managed. Each stand is assessed annually in the context of its STP, and the agent decides if an activity needs to be implemented for this particular stand. This bottom-up scheduling of activities is constrained by overarching management goals and limitations, such as legal constraints (maximum clearcut size) or the management goal of sustainable harvesting (i.e. the annual harvested amount must not exceed the annual allowable cut, which is calculated based on increment). The agent continuously assesses the difference between planned and executed activities and adjusts the management dynamically (e.g. reducing harvest levels after substantial disturbances).

Agent behaviour can be differentiated by agent type (e.g. a large forest enterprise or a small-scale private owner) and agent traits (e.g. education and age, determining the degree of risk taking). In this study, the same default agent configuration was used for the entire landscape, as the study area is exclusively managed by a single forester. The differentiation among management strategies was achieved through a set of different silvicultural treatments implemented for each strategy.

For this study, the version 0.9 of iLand was used. For detailed information on iLand and ABE, please refer to the model website (http://iLand.boku.ac.at), where the executable as well as the full source code can be downloaded.

3.3 Initialisation data and drivers

Data preparation as well as all analysis were done using the R Project for Statistical Computing version 3.3.0 (R Core Team, 2016).

The initialisation of the landscape (vegetation, and soils) as well as the preparation of climate and disturbance scenarios were done by Dominik Thom and Werner Rammer within the frame of the research project DICE (Climate sensitivity of disturbance regimes and implications for forest ecosystem management), and are briefly described here to enhance the understanding of the simulation process and aid the interpretation of the results.

3.3.1 Natural environment

a) Vegetation data

To estimate the initial state of the vegetation, data from the management plans of the Austrian Federal Forests for the period 2010-2020 as well as inventory plot data (from 2004-2005) and Digital Elevation Models from ALS data (Airborne Laser Scanning recorded between 2009 and 2013) were used. Growing stock, tree species shares, and stand age were determined from the management data for each stand. In total, 1686 stands were initialised with an average stand area of 3.4 ha. The information about individual trees (height and diameter at breast height (DBH)) within a stand was gathered from plot-level inventory data. Individual trees were then iteratively sampled to meet the stand characteristics described in the management plans. ALS data was used to determine vertical (i.e. tree heights) and horizontal stand structure (e.g. clustering of trees, gaps). To account for unstockable area (e.g. rocks), larger areas which do not allow for tree growth were first excluded based on a visual classification of orthophotos. Additionally, the share of smaller unstockable areas (e.g., small rocky outcrops) was estimated from data from a detailed inventory in Kalkalpen National Park (KANP) (Thom et al., 2016a), and distributed randomly across the landscape. As the two landscapes are located only approximately 50 km apart (Land Oberösterreich, 2016) and the natural conditions (climate, geology, vegetation) are fairly similar (Kilian et al., 1994), data from KANP was assumed to also apply to the present study area Weissenbachtal.

b) Soil data

Information from the site classification of the Austrian Federal Forests (Weinfurter, 2004), the Austrian National Forest Inventory (Seidl et al., 2009), and the Kalkalpen National Park (Thom et al., 2016a) were used to characterize soils with regard to their soil type, soil depth, soil texture, plant-available nitrogen, and soil carbon. Soil data was prepared derived on a 100 m grid.

In a first step, National Forest Inventory (NFI) data was stratified by site type (Weinfurter, 2004, see Figure 4 for the spatial distribution of site types on the landscape) and elevation, and information regarding soil type, soil depth, soil carbon, and plant available nitrogen derived via random sampling for each stratum. To assess soil texture, KANP inventory data was used for soil types which were both present in the national park and the current study area. For the remaining soil types, data from Leitgeb et al. (2013) was used to derive soil texture. In a final step, soil depth was reduced to effective soil depth by subtracting soil fraction, derived from Leitgeb et al. (2013). For comparison among site types, mean and standard deviation for effective soil depth and plant available nitrogen are presented in Table 1.

Table 1: Overview (mean and standard deviation) the soil parameters effective soil depth and plant available nitrogen which were initalised for each of the site types (Weinfurter, 2004) present on the landscape. If no standard deviation is presented, only one stand was present for this site type.

Site type	**Effective soil depth [cm]**		**Plant available nitrogen [kg m^{-2} $year^{-1}$]**	
	Mean	Standard deviation	Mean	Standard deviation
11	18.3	5.3	49.2	3.4
12	20.5	5.4	50.3	3.9
13	17.7	5.4	49.9	3.6
21	18.6	5.4	49.1	3.4
22	18.4	5.5	49.6	3.2
23	25.8	7.8	49.8	3.6
26	23.7	4.0	54.0	3.5
32	26.6	8.1	49.7	3.5
41	38.6	12.4	50.5	3.4
51	30.3	NA	53.0	NA
53	48.9	12.9	49.7	3.0
56	39.8	10.4	57.2	4.7
58	42.5	11.1	49.3	3.4

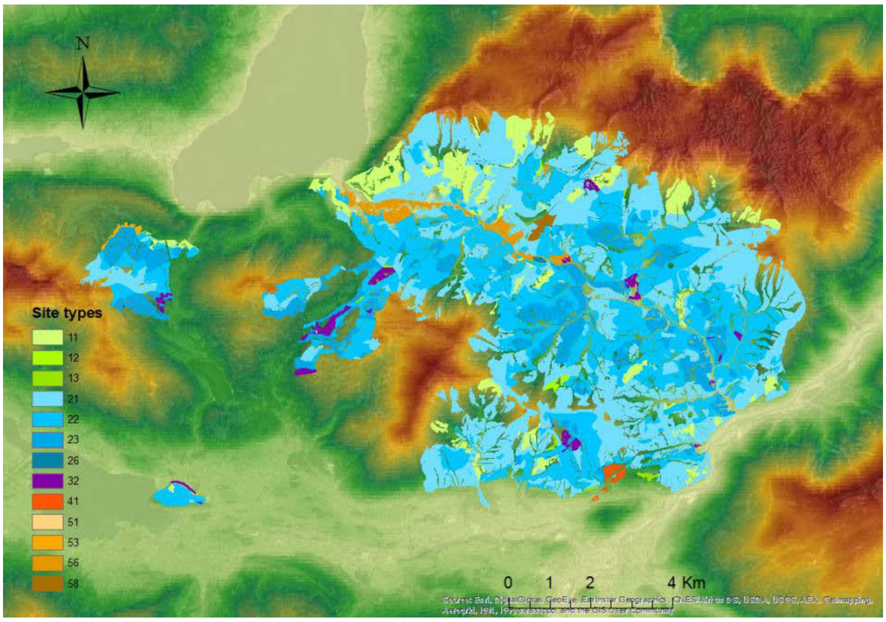

Figure 4: Site types according to the definition of Weinfurter (2004). Higher numbers indicate more productive sites

c) Climate data

In total, four climate scenarios were analysed in this study. One baseline climate scenario which assumed no change in climate compared to the reference period 1950-2010 (random resampling of years from the reference period for the length of the simulation period) and three different climate change scenarios based on combinations of different global and regional circulation models under A1B forcing. The A1B family of emission scenarios is characterized by fast economic and technological development. A balanced use of fossil and non-fossil fuel sources is assumed as well as "balanced" land use changes (IPCC, 2000). The circulation models used were CNRM-RM4.5 driven by ARPEGE (Radu et al., 2008), referred to as ARPEGE in the following, MPI-REMO (Jacob, 2001), referred to as REMO and ICTP-RegCM3, referred to as ICTP, both driven by ECHAM5 (Pal et al., 2007). For all climate change scenarios, a stabilization of climate conditions at the level of 2080 - 2100 was assumed, with additional simulation years resampled from this period. The climate change scenarios assume an increase in the mean annual temperature of 3.2 – 3.3°C and a change in mean annual precipitation of -84 to +160 mm until the end of the 21st century relative to the baseline period 1950-2010.Climate model data was statistically downscaled to a 100 x 100 m grid using data from the Central Institute of Meteorology and Geodynamics Vienna (c.f. Thom et al., 2016b).

Two different wind scenarios were used to address the wider range of uncertainties regarding the future extreme wind climate. The baseline wind scenario was based on a distribution of historic wind speeds, with the historic “top events” Kyrill (in 2007), Emma (2008) and Paula (2008) representing the 90th percentile of the wind speed distribution. To study the impacts of a potential increase in extreme wind events, which has been hypothesised as a plausible development in the future (Lindner et al., 2014), a wind scenario was designed which features a 10 % increase in wind speed across the entire wind distribution, following the analyses by Pryor and Barthelmie (2010). This resulted in a total of seven climate scenarios (baseline climate + three downscaled climate scenarios × two wind scenarios).

3.3.2 Management

Four alternative management strategies were studied in the analysis. Two of them were derived in a stakeholder process, and are based on information obtained during workshops with the responsible forest managers and the local forest authorities. Based on the specifications and suggestions by the stakeholders, I designed detailed treatment programmes for each stand and implemented them in the simulation model. Two additional strategies, representing strongly contrasting management approaches, were also included, bracketing the strategies derived via stakeholder interaction. This approach to developing alternative management strategies ensured that locally meaningful silvicultural approaches are investigated but also that a broader gradient of potential management strategies is considered. The management strategies stay static over time, which means there is no change in terms of target species composition and silvicultural activities over the course of the simulation within each strategy. The strategies themselves represent a gradient from historical management (PIAB strategy) to current (AFF and FSUA strategies) and forward-looking, pro-active (PNV strategy) management approaches.

a) Design of management strategies

<u>Austrian Federal Forests (AFF)</u>

This strategy is based on the current management of the landscape by the Austrian Federal Forests and represents a “business as usual” approach. During a workshop in March 2015 in Bad Goisern (Figure 5a, b), local forest managers shared their current management approach for the landscape and discussed possible adaptation possibilities to climate change with the team of the DICE project. The current management is focused on timber production (and protection); following the currently dominating forest functions determined for the landscape (see also Figure 1). The AFF provide management recommendations based on their site type classification (Weinfurter, 2004), which form the basis of the current management and were also consulted in designing the AFF strategy for this study. The main tree species are spruce and larch, which together make up between 50 and 80 percent of the total target basal area, depending on the site type. Broadleaved species (mainly beech) are also part of the target species composition, especially on less productive sites. Depending on site quality, either one or two thinnings per stand are executed. The rotation period varies between 120 years on more productive sites and 130 or 140 years on less productive sites.

Forest Service Upper Austria (FSUA)

The recommendations of the Forest Service Upper Austria, which is in charge of enforcing the Austrian Forest Act and supporting local managers in the area, were collected by the project team during a second workshop in March 2015 in Unterach (Figure 5c, d). Additionally, information from the Forest Service's handbook on choosing target tree species in the limestone alps (Jasser and Diwold, 2014) was used in the specification of the FSUA management strategy. The target tree species in this strategy are spruce, beech, larch, fir and Scots pine *[Pinus sylvestris* (L.)], varying in importance with site quality and water availability. All stands are thinned twice to achieve higher stability, and the rotation period is uniformly set to 120 years to reduce the disturbance risk in old stands.

Figure 5: Workshops on management strategies with local stakeholders from the Austrian Federal Forests at Bad Goisern (a and b) and the Forest Service Upper Austria at Unterach (c and d)

Spruce-oriented (PIAB)

As one extreme end of the management gradient, a strategy corresponding to historical, maximum-yield based management was designed. In this strategy, the only target tree species is spruce. While spruce is planted exclusively and all management activities aim to maximise the share of this species, other tree species are not completely eradicated, i.e.

natural regeneration of other species which occurs on the landscape is not categorically removed. The silvicultural treatment programmes for this strategy (i.e., thinnings, rotation period) follow the activities defined for the AFF strategy.

Future Potential Natural Vegetation (PNV)

The fourth management strategy bookends the management gradient on the opposite end of the PIAB strategy. It represents a future-oriented management approach which seeks to actively adapt to changes in the environment. It is based on the future potential natural vegetation, explicitly considering the impacts of climate change on the realized niche of tree species. In order to obtain an estimate of future PNV, an iLand simulation was run for 2500 years, starting from bare ground and allowing natural succession to proceed under climate change but without disturbances. The target species shares for the PNV strategy were subsequently based on the final state of the PNV at the end of the simulation period, and thus represent the synecologically most competitive tree species of the future. The main target species of this strategy is beech; other admixed species are spruce, fir, pine and oaks [*Quercus petrea* (Matt.) and *Quercus robur* (L.)]. As disturbances were excluded during this run, early successional species such as larch only play a minor role in the PNV strategy. Silvicultural treatments (i.e., thinnings, rotation period) are the same as in the FSUA strategy.

b) Implementation of management strategies in the model

In order to implement the four management strategies in iLand, specific treatment programmes for each stand were defined. In a first step, I divided the stands into different management groups (stand treatment programmes - STP). Here, a classification suggested by the local managers during the workshop was used, dividing the stands according to aspect, slope position, and their site type. The same classification was used for all four management strategies to aid comparison among strategies.

Site type: As suggested by the Austrian Federal Forests during the workshop, the stands were separated into less productive (site type below 23 according to AFF site type classification (Weinfurter, 2004)) and more productive stands (site type 23 and higher).

Aspect: Stands on the sun-exposed, south-facing slope of the valley with generally drier conditions were separated from stands on the more shaded north-facing slope. The classification was made according to the aspect of each stand as stated in the stand description in the management plans of the Austrian Federal Forests. Stands with southerly, south-easterly, south-westerly and westerly aspects were classified as south-facing, stands with northerly, north-westerly, north-easterly and easterly aspects as north-facing.

Slope position: Stands were separated into those on the lower slope, which are generally assumed to be more productive due to nutrient and water accumulation, and upper slope stands, where an export of nutrients and water are generally assumed to result in lower productivities. The classification was done in a two-step routine, first classifying stands with a higher productivity (>23) and a short rotation age (<130) as "lower slope" to account for local accumulation sites and then setting an elevation limit (1000 m a.s.l.) for a global classification of all remaining stands.

This classification resulted in a total of eight different management clusters (Table 2), for which individual stand treatment programmes were assigned (Figure 6).

Table 2: Assignment of stand treatment programmes. Sites were separated according to site type (types with a classification number <23 represent less productive sites, sites of type 23 and higher are more productive), aspect and slope location ("lower" slopes represent nutrient and water accumulating sites, "upper" slopes signifies an export of nutrient and water)

Stand Treatment Programme	**Site type**	**Aspect**	**Slope position**	**Area [ha]**	**% of landscape**
stp01	<23	N	upper	391.36	6.79
stp02	<23	N	lower	1537.31	26.68
stp03	<23	S	upper	838.87	14.56
stp04	<23	S	lower	2027.56	35.97
stp05	>=23	N	upper	2.44	0.04
stp06	>=23	N	lower	553.12	9.60
stp07	>=23	S	upper	10.04	0.17
stp08	>=23	S	lower	355.44	6.17

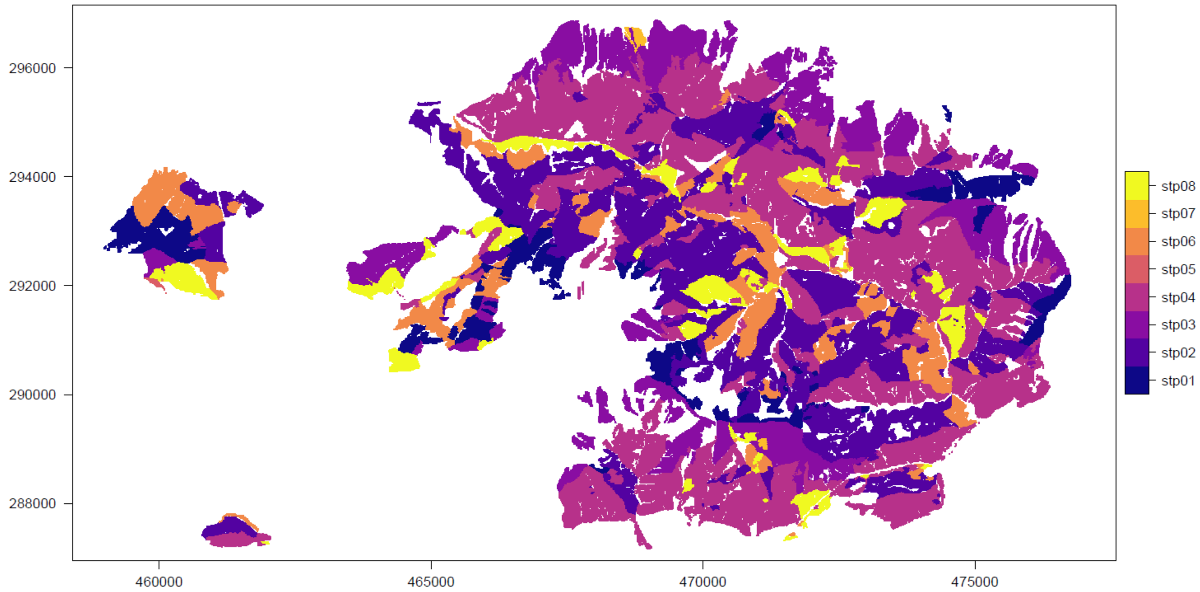

Figure 6: Spatial distribution of Stand Treatment Programmes (STP). See Table 2 for details.

For each of the eight STPs, specific silvicultural treatments were defined. Treatments encompass management activities pertaining to planting, tending, thinning, harvesting, and disturbance management. In the following, the general types of activities comprised in the silvicultural treatment programmes within ABE are described. For a detailed breakdown of the treatment programs used in each management strategy, refer to Tables 3 and 4; for examples of the Java Script Code used in ABE, see Appendix I.

Planting and natural regeneration

In ABE, there are two options for planting trees. Plantings can be defined as “wall-to-wall-planting”, where trees are regularly planted across the stand. Height of planted saplings and fraction of the area that should be planted can be defined (e.g. 30 % of all 2x2 m pixels). Alternatively, trees can be planted in groups of the same species. The patches have pre-defined shapes and sizes (e.g., a rectangular patch of 10x10 pixels) and can be allocated randomly on the landscape or assigned to certain areas using grid coordinates. This latter option allows introducing trees in clusters, which is a frequently practiced silvicultural approach in the regeneration of mixed forests. A mix of both planting approaches was used, depending on the target species composition and species identity. Where possible, STPs made use of the simulated natural regeneration, with enrichment plantings where necessary to reach the target species composition (Table 3). This approach mimics the practice of choosing the regeneration method that is the least cost and resource intensive to reach the intended target species composition.

Thinnings

Thinnings are meant to increase stand stability, influence the species composition, and contribute to timber production. In ABE, either a pre-defined thinning (“thinning from below” or “thinning from above”) or a custom thinning can be executed. In the case of my study custom thinnings were used, allowing for the specification of certain target variables (e.g. volume, stems) and a percentage of removal (e.g. 30 % of the standing volume). Removals can also be specified separately for DBH classes, and constraints for the activity (e.g., a minimum age or top height of the stand below which the thinning is not implemented) can be specified (Table 3). During tending and thinning operations the species composition can actively be directed towards the target tree species shares (Table 3). In order to do this, the species composition before the intervention is assessed by the virtual forester and compared to target species shares (in this case, assessed as shares on total stand basal area). The removal of trees is then adjusted dynamically by calculating a removal probability for each species to approach the desired tree species composition.

Final harvest

For all management strategies, a shelterwood system was implemented as the final harvesting regime. A first cut was executed approximately 10 years before the stand reached rotation age. This first cut is intended to stimulate the natural regeneration of shade-tolerant target trees such as spruce, beech, and fir. The final cut is executed as a clearcut at approximately the specified harvest age. The actual time of harvest is defined by the rotation length, but also by landscape-level considerations of sustainable harvest and spatial configuration (e.g., harvest of a stand may be postponed if the total sustainable harvest on the landscape for a given year has already been reached or if adjacent stands have been recently harvested, resulting in a total clear cut area exceeding legal constraints). This means that not all stands will be harvested exactly at the prescribed age in the simulation.

Salvaging

The salvaging activity within ABE deals with trees which have been killed by disturbances. After a disturbance event, killed trees are detected and removed if they exceed a certain minimum DBH. This is in line with practical management as the removal (or chemical/mechanical treatment) of trees which could potentially serve as breeding ground for bark beetles is mandated by the law in Austria to avoid mass outbreaks (Anonymous, 2003). This makes salvage logging after disturbances a legal requirement, especially in the case of large disturbances. The salvage activity is also able to place so-called “trap trees”, i.e. felled stems which are used to attract mature bark beetles. These trees are subsequently removed before the brood is fully developed and emerges from the trap tree, allowing a reduction of the bark beetle population by management (Seidl and Rammer, 2016). If more than 90 % of the stand (measured in percent forest cover) has been destroyed, the STP can be reset and a new rotation period started. Alternatively, stands can be split into smaller, relatively homogenous management units if between 10 and 90 % have been affected by disturbance. For gaps bigger than 0.25 ha, a new stand is created, which inherits the stand treatment programme of the original stand, but begins a new rotation period.

Table 3: Target tree species composition (at the end of a rotation period) and planted species shares for each stand treatment programme. If enough natural regeneration of a species is present in the simulation (e.g., seeding in from neighbouring stands), it is not planted or the number of planted trees are adjusted downwards accordingly. Trees are either planted uniformly across the stand in the specified shares or in species clusters (patch). Values are relative basal area shares. PIAB, AFF, FSUA and PNV represent the four management alternatives. piab: Picea abies, lade: Larix decidua, fasy: Fagus sylvatica, abal: Abies alba, pisy: Pinus sylvatica, qupe: Quercus petrea, qusp: Quercus sp.

STP	Target species composition				Planted species			
	PIAB	AFF	FSUA	PNV	PIAB	AFF	FSUA	PNV
stp01	1.0 piab	0.3 piab, 0.3 lade, 0.4 fasy	0.3 piab, 0.4 lade, 0.2 fasy, 0.1 abal	0.1 piab, 0.7 fasy, 0.1 abal, 0.1 pisy+qusp	1.0 piab	0.3 piab, 0.3 lade (patch), 0.4 fasy	0.4 lade (patch), 0.2 fasy, 0.1 abal	0.7 fasy, 0.1 abal, 0.05 pisy (patch), 0.05 qupe (patch)
stp02	1.0 piab	0.4 piab, 0.3 lade, 0.3 fasy	0.3 piab, 0.4 lade, 0.2 fasy, 0.1 abal	0.1 piab, 0.6 fasy, 0.1 abal, 0.1 pisy, 0.1 qusp	1.0 piab	0.3 piab, 0.3 lade (patch), 0.4 fasy	0.4 lade (patch), 0.2 fasy, 0.1 abal,	0.6 fasy, 0.1 abal, 0.05 pisy (patch), 0.05 qupe (patch)
stp03	1.0 piab	0.3 piab, 0.2 lade, 0.5 fasy	0.1 lade, 0.6 fasy, 0.1 abal, 0.1 pisy	0.2 piab, 0.6 fasy, 0.2 abal, 0.1 abal, 0.1 pisy+qusp	1.0 piab	0.3 piab, 0.3 lade (patch), 0.4 fasy	0.1 lade (patch), 0.6 fasy, 0.1 abal, 0.2 pisy (patch)	0.6 fasy, 0.1 abal, 0.05 pisy (patch), 0.05 qupe (patch
stp04	1.0 piab	0.7 piab, 0.1 lade 0.2 fasy	0.1 lade, 0.6 fasy, 0.1 abal, 0.1 pisy	0.1 piab, 0.5 fasy, 0.1 abal, 0.1 pisy, 0.2 qusp	1.0 piab	0.3 piab, 0.3 lade (patch), 0.4 fasy	0.1 lade (patch), 0.6 fasy, 0.1 abal, 0.2 pisy (patch)	0.5 fasy, 0.1 abal, 0.1 pisy (patch), 0.2 qupe (patch)
stp05	1.0 piab	0.7 piab, 0.1 lade 0.2 fasy	0.5 piab, 0.2 lade, 0.2 fasy, 0.1 abal	0.1 piab, 0.7 fasy, 0.1 abal, 0.1 pisy+qusp	1.0 piab	0.6 piab, 0.2 lade (patch), 0.2 fasy	0.2 lade (patch), 0.1 fasy, 0.1 abal	0.7 fasy, 0.1 abal, 0.05 pisy (patch), 0.05 qupe (patch)
stp06	1.0 piab	0.7 piab, 0.1 lade 0.2 fasy	0.5 piab, 0.2 lade, 0.2 fasy, 0.1 abal	0.1 piab, 0.6 fasy, 0.1 abal, 0.1 pisy, 0.1 qusp	1.0 piab	0.6 piab, 0.2 lade (patch), 0.2 fasy	0.2 lade (patch), 0.1 fasy, 0.1 abal	0.6 fasy, 0.1 abal, 0.05 pisy (patch), 0.05 qupe (patch)
stp07	1.0 piab	0.7 piab, 0.1 lade 0.2 fasy	0.3 piab, 0.1 lade, 0.5 fasy, 0.1 abal	0.1 piab, 0.6 fasy, 0.1 abal, 0.1 pisy, 0.1 qusp	1.0 piab	0.6 piab, 0.2 lade (patch), 0.2 fasy	0.1 lade (patch), 0.5 fasy, 0.1 abal	0.6 fasy, 0.1 abal, 0.05 pisy (patch), 0.05 qupe (patch
stp08	1.0 piab	0.7 piab, 0.1 lade 0.2 fasy	0.3 piab, 0.1 lade, 0.5 fasy, 0.1 abal	0.1 piab, 0.6 fasy, 0.1 abal, 0.1 pisy, 0.1 qusp	1.0 piab	0.6 piab, 0.2 lade (patch), 0.2 fasy	0.1 lade (patch), 0.5 fasy, 0.1 abal	0.6 fasy, 0.1 abal, 0.05 pisy (patch), 0.05 qupe (patch)

Table 4: Approximate scheduling for prescribed silvicultural activities (thinnings, tendings, final harvest) for each stand treatment programme. Actual scheduling is done dynamically within the model. Treatment times are given as years since stand establishment.

STP	**Rotation period (years)**				**Number of thinnings (years)**				**Thinning age (years)**				**Number of tendings**				**Tending (age)**			
	PIAB	AFF	FSUA	PNV	PIAB	AFF	FSUA	PNV	PIAB	AFF	FSUA	PNV	PIAB	AFF	FSUA	PNV	PIAB	AFF	FSUA	PNV
stp01	140	140	120	120	1	1	2	2	60	60	30/60	30/60	1	1	1	1	10	10	10	10
stp02	130	130	120	120	2	2	2	2	40/60	40/60	30/60	30/60	1	1	1	1	10	10	10	10
stp03	140	140	120	120	1	1	2	2	60	60	30/60	30/60	1	1	1	1	10	10	10	10
stp04	130	130	120	120	2	2	2	2	40/60	40/60	30/60	30/60	1	1	1	1	10	10	10	10
stp05	120	120	120	120	2	2	2	2	40/60	40/60	30/60	30/60	2	2	1	1	2/10	2/10	10	10
stp06	120	120	120	120	2	2	2	2	40/60	40/60	30/60	30/60	2	2	1	1	2/10	2/10	10	10
stp07	120	120	120	120	2	2	2	2	40/60	40/60	30/60	30/60	2	2	1	1	2/10	2/10	10	10
stp08	120	120	120	120	2	2	2	2	40/60	40/60	30/60	30/60	2	2	1	1	2/10	2/10	10	10

3.4 Simulation design

For this study, 28 different treatment combinations (four management strategies × seven climate scenarios) were simulated. For each combination 20 replicates were run to account for stochastic processes within the simulation. This resulted in a total of 560 runs, which were simulated for 200 years to capture at least one full rotation for each stand. The year 2013 was used as starting point for all simulations. In the subsequent analyses, the historic climate and wind regime is considered as the baseline scenario. The various combinations of climate change scenarios (ARPEGE, REMO, ICTP) and wind scenarios (historic and increased wind activity) are jointly analysed as the climate change signal.

The scenario runs presented in this thesis were done on the Vienna scientific cluster (VSC).

3.5 Model evaluation

The iLand model has been extensively evaluated in previous studies (Seidl et al., 2014a, 2014b, 2012a; Thom et al., 2016a). I here thus focused on further evaluating the performance of ABE (Rammer and Seidl, 2015; Seidl et al., 2016b). In particular, the ability of the model to observe a sustainable harvest level (i.e., the relation between increment, allowable harvest and realized harvest) and the scheduling of activities (specifically the scheduling of final harvests) were assessed. As the management strategies are mainly defined by contrasting target species compositions, a main focus of my evaluation was also the comparison of the actual tree species composition throughout the simulation against the target species composition for each management, both at the level of specific stand treatment programs and at the landscape level. Here the objective was to test whether ABE is able to realistically simulate transitions to a wide range of different tree species compositions from todays' state of the forest.

3.6 Impacts on ecosystem services provisioning

The Millennium Ecosystem Assessment (MEA, 2005) defines ecosystem services as "the benefits people obtain from ecosystems", and provides a classification system dividing them into provisioning services, regulating services, and cultural services. Additionally, supporting services are considered, which are needed in order to provide all other services. Biodiversity is here also considered as the fundamental prerequisite of ecosystem functioning and integrity (Figure 7).

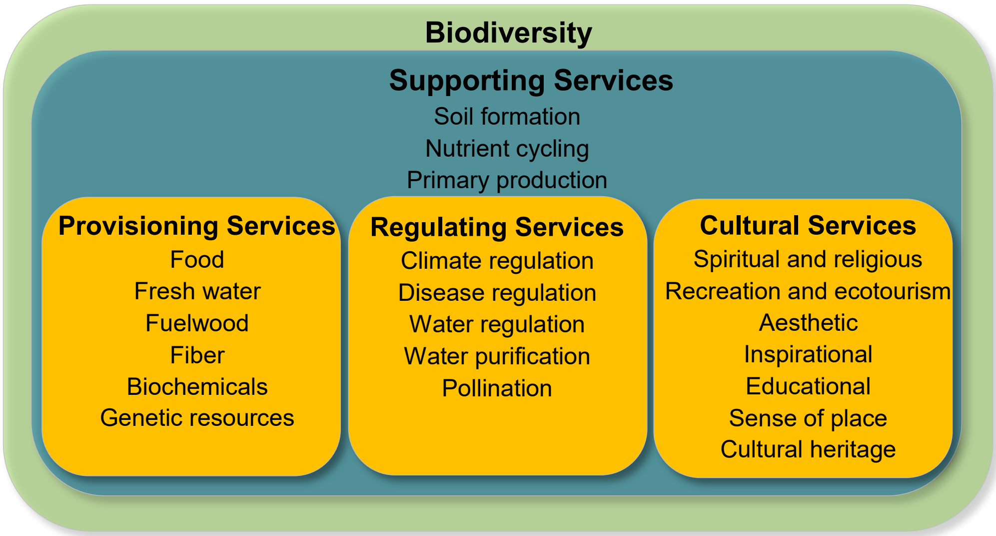

Figure 7: Framework of Ecosystem Services (adapted from Millennium Ecosystem Assessment, 2005)

Within this framework, four locally relevant ecosystem services were chosen for investigation in this study: wood production, which falls into the provisioning category, climate regulation and site protection (both regulating services), and biodiversity as the backbone of ecosystem functioning and integrity. For each of these services, two indicators were chosen to quantify their performance. Apart from biodiversity, which is represented by two stock indicators (i.e., states at a given point in time), one stock indicator and one flow indicator (i.e., changes over a certain time period) were chosen for each service (see Table 5 for an overview of the indicators used). All indicators were first assessed with regard to their absolute performance under baseline conditions (stable climate, past wind conditions) at four points in time for stock indicators (simulation years 50,100,150,200) and over four time periods for flow indicators (simulation years 0-50, 50-100, 100-150, 150-200). The average performance over the entire 200-year simulation period was also calculated. Subsequently, to assess the stability of ecosystem service provisioning under climate change, the change of ecosystem service indicators under climate change was calculated relative to the performance under baseline conditions for each management strategy. In the following, a detailed description of the indicators used for each ecosystem service is provided.

3.6.1 Timber production

Timber production is one of the most important goals within the current management. It is expected to also have considerable importance in the future, considering the possibilities of using wood to replace fossil-based resources (Hetemäki, 2014). I assessed both the timber stocks available on the landscape (indicator volume) and the flow of merchantable timber from the landscape (indicator regular harvest).

a) Volume

The volume indicator refers to the standing timber volume in $m^3\ ha^{-1}$ present on the landscape. A high growing stock represents a high availability of harvestable wood, ensuring a sustainable and continuous wood production. It is an indicator commonly used in the assessment of forests regarding wood production (MCPFE, 2003). As a stock indicator, volume is assessed at four points in time. The volume was directly derived from iLand simulations, based on the underlying simulation of individual trees.

b) Regular harvest

The indicator "regular harvest" quantifies the amount of wood which is harvested annually ($m^3\ ha^{-1}$). This includes thinnings as well as final harvests, but excludes wood which was salvaged after disturbances. Even though salvage harvest can contribute a sizeable amount to the annual harvest and is economically important for timber production, I here focused on regular harvest to emphasise predictability in planning, and to account for the fact that salvaging disturbed areas usually results in high harvesting costs and timber losses (Prestemon and Holmes, 2008). A high regular harvest indicates a strong performance regarding the ecosystem service wood production. As a flow indicator, regular harvest is assessed as the average over 50-year periods. This indicator is derived directly from ABE, and is calculated based on the individual trees simulated in iLand.

3.6.2 Climate regulation

The possible contribution of forests to climate mitigation through carbon sequestration and storage is garnering increasing amounts of attention, making this an increasingly important ecosystem service in the future (Canadell and Raupach, 2008). The two indicators were chosen to provide an insight into both carbon storage and carbon sequestration of the landscape. Both climate regulation indicators only assess the in situ carbon balance of the landscape, and do not consider the climate regulation effect of substitution of fossil fuels and C stored in wood products.

a) Carbon stock

The carbon stock indicator was calculated by summing all carbon pools simulated in iLand to obtain the total amount of carbon (t ha^{-1}) stored in the ecosystem. This includes living and dead aboveground biomass (stem, branches, leaves, regeneration, deadwood, litter), belowground biomass (coarse and fine roots) and soil organic carbon. Climate mitigation efforts require to keep carbon stocks in forests on a high level in order to ensure continued carbon sequestration (Pan et al., 2011).

b) Net Ecosystem Productivity

Net Ecosystem Productivity (NEP) refers to the net carbon accumulation of an ecosystem (Chapin et al., 2006) and can be defined either as the Net Primary Production reduced by heterotrophic respiration and carbon which leaves the system due to disturbances and management; or as the net changes over all carbon pools of the system. It therefore signifies whether the forest in question is acting as a carbon sink (positive NEP) or a carbon source (negative NEP) to the atmosphere. In the context of climate mitigation, the aim is to maximise the carbon uptake of a forest and to continually have it act as a carbon sink (Canadell and Raupach, 2008). Here NEP was calculated as the annual net change in carbon stored on the landscape. As a flow indicator, it was assessed as a mean over each of the four time periods.

3.6.3 Site Protection

The study area is highly prone to erosion and soil loss, making site protection a very important ecosystem service in the area (Reger et al., 2015). The two indicators selected to represent this service were chosen to characterise the forests' ability to prevent erosion.

a) Leaf Area Index

The Leaf Area Index (LAI) is a measure for the vegetation cover per unit ground area (Watson, 1947). Here it is used to indicate the density and distribution of tree cover on the landscape. In the context of site protection it serves as a proxy for the forest's capability to intercept precipitation and protect the soil from the direct effect of environmental extremes such as direct solar radiation, heavy precipitation events (Chen et al., 2015). Therefore, a higher LAI indicates a better performance regarding the ecosystem service site protection. It is an important process variable in iLand, calculated from individual tree C allocation to the foliage pool, and was thus derived directly from iLand simulations. It represents the single-sided LAI [m^2 m^{-2}] and was assessed at the four time steps.

b) Water runoff

This indicator quantifies the amount of water which leaves the system, and therefore has the potential to contribute to erosion. It was derived from the daily water cycle calculations in iLand as precipitation – interception - transpiration change in soil water content ± water entering or leaving the snow cover pool; and was aggregated to mm runoff per year. It was assessed over the 4 time periods. Contrary to the other indicators, a lower value of the indicator here signifies a better performance, as it means that there is less water flowing out of the system and therefore less potential for erosion through overland-flow (Brogna et al., 2017; Inbar et al., 1998).

3.6.4 Biodiversity

Biodiversity is crucial for ecosystem functioning and is receiving increasing attention also in managed forest ecosystems (Lexer and Seidl, 2009). Here, both the diversity of tree species as well as that of a wide range of forest-dwelling species was assessed.

a) Tree species diversity

Tree species diversity is calculated as an exponential Shannon index (Jost, 2006) based on the basal area of tree species (see also Thom et al., 2016). It is a dimensionless number (effective number of species present in the landscape), calculated at the level of 100 x 100m grid cells and then averaged for the entire landscape. The Shannon Index was used because it incorporates the abundance and richness of species. Presenting the exponential Shannon index allows for a more straightforward interpretation than the classical index presenting a hypothetical number of evenly distributed species. A higher number of tree species is seen as favourable, as it increases stability under a variety of environmental conditions (Jactel et al., 2005).

b) Diversity of forest-dwelling species

In order to also assess biodiversity in forests beyond tree species, I looked at the diversity of forest-dwelling non-tree species groups. Forest-dwelling species such as certain insects are commonly used to measure the effects of forest management on biodiversity (Lindenmayer et al., 2000).

Individual Generalised Linear Models (GLMs) of the diversity of several groups of forest-dwelling species were developed by Thom et al. (2016a), using empirical data from Central Europe. The GLMs provide species numbers within each group based on vegetation predictors such as the species shares of beech, spruce, and oak/hornbeam as well as crown cover. The summed yearly precipitation and the mean annual temperature are also included as predictors. Therefore, the GLMs are sensitive both to climate and to forest composition. I here used the GLMs for the groups Hymenoptera (Insecta), Hemiptera (Insecta), Aranae (Arachnida), Mollusca, and ground vegetation. As the individual GLMs provide an estimate of the total number of species within the respective group, and species numbers vary widely between groups, the values calculated from the GLMs were scaled between 0 and 1 (0 being the lowest observed number and 1 the highest) and then averaged to derive a single indicator for forest-dwelling species, scaled between 0 and 1.

Table 5: Overview of indicators used to quantify ecosystem services. Stock indicators are assessed at four time steps and flow indicators over four time periods

Service	Indicator	Category	Assessment time	Definition	Unit
Timber production	Volume	stock	point in time	standing live timber volume	$m^3\ ha^{-1}$
	Regular harvest	flow	period	planned harvest (thinning and final harvest), excluding salvage harvest	$m^3\ ha^{-1}\ year^{-1}$
Climate regulation	Carbon stock	stock	point in time	total ecosystem carbon derived by summing all carbon pools simulated in iLand	$t\ C\ ha^{-1}$
	Net Ecosystem Production	flow	period	Net carbon accumulation of the ecosystem	$t\ C\ ha^{-1}\ year^{-1}$
Site protection	Leaf Area Index	stock	point in time	one-sided leaf area index	m^2m^{-2}
	Water runoff	flow	period	water flowing out of the system	$mm\ year^{-1}$
Biodiversity	Tree species diversity	stock	point in time	Effective number of tree species (Shannon exponent)	dimensionless
	Diversity of forest-dwelling species	stock	point in time	Relative diversity of non-tree forest-dwelling species, aggregated indicator following Thom et al., (2016)	0-1

4 Results

4.1 Model evaluation

In a first step, the adaptive implementation of sustainable forest management was tested. To this end an exploratory assessment of the relationship between mean annual increment, the planned harvest as calculated by the model, and the actual executed harvest including salvage cuttings was done. Figure 8 shows the cumulative sums (mean over all replicates) for the baseline scenario for each of the four management strategies. The cumulative realized harvest remained well below the cumulative planned harvest in all four cases. This illustrates that the model considers bottom-up constraints to harvesting realistically, e.g. due to the spatial configuration or structure of stands scheduled for harvesting. The cumulative planned harvest, in turn, was close to or slightly below the cumulative mean annual increment. This means that the model calculates the sustainable forest level correctly and that the scheduled harvest does not exceed the increment over the 200 year period. At the beginning of the simulation period, realized harvests were higher than planned harvests and mean annual increment, which is the result of the presence of many old stands in the initialization (see also Figure 1), resulting in a peak in harvested volume in the first decades of the simulation.

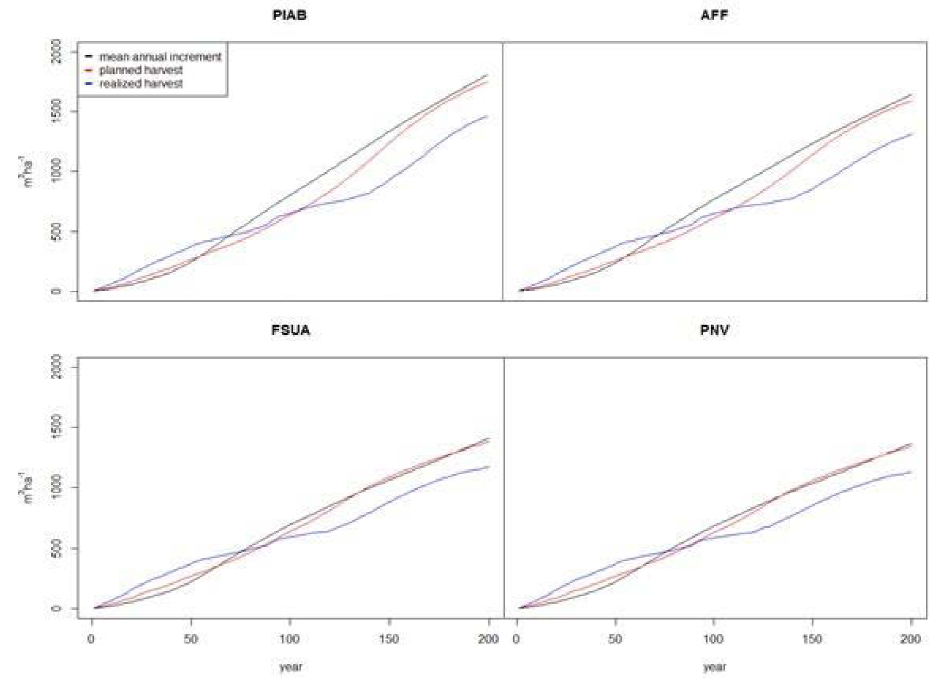

Figure 8: Comparison of cumulative mean annual increment (black), cumulative mean planned harvest (red) and cumulative mean realised harvests (blue). Figures shown are the mean of 20 replicates under the baseline scenario.

Secondly, the implementation of final harvests was analysed, comparing planned rotation lengths to the actual stand age at time of final harvest. Figure 9 shows the distribution of stand ages at the time of final harvest (over all 20 replicates) for the eight stand treatment programmes of the four management strategies under baseline conditions. For PIAB and AFF, realized harvest ages were generally higher than the planned rotation length, even though these strategies are characterized by longer rotations than FSUA and PNV. For FSUA and PNV, the realized harvest age on average corresponds well with the planned rotation length, with a tendency to a later harvest than planned.
Stands where a new rotation period was started due to a stand-replacing disturbance are not included in this analysis. The longer realized rotation period for PIAB and AFF can also be attributed to the higher disturbance impact. When higher amounts of salvage logging are necessary due to disturbances, regular harvests are postponed in order to not exceed the maximum allowable cut. This directly results in a higher harvest age.

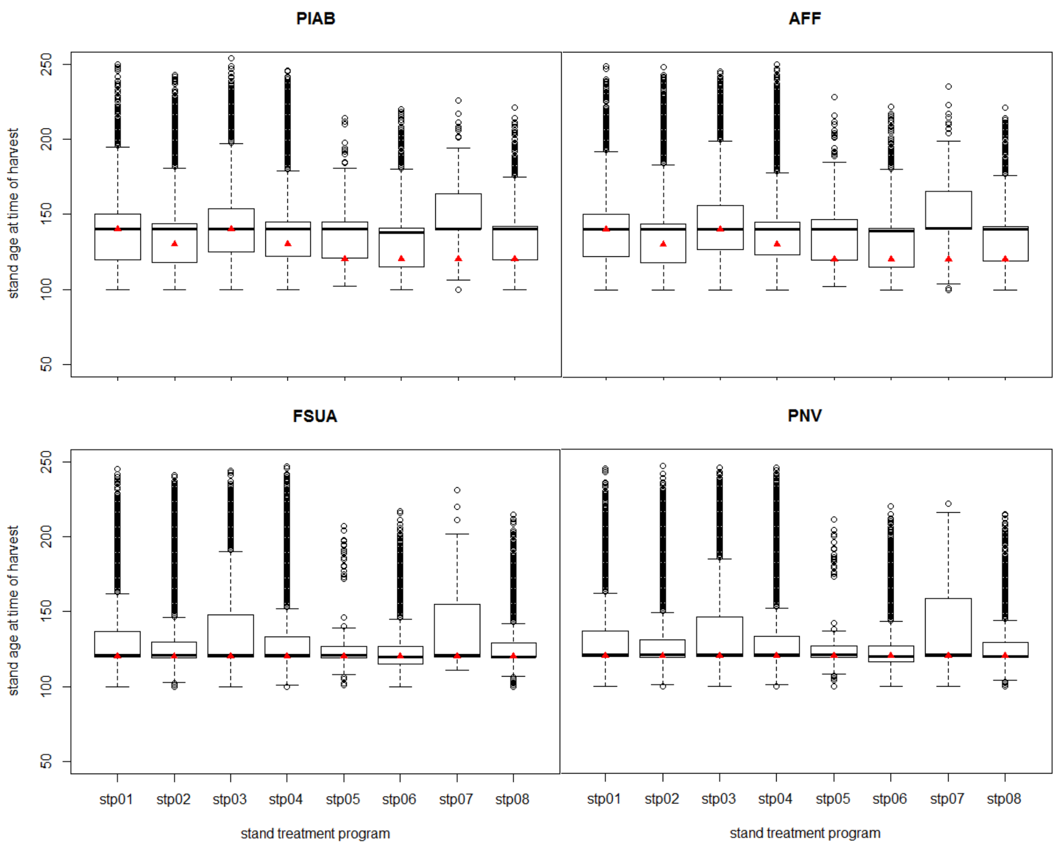

Figure 9: Realised harvest ages (boxplots) compared to planned harvest ages (red triangles)

During the implementation of the management strategies, the realized species composition at the level of stand treatment programmes was iteratively compared to the target species composition to assure that the prescribed stand treatments had the desired effect. An example for the most common STP (stp04, covering 36 % of the landscape) of the AFF strategy is shown in Figure 10 (mean over all stands under STP 3 in one simulation run). Realised species composition was assessed at the time of final harvest, and the evaluation was conducted separately for final harvests occurring in the first and second century of the simulation, respectively. This separation allows the assessment of trajectories over time, i.e. whether the system if gradually approaching the target composition, or is moving away from it. As seen in the example, species compositions approached the target species shares in the second century of the simulation, i.e. after a full rotation of the respective management was implemented.

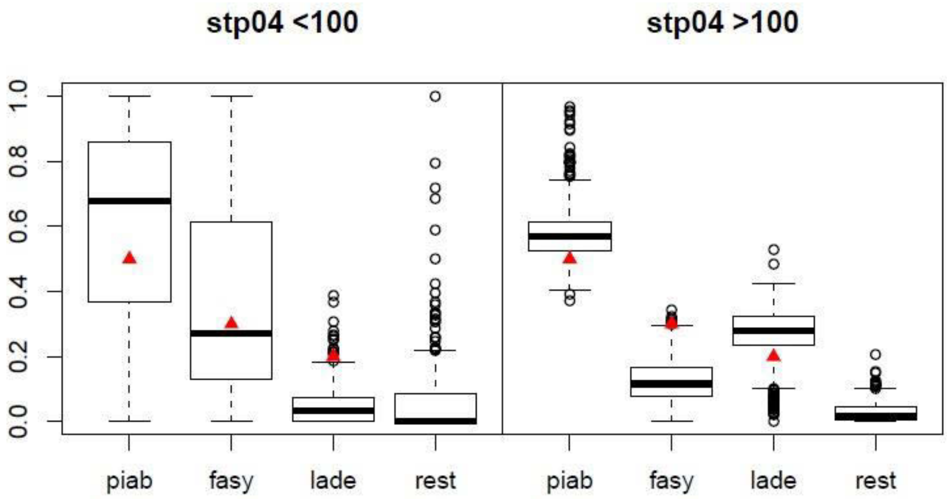

Figure 10: Realised tree species shares (boxplots) for target species compared to target shares (red triangles) in the first (left) and second (right) century of simulation

To assess the effects of the different management strategies at the landscape level, target species shares of each stand treatment programme were weighted with the area covered by said treatment programme, producing landscape target species shares for each management strategy. These were then compared to the actual species composition on the landscape over the full 200 year simulation period. In general, realized species shares approached the target shares over the course of the simulation. Figure 11 shows the target share and actual share (mean and 5th to 95th percentile range over all 20 runs for the baseline scenario) for each of the four managements. It demonstrates the different developments of tree species shares on the landscape under different managements. Natural forest dynamics and competition with other tree species prevented a complete match between the simulation and the target species composition. This is especially the case in the PIAB scenario, in which the intended tree species composition is quite different from the natural species composition of the area. Succession effects were also visible, with larch initially reaching higher shares due to its ability to colonize open areas on the landscape, and declining in later parts of the study period, after being replaced by more shade-tolerant species.

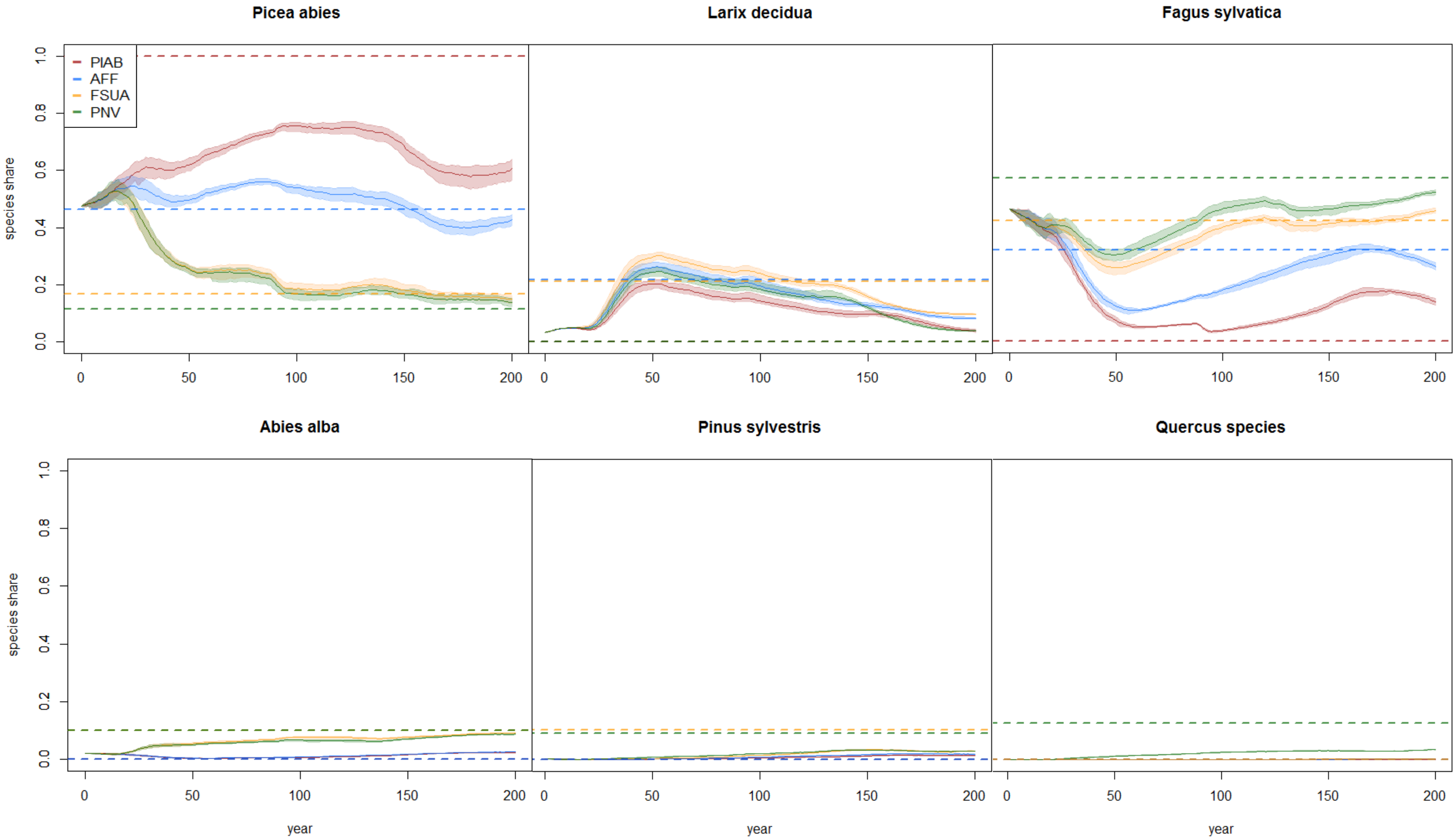

Figure 11: Development of tree species shares at the landscape scale (mean and 95th percentile range shown) in relation to target species shares (dashed lines) in the different management strategies

4.2 Effects of management and climate on forest structure and composition

Several of the ecosystem service indicators are strongly dependent on forest structure and composition. An assessment of the effects of management and climate on forest vegetation dynamics is thus important for putting differences in ecosystem service provisioning into context.

As shown previously, the four management strategies differed distinctly in their realized tree species composition (Figure 12). While less clearly discernible, there is also a management impact on the age class distribution on the landscape (Figure 13). The difference in age class structure is mainly caused by different rotation lengths, and differences thus particularly distinct between AFF (and PIAB) vs. FSUA (and PNV). Differences in the disturbance regime (see below) further result in diverging age class structure between the strategies.

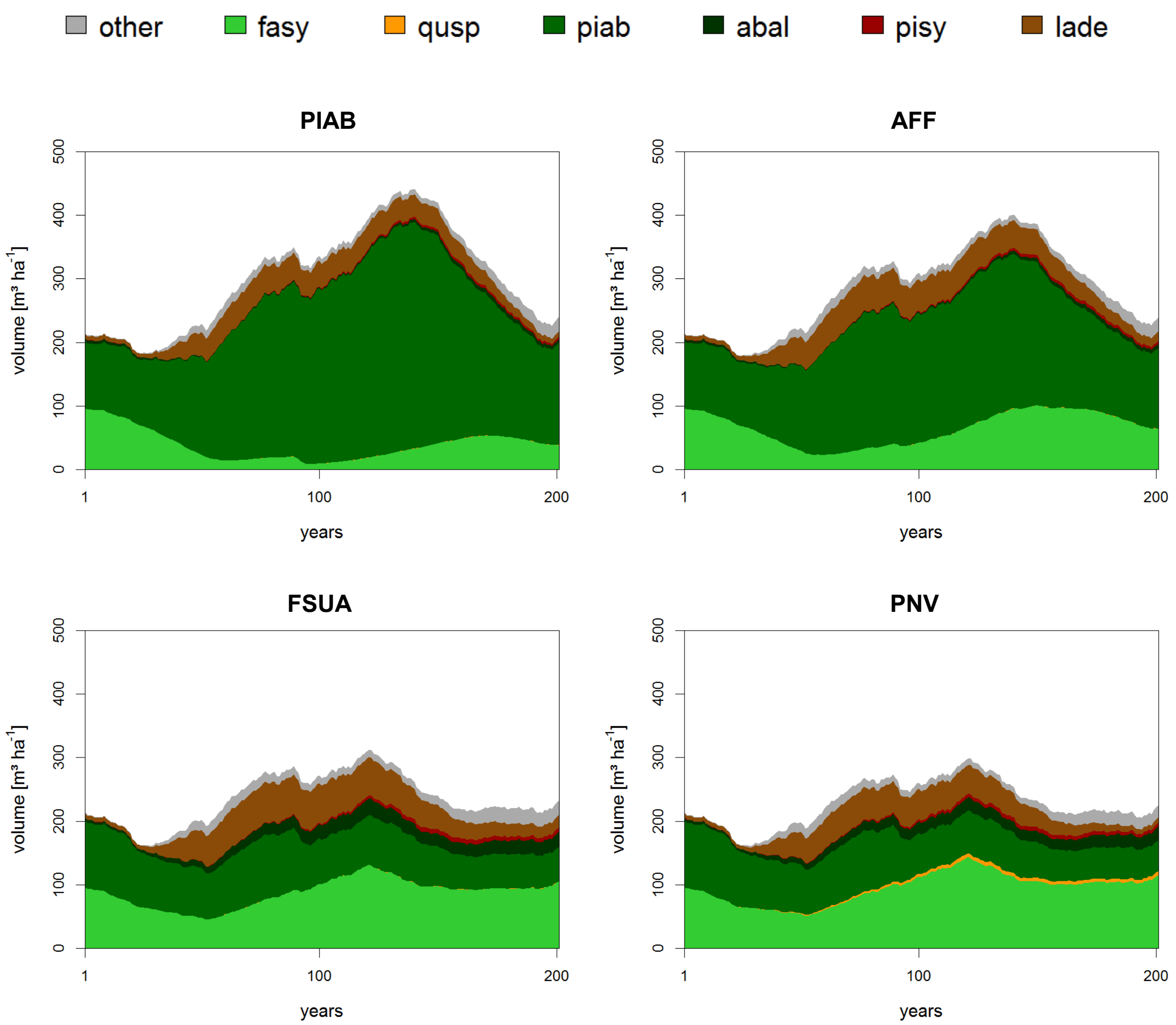

Figure 12: Standing volume [m^3 ha^{-1}] on the landscape for each management strategy under baseline climate

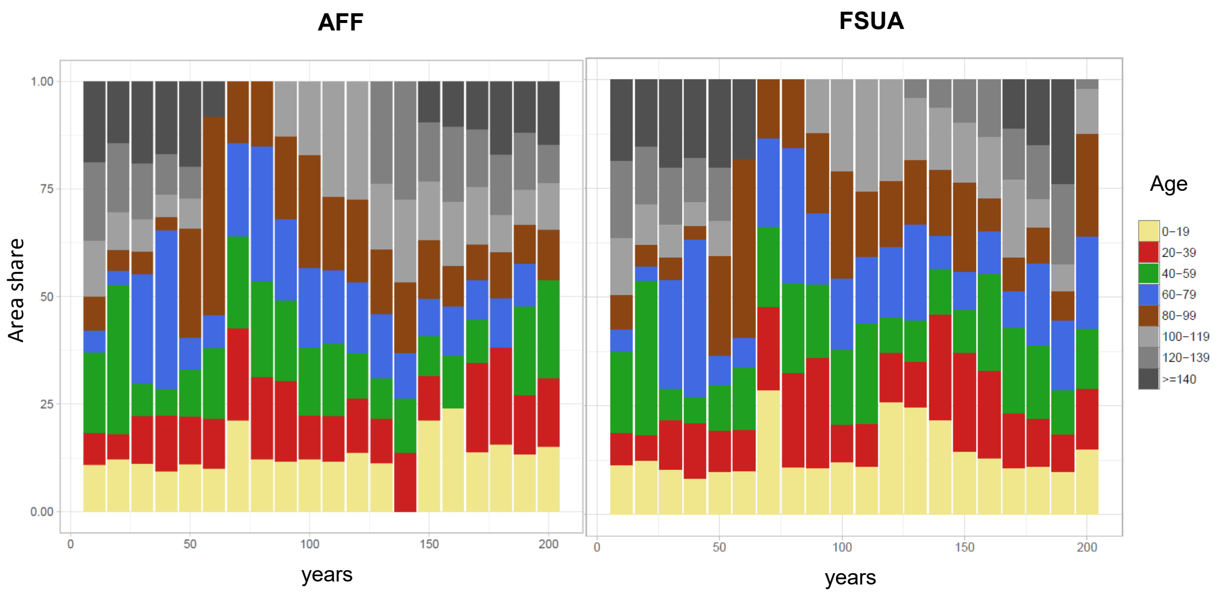

Figure 13: Age class structure under baseline climate for AFF and FSUA

Under climate change (mean over all climate scenarios), the realized tree species composition changed in all management strategies, even though the management goals remained the same (Figure 14). This demonstrates that changing climate and disturbance conditions strongly affected the ability to reach tree species targets in the different management strategies. The strategies prescribing a higher target share of spruce (PIAB and AFF) were more strongly affected by disturbances (see details below), which resulted in a lower volume and a lower share of spruce under climate change compared to baseline conditions in these scenarios. The more future-oriented management strategies were able to approach their tree species composition goals more closely under climate change. They even showed a small increase in standing volume as species such as oak and pine encountered more suitable environmental conditions.

Regarding the age class structure, the impacts of changing climate and disturbance regimes resulted in a higher prevalence of younger age classes, especially in the strategies more affected by disturbances (see Figure 15 for an example).

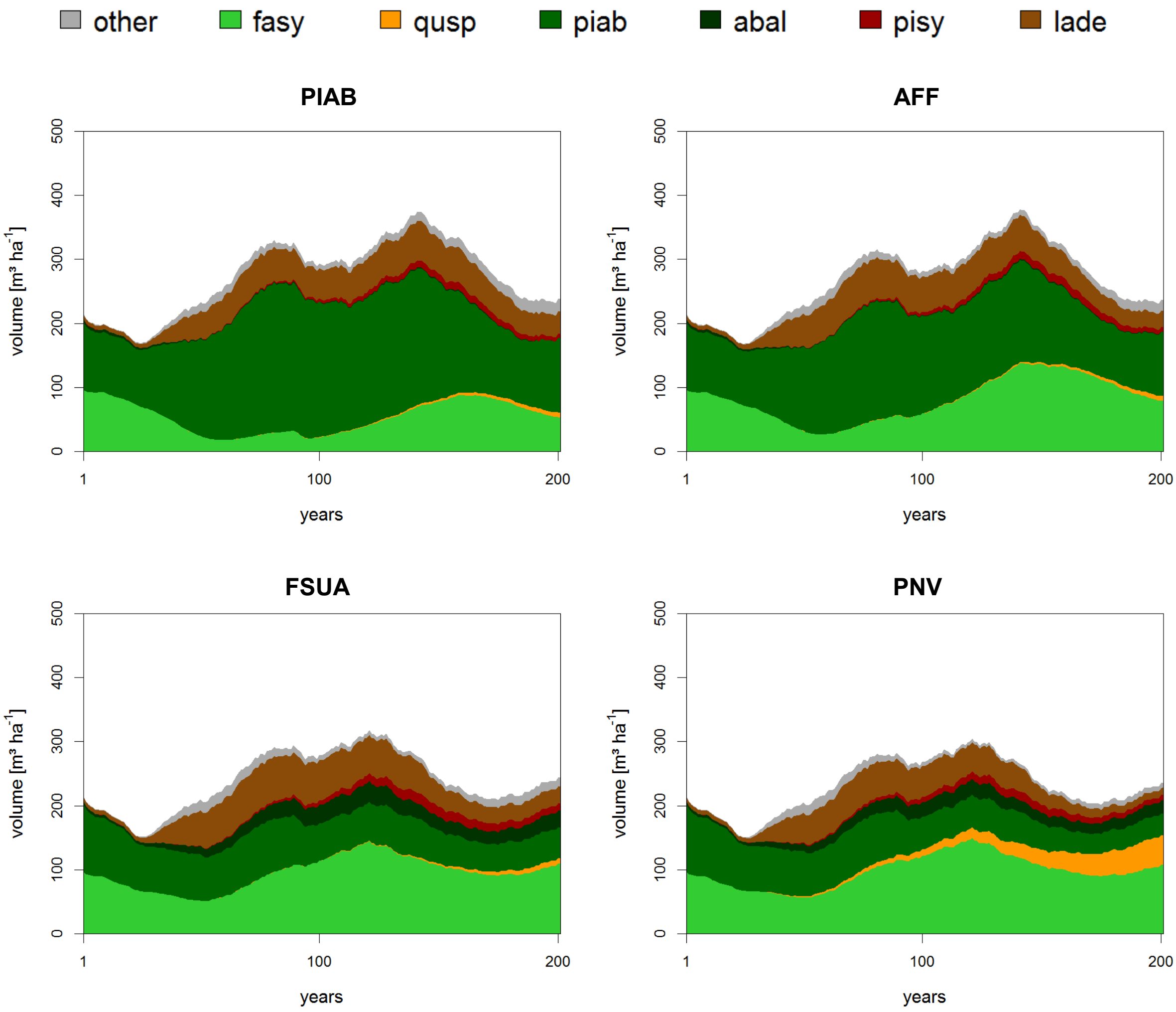

Figure 14: Volume [m³ ha^{-1}] on the landscape for each management strategy under climate change

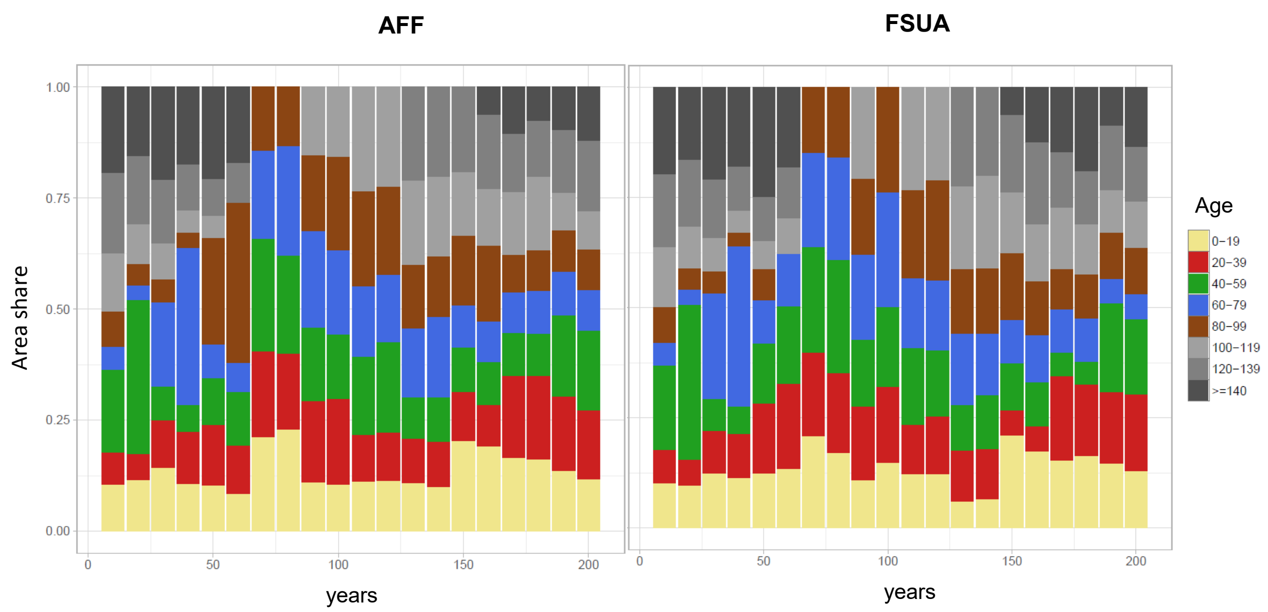

Figure 15: Age class structure under climate change (ICTP scenario) for AFF and FSUA

4.3 Development of disturbances over time

Disturbances can have a strong effect on the ability of an ecosystem to provide certain services, and strongly influence the temporal stability of service provisioning. Therefore, the four management strategies were characterised regarding their susceptibility to disturbance. Figure 16 visualizes disturbance impacts on under the different strategies, calculated as the mean amount of salvaged timber per ha and year. A difference in susceptibility between strategies only becomes visible after the first 50 years of the simulation, when strategies start to diverge regarding vegetation structure and species composition (see figures 12 and 14). Furthermore, the periods with the highest disturbance impacts were also the periods when the share of older stands is highest on the landscape (cf. Figure 13 and 15). This effect was much more pronounced under the PIAB and AFF strategies than under the FSUA and PNV strategies (Figure 16). Climate change led to an increase in disturbance impacts across all strategies, with PIAB and AFF being considerably more susceptible than FSUA and PNV. The amount of salvaged wood over the full simulation period increased by 41 % under climate change in the PIAB strategy, by 40 % for AFF but only by 25 % in the FSUA strategy and 17 % for PNV.

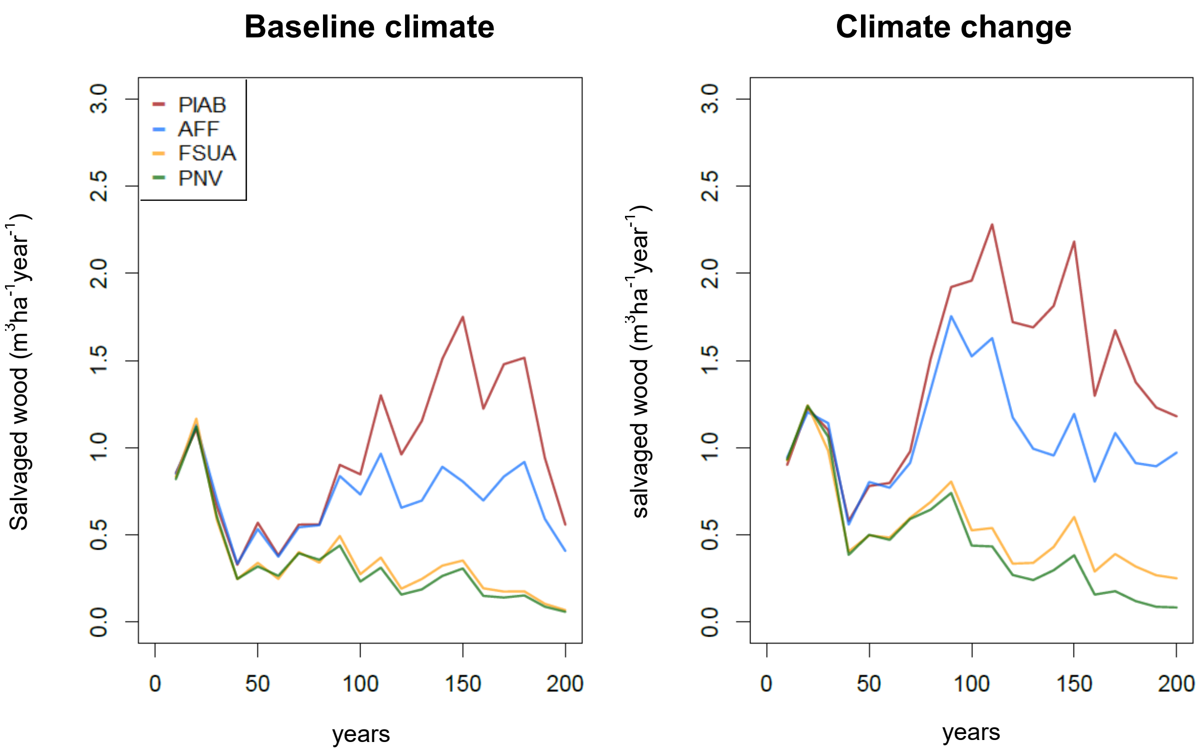

Figure 16: Impact of disturbances (salvaged wood) over time

4.4 Effect on provisioning of ecosystem Services

In this section, results are presented individually. A joint overview across all ecosystem services is presented at the end of this section (Table 6, Table 7).

4.4.1 Timber production

a) Volume

Under baseline climate (Figure 17), the spruce-oriented management strategies PIAB and AFF clearly resulted in a better absolute performance, with a mean standing timber volume of 301.4 m³ ha^{-1} and 284.8 m³ ha^{-1} , respectively, compared to 233.4 m³ ha^{-1} and 226.1 m³ ha^{-1} for FSUA and PNV (mean over 200 year study period). A strong disparity between periods was visible and can be explained by the different rotations lengths of the strategies. These resulted in a reduction of standing volume between the simulation years 100 and 150 for FSUA and PNV, while PIAB and AFF still increased their volume, and reduce it between the years 150 and 200. Another effect factoring into this development was the more intense impact of disturbance on the strategies with a higher share of spruce (Figure 18). Disturbances contributed to a lower volume at the end of the simulation period particularly in the PIAB and AFF strategies.

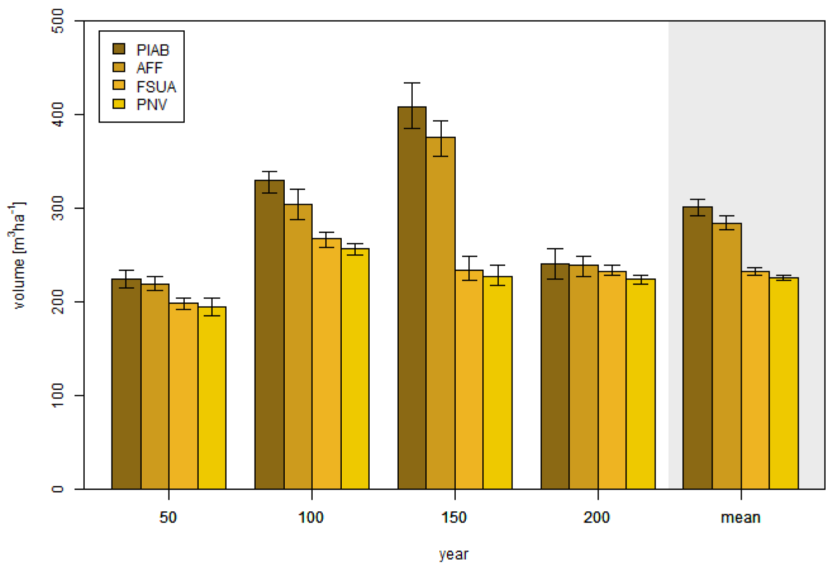

Figure 17: Standing timber volume under baseline climate (mean and 5th to 95th percentile range over all 20 replicates)

Under climate change, there was a clear change regarding the performance of the four strategies (Figure 18). On average over the 200 years there was a slight increase in the performance of FSUA (+ 4.0 %) and PNV (+3.7 %), while PIAB (-6.4 %) and AFF (-3.7 %) showed reduced performance. However, even under climate change, PIAB remained the strategy with the highest mean standing volume stock (PIAB: 276.5 m³ ha^{-1}, AFF: 271.5 m³ ha^{-1}, FSUA: 242.8 m³ ha^{-1}, PNV: 234.5 m³ ha^{-1})

There was a slight increase in standing volume for all strategies in the first decades (year 50). A stronger differentiation between strategies became apparent at later time steps, resulting from the progressing change in tree species composition and the following differentiation in disturbance impact. PIAB and AFF were strongly affected by disturbances under climate change, resulting in a distinct reduction of volume compared to the baseline scenario, especially in the second half of the study period. The reduction in the share of spruce in PIAB and AFF over (Figure 14) resulted in a reduced disturbance impact toward the end of the simulation period. Accordingly, the differences in the change of standing volume under climate change are less pronounced in the year 200 than at previous assessment times. Overall, FSUA and PNV showed a more stable performance under climate change regarding timber volume than PIAB and AFF.

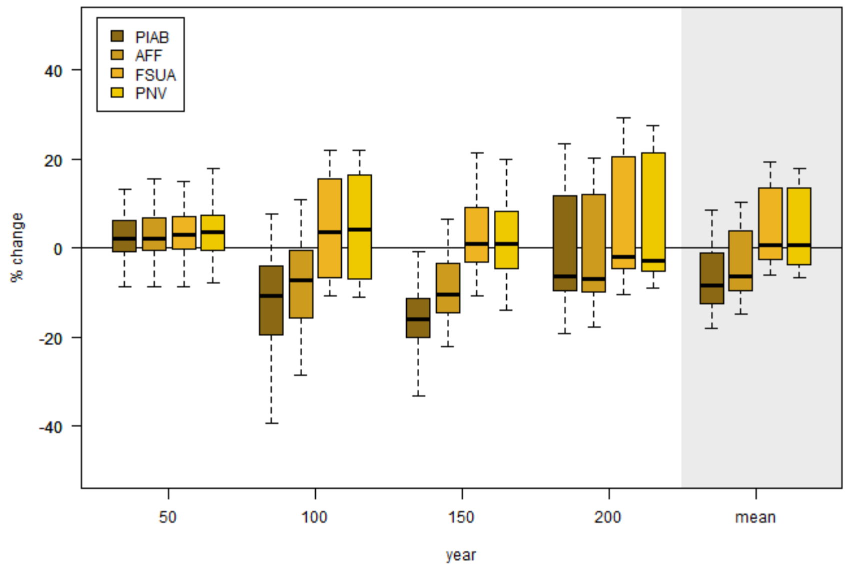

Figure 18: Climate sensitivity of standing volume, derived as relative change to baseline conditions over all studied scenarios (boxplots show the median, interquartile range and extreme values)

b) Regular harvest

Under the baseline scenario, the regular harvest over the whole simulation period was relatively similar among managements (Figure 19), with PIAB (4.35 m³ ha^{-1} $year^{-1}$) slightly outperforming FSUA (4.28 m³ ha^{-1} $year^{-1}$), AFF (4.26 m³ ha^{-1} $year^{-1}$) and PNV (4.16 m³ ha^{-1} $year^{-1}$). However, there was high variability of harvested volume among periods and between managements, with FSUA and PNV performing better in the first and third assessment period, while PIAB and AFF performed better in the second and fourth period. These differences were again largely driven by the difference in rotation period lengths between the managements. If salvage harvest is included in addition to regular harvest, PIAB and AFF clearly outperform the other two strategies (Figure 20).

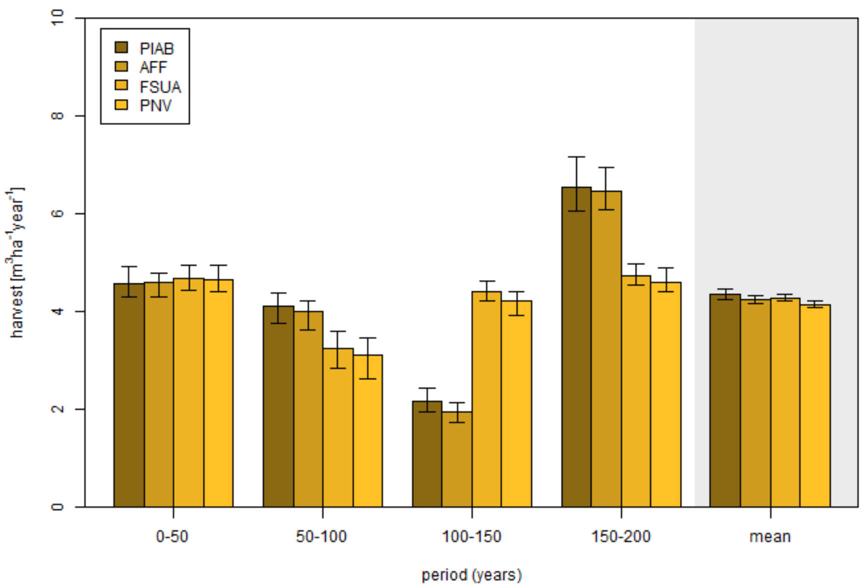

Figure 19: Regular harvest under baseline climate (mean and 5th to 95th percentile range over all 20 replicates)

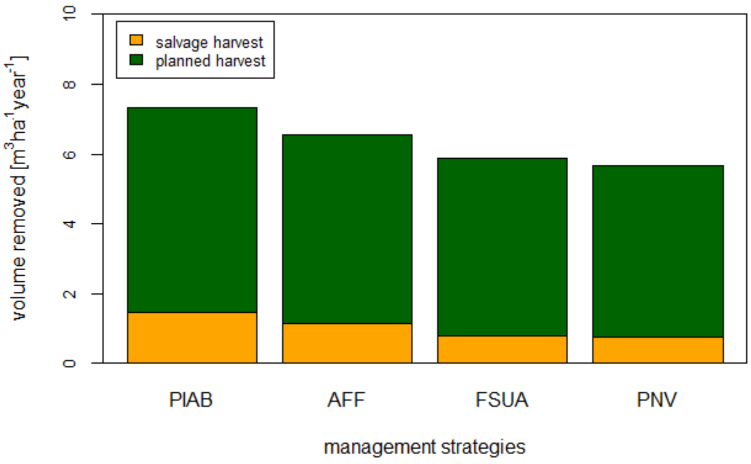

Figure 20: Total harvested volume (including regular and salvage harvest) under baseline climate (mean over all replicates)

Under climate change all strategies experienced a decline in regular harvest, which can be attributed to a higher disturbance impact being compensated (Figure 21). PIAB (-9.17 % mean decrease over the 200 year period) and AFF (-7.7 %) were impacted more strongly, while FSUA (-1.2 %) and PNV (-1.4 %) only experienced minor declines in regular harvest, showing a considerably more stable performance overall. The strategies differed more strongly in the later assessment periods, where the differences in tree species composition resulted in considerably reduced disturbance impact in the FSUA and PNV strategies. Regarding absolute performance under climate change, FSUA (4.24 m³ ha^{-1} $year^{-1}$) and PNV (4.11 m³ ha^{-1} $year^{-1}$) outperformed the other two strategies (PIAB: 3.89 m³ ha^{-1} $year^{-1}$, AFF: 4.98 m³ ha^{-1} $year^{-1}$), reversing the ranking obtained under baseline climate.

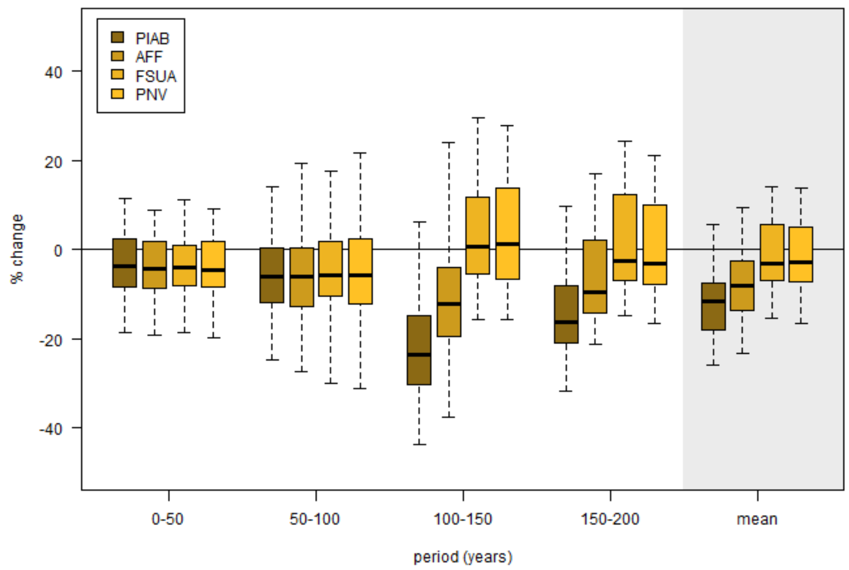

Figure 21: Climate sensitivity of regular harvest, derived as relative change to baseline conditions over all studied scenarios (boxplots show the median, interquartile range and extreme values).

4.4.2. Climate regulation

a) Carbon stock

Carbon storage on the landscape generally followed a similar pattern as timber volume under baseline conditions (Figure 22). PIAB performed best (348.9 t C ha^{-1}) and was followed closely by AFF (342.5 t C ha^{-1}) and, at a lower level, FSUA (325.0 t C ha^{-1}) and PNV (324.5 t C ha^{-1}). The differences in performance under baseline climate can mostly be attributed to differences in the stem carbon pool, which is closely correlated with the differences in standing volume reported above. This also explains the largely similar development of the two indicators over time. However, as the carbon stock indicator also includes the slowly responding soil carbon pool, scenario differences were less pronounced. The overall increase of carbon storage for all strategies can mainly be attributed to a moderate increase in soil carbon storage.

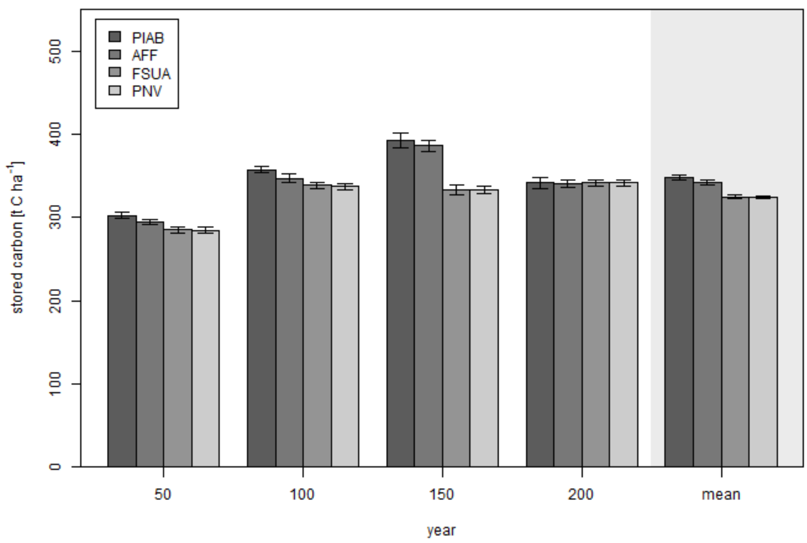

Figure 22: Carbon storage under baseline climate (mean and 5th to 95th percentile range over all 20 replicates)

Under climate change, similar to standing volume, all management strategies experienced a reduction in carbon storage (Figure 23). However, PNV (-4.3 %) and FSUA (-5.6 %) showed a smaller reduction in carbon storage than AFF (-7.7 %) and PIAB (-9.2 %), due to the lower disturbance impacts on the two strategies featuring a lower spruce share. The reduction in carbon storage can mainly be attributed to a decrease in the two quantitatively most important carbon pools, soil carbon and stem carbon. Both pools were negatively impacted by changes in climate, which reduced the increase in C storage observed under baseline conditions. Nonetheless, PIAB (315.7 t C ha^{-1}) and AFF (315.3 t C ha^{-1}) remained the strategies with the highest amount of carbon stored also under climate change (FSUA: 306.5 t C ha^{-1}, PNV: 310.4 t C ha^{-1}).

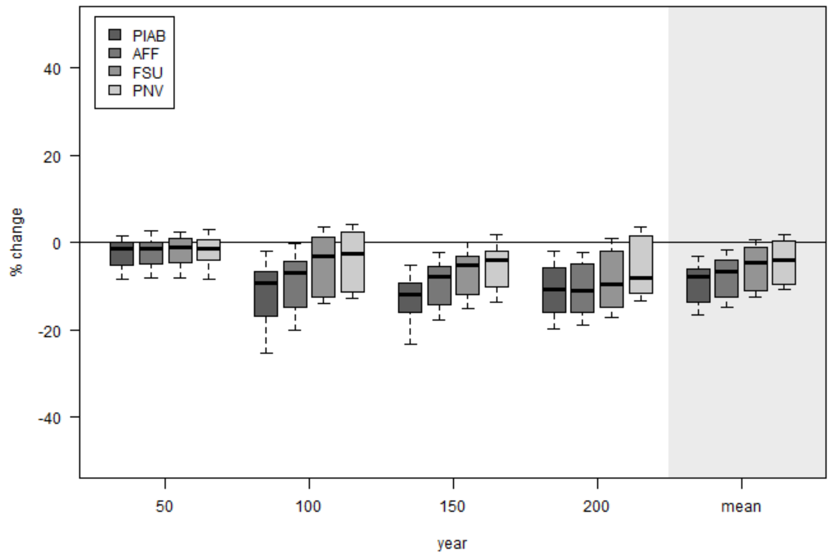

Figure 23: Climate sensitivity of carbon storage, derived as relative change to baseline conditions over all studied scenarios (boxplots show the median, interquartile range and extreme values).

b) Net Ecosystem Productivity

Under baseline climate conditions, the performance of all management strategies regarding Net Ecosystem Production was on average very similar over the 200 year study period (Figure 24). All strategies resulted in the landscape acting as a net carbon sink overall (PIAB: 0.390 t C ha^{-1} $year^{-1}$ uptake, AFF: 0.390 t C ha^{-1} $year^{-1}$, FSUA: 0.392 t C ha^{-1} $year^{-1}$, PNV 0.392 t C ha^{-1} $year^{-1}$). There was, however, a strong disparity between periods, as well as between managements within periods. During the third (in the case of FSUA and PNV) and fourth (PIAB and AFF) assessment period the landscape even acted as a carbon source to the atmosphere (i.e., more carbon left the system than was being taken up). These periods of negative NEP resulted from an increased harvesting activity and increased disturbances in these periods, in response to a high share of mature stands which are more likely to be harvested but also more likely to be affected by disturbances.

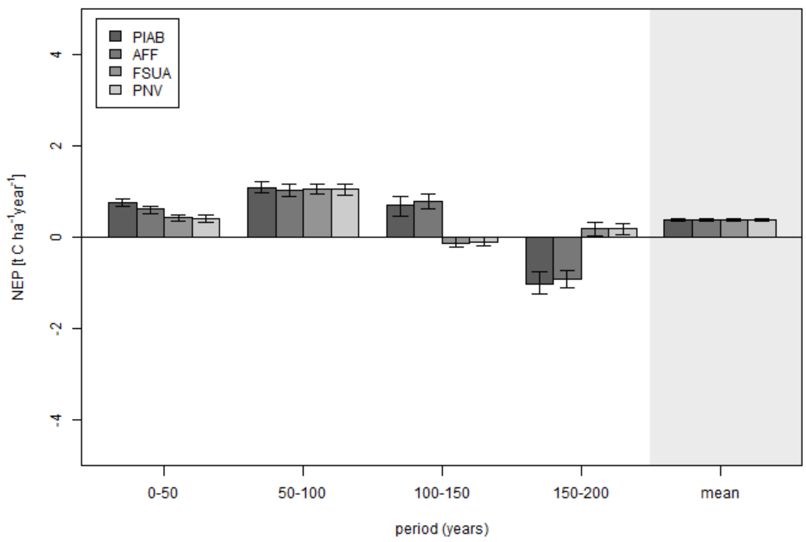

Figure 24: Net Ecosystem Productivity under baseline climate (mean and 5th to 95th percentile range over all 20 replicates)

NEP was generally strongly negatively affected by climate change (Figure 25), resulting from an increased disturbance impact and the corresponding removal of carbon from the system via salvage harvesting. However, the two management strategies most affected by disturbances experienced a lower reduction in NEP (PIAB: -19.8 %, AFF -20.0 %) over the 200 year study period than FSUA (-60.0 %) and PNV (-42.2 %). FSUA and PNV were especially negatively affected in the third and fourth period, which are the periods with the highest disturbance effects. Overall, while the impact of climate change on Net Ecosystem Production is negative for all strategies, the landscape remains a net sink of carbon to the atmosphere in all cases. Despite a strong relative loss in NEP compared to their own respective baselines PNV (0.291 t C ha^{-1} year^{-1}) and FSUA (0.245 t C ha^{-1} year^{-1}) remained the strategies with the highest NEP also under climate change (PIAB: 0.208 t C ha^{-1} year^{-1}, AFF: 207 t C ha^{-1} year^{-1})

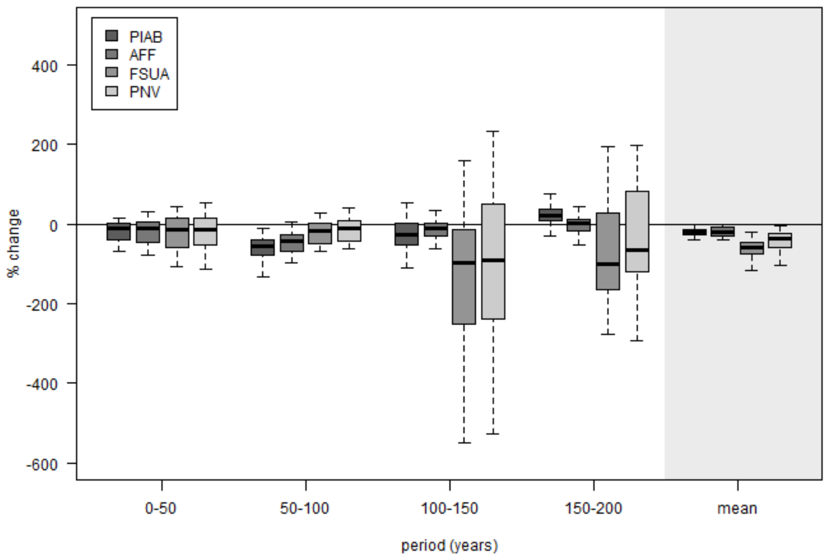

Figure 25: Climate sensitivity of Net Ecosystem Productivity, derived as relative change to baseline conditions over all studied scenarios (boxplots show the median, interquartile range and extreme values, note that y-axis is scaled differently than for other indicators)

4.4.3 Site protection

a) Leaf Area Index

Under baseline climate (Figure 26), the two most extreme management strategies performed best. PIAB showed the best overall performance with a mean LAI of 3.80 m^2m^{-2}, followed by AFF (3.53 m^2m^{-2}), PNV (3.46 m^2m^{-2}) and FSUA (3.32 m^2m^{-2}). The LAI for PIAB remained stable over the entire study period, while AFF and especially FSUA and PNV showed more variation over time, in response to harvests and disturbances. This is likely due to the ability of spruce to support a relatively high LAI in all stages of stand development.

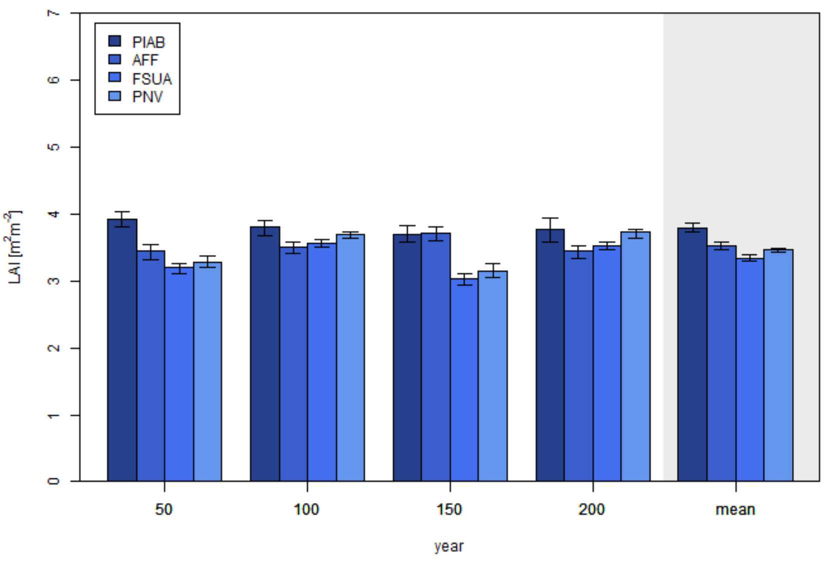

Figure 26: Leaf Area Index (LAI) under baseline climate (mean and 5th to 95th percentile range over all 20 replicates)

Under climate change, all management strategies slightly increased their LAI (AFF: +2.1 %, FSUA: +6.3 %, PNV: + 7.9 %) with the exception of PIAB, for which LAI decreased by -2.5 % in comparison to the baseline scenario (Figure 27). This decrease as well as the comparatively smaller increase in LAI for AFF can be attributed to stronger impacts of disturbances in these strategies. In absolute terms, the difference between strategies decreases under climate change, with PNV (3.74) and PIAB (3.70) outperforming AFF (3.61) and FSUA (3.54).

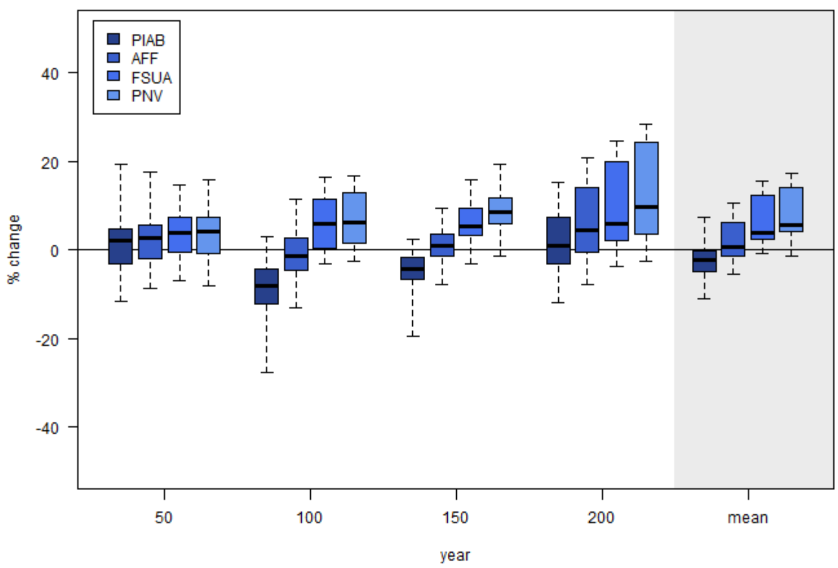

Figure 27: Climate sensitivity of Leaf Area Index, derived as relative change to baseline conditions over all studied scenarios (boxplots show the median, interquartile range and extreme values).

b) Water runoff

The annual average water runoff of the landscape was only marginally impacted by management under baseline scenario (Figure 28), indicating that it is predominantly driven by precipitation. The small variation between the management strategies over the 200 year study period (PIAB: 929.1 mm year^{-1}, AFF 929.9 mm year^{-1}, FSUA 941.1 mm year^{-1} and PNV: 941.4 mm year^{-1}) can be attributed to differences in interception (higher for conifer species). Overall, as PIAB and AFF had somewhat lower runoff they performed slightly better regarding the protection function than FSUA and PNV did.

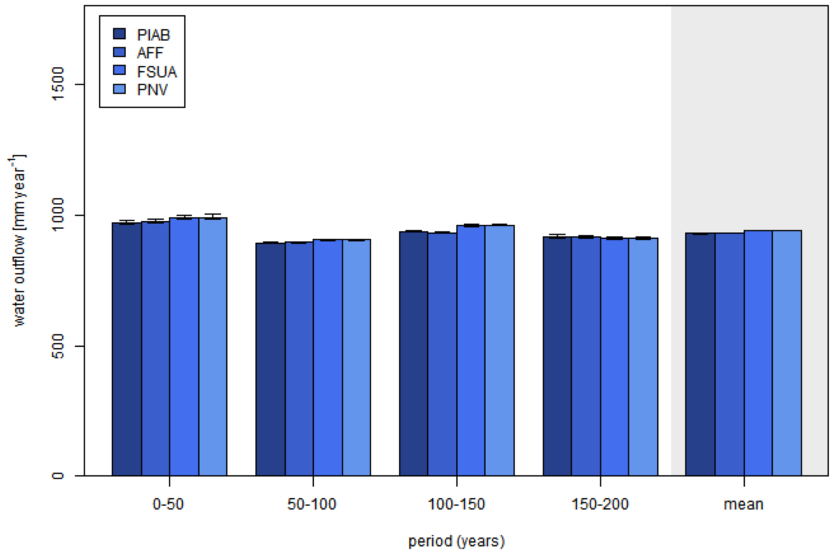

Figure 2813: Water runoff under baseline climate (mean and 5th to 95th percentile range over all 20 replicates)

There was almost no change in water runoff under climate change (figure 29), and the differences relative to baseline conditions remained negligible (PIAB: +2.7 %, AFF +1.5 %, FSUA +0.91 %, PNV +0.91 %). There were slight differences between periods and among managements within periods, but overall all management strategies were similarly affected by climate change regarding runoff. This suggests that the differences under climate change are mainly attributable to changes in precipitation, rather than management-induced changes in forest cover and species composition. The ranking remained the same under climate change as under baseline climate, with PIAB (945.5 mm year^{-1}) and AFF (944.1 mm year^{-1}) having a narrow lead over FSUA (950.5 mm year^{-1}) and PNV (950.8 mm year^{-1}).

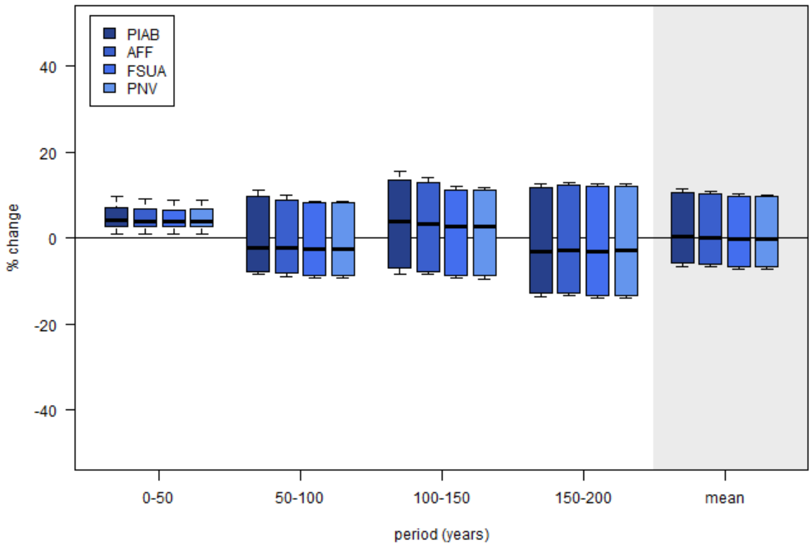

Figure 29: Climate sensitivity of water runoff, derived as relative change to baseline conditions over all studied scenarios (boxplots show the median, interquartile range and extreme values).

4.4.4 Biodiversity

a) Tree species diversity

As expected, the strategies which were designed to include more tree species in their target species composition resulted in a higher tree species diversity in the simulations (FSUA: 4.58, PNV: 4.50, AFF: 3.82, PIAB: 3.05). Tree species diversity was thus strongly driven by management. However, management does not completely control natural species dynamics, and there is an increase in tree species diversity over time (Figure 30), even for the scenarios which focus solely on a small number of species. The increase in effective tree species number over time particularly in FSUA and PNV is the effect of a successful implementation of a strategy to diversify tree species and manage for mixed species stands.

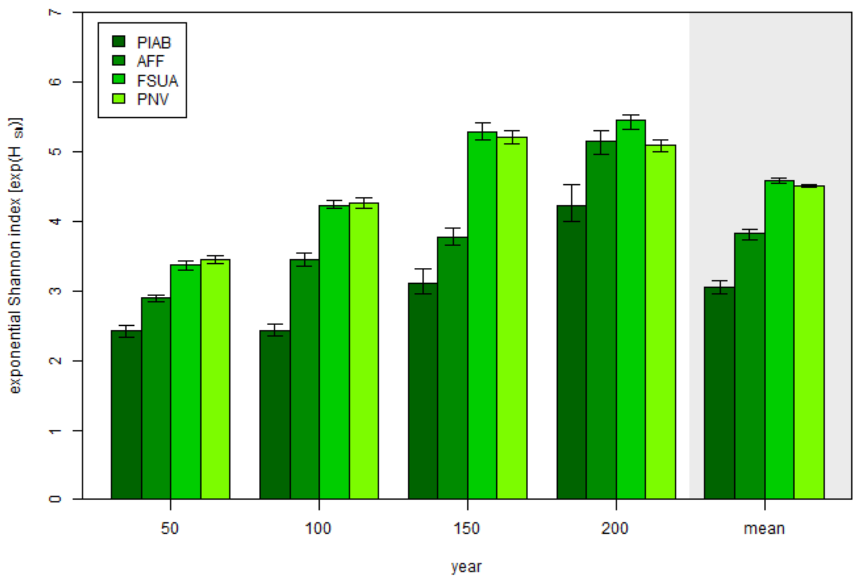

Figure 30: Effective tree species diversity under baseline climate (mean and 5th to 95th percentile range over all 20 replicates).

Under climate change PIAB showed an increase in the effective number of tree species on the landscape (+12.1 %), while diversity slightly decreased in all other management strategies (FSUA: - 4.0 %, PNV: - 2.0 %, AFF: -0.9) (Figure 31). In the case of PIAB, the increase can be attributed to a reduced dominance of spruce under climate change due to increased disturbance. The decrease of diversity in the AFF, FSUA, PNV strategies is likely due to the increasing dominance of beech as a result of its increasing competitiveness in a warming world, which in turn decreases the effective number of tree species. For AFF, this process was somewhat buffered by the simultaneous loss of spruce dominance as a result of disturbances. The tree species diversity under climate change was 4.4 for PNV and FSUA, 3.8 for AFF and 3.4 for PIAB.

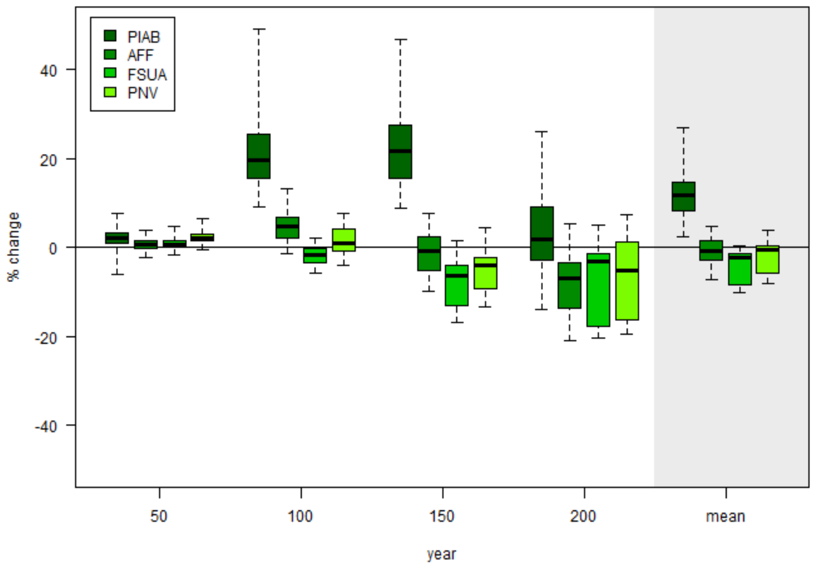

Figure 31: Climate sensitivity of effective tree species diversity, derived as relative change to baseline conditions over all studied scenarios (boxplots show the median, interquartile range and extreme values).

b) Diversity of forest dwelling species

Under baseline conditions FSUA (0.377) and PNV (0.369) had higher values of the compound indicator of forest-dwelling species diversity than AFF (0.300) and PIAB (0.267) (Figure 32). This can be attributed to the fact that several of the species groups contained in the indicator are negatively related to spruce presence and positively related to broad-leaved species. The change over time was largely related to tree species composition, but also - especially in the case of PIAB - to the presence of gaps within the canopy, to which several of the species groups react positively. While the landscape was still relatively open at year 50, tree cover increased toward year 100, resulting in lower biodiversity values. Subsequently, the landscape opened up again due to disturbances and management, which caused biodiversity values to rise again.

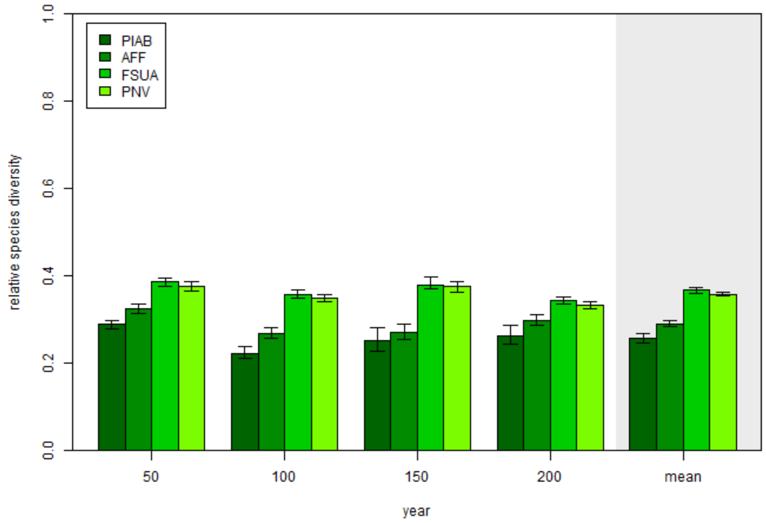

Figure 32: Diversity of forest dwelling species under baseline climate (mean and 5th to 95th percentile range over all 20 replicates)

Under climate change, a sharp increase in biodiversity could be observed (Figure 33), especially for PIAB (+93.4 %), but also for all other management strategies (AFF: + 76.0 %, PNV: + 68.5 %, FSUA + 61.6 %). This can be attributed to the tree species change resulting from a changing climate, which also allows new species such as oak (positively related to several of the indicator groups) to establish in the landscape. Furthermore, increasing disturbances also positively affect biodiversity, especially under PIAB and AFF strategies. While climate change reduced the differences in diversity between the management strategies (stronger increase in diversity in strategies less diverse under baseline climate), PNV (0.615) and FSUA (0.605) remained the strategies with the highest total diversity of forest-dwelling species also under climate change (AFF: 0.520, PIAB: 0.506).

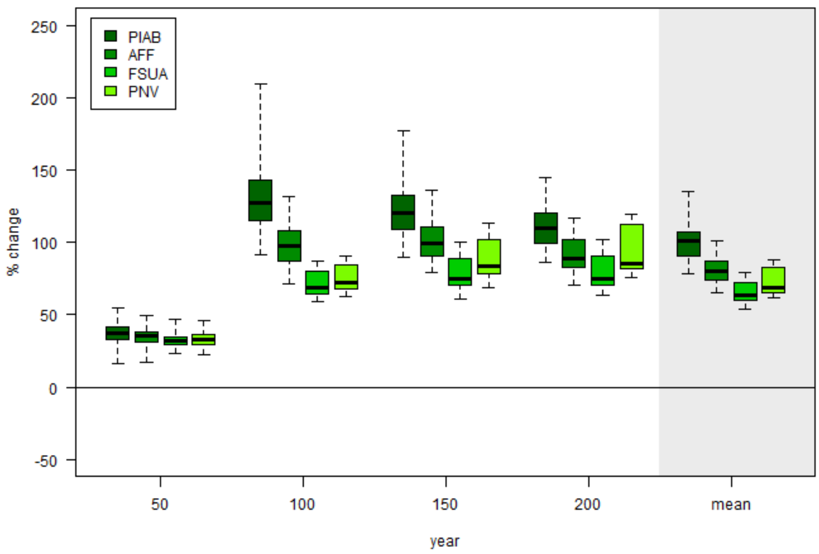

Figure 33: Climate sensitivity of the number of forest dwelling species, derived as relative change to baseline conditions over all studied scenarios (boxplots show the median, interquartile range and extreme values, note that y-axis is scaled differently than for other indicators)

Table 6: Means (over the full 200 year simulation period and all replicates) of indicator values for total ecosystem services provisioning under baseline climate

Management alternative	**Ecosystem service indicator (total provisioning under baseline climate)**							
	Volume [m³ ha^{-1}]	Regular harvest [m³ ha^{-1} $year^{-1}$]	Carbon storage [t C ha^{-1}]	NEP [t C ha^{-1} $year^{-1}$]	LAI [m m^{-1}]	Water runoff [mm $year^{-1}$]	Tree species diversity [dim.]	Diversity of other species
PIAB	301.4	4.35	348.9	0.390	3.80	929.1	3.05	0.267
AFF	284.8	4.26	342.5	0.386	3.53	929.9	3.82	0.300
FSUA	233.4	4.28	325.0	0.392	3.33	941.1	4.58	0.377
PNV	226.1	4.16	324.5	0.392	3.46	941.4	4.50	0.369

Table 7: Mean change (over the full 200 year simulation period and all replicates) in indicator values for ecosystem services provisioning under climate change

Management alternative	**Ecosystem service indicator (relative change under climate change)**							
	Volume [%]	Regular harvest [%]	Carbon storage [%]	NEP [%]	LAI [%]	Water runoff [%]	Tree species diversity [%]	Diversity of other species [%]
PIAB	-6.4	-11.6	-9.2	-9.2	-2.5	+1.7	12.1	+93.4
AFF	-3.7	-7.1	-7.7	-7.7	+2.1	+1.5	-0.9	+76.0
FSUA	+4.0	-1.2	-5.6	-5.6	+6.3	+0.9	-4.0	+61.6
PNV	+3.7	-1.4	-4.3	-4.3	+7.9	+0.9	-2.0	+68.5

5 Discussion

5.1 Implementation of management strategies in the simulation

To study the effect of forest management on the capacity to provide various ecosystem services, a range of management strategies was analysed. To this end, four management strategies with differing target species compositions, rotation lengths, and harvesting regimes were designed. Tests of the implementation of the alternative strategies showed that they were successfully able to produce four trajectories with clear differences in realised species composition and landscape structure. This, in turn, resulted in a gradient of susceptibility to disturbances and climate change, allowing me to study a wide range of potential management effects with regard to their implications for future ecosystem services provisioning.

The scenarios PIAB and AFF share the same set of thinning and harvesting activities and the same rotation lengths for all the stand treatment programmes, as do FSUA and PNV. This potentially contributed to a clustering of the results in these two groups of strategies with regard to several ecosystem services indicators. It can be assumed that the results would have been more differentiated across the gradient if the management strategies had differed more strongly regarding their silvicultural treatment plans. However, all strategies showed clear differences in their realised species composition, which was the main focus of differentiation in their design. This is important as previous work has found that species composition affects a forest's ability to provide ecosystem services both directly (Rasche et al., 2013) and through its effect on the susceptibility to disturbances (Thom et al., 2013).

5.2 Effects of management and climate change on forest ecosystem services

To assess the performance of the four strategies regarding ecosystem service provisioning, four ecosystem services were chosen which are of particular importance in the studied landscape, and will most likely be relevant also in the future (timber production and site protection), or are of interest specifically in the context of tackling challenges of global concern (climate regulation, biodiversity). However, this is by no means an exhaustive list of ecosystem services which are (and could be) provided by the landscape. Another potential service of interest in the region that has not been assessed here is, for example, recreation. Nonetheless, the indicators studied here cover the most relevant services for local managers. A similar selection of services has also been used in recent studies investigating forest ecosystem provisioning under climate change and forest management alternatives (e.g. Mina et al., 2016; Rasche et al., 2013; Schuler et al., 2016; Zlatanov et al., 2015). For each of the services, two indicators were chosen to provide a more robust assesment regarding the development of its provisioning. Both indicators for any given service followed the same trend in most cases and no major divergences were identified. Studying services provisioning with different indicators allowed further insights, which will be discussed in depth in the following paragraphs.

For timber production, both indicators showed a considerable influence of forest management and climate change on the provisioning of timber. Under baseline climate, the strategies which had the highest share of Norway spruce (AFF and especially PIAB) clearly showed the best performance for both indicators. In absolute terms, they also remained the highest performing strategies regarding growing stock also under climate change, even though there was a clear decrease in performance due to disturbances. FSUA and PNV showed an improved performance under climate change. The increase is in line with an increase in productivity under climate change due to reduced temperature limitations and increased atmospheric CO_2, which has been widely reported for forest ecosystems (Boisvenue and Running, 2006). At the first time point (year 50) this positive effect was noticeable for all strategies. In the case of PIAB and AFF however, it could not compensate the increasing impact of disturbances. Similarly, regular harvest was more climate-sensitive in PIAB and AFF due to the stronger disturbance impact. In this case, FSUA and PNV even became the best-performing strategy under climate change in absolute terms.

Additionally, it should be noted that potential site-degrading effects caused by high shares of spruce and their impact on productivity are not considered in the model applied here. Pure spruce stands have been shown to cause acidification of the soil due to a slower composition of leaf litter than in mixed stands (Berger, 2001). This effect has been named by local stakeholders as a reason to pure spruce stands and could reduce the productivity in the PIAB and AFF strategies below what is reported here.

Overall, timber production was negatively impacted by climate change. Management strategies with a higher tree species diversity and shorter rotation periods were less negatively impacted by climate change, which is in line with previous findings from Rasche et al. (2013) and Irauschek et al. (2015). Mina et al. (2016) and Pardos et al. (2016), on the other hand, found no clear impact of climate change on timber production, but did not consider biotic and abiotic disturbances in their analyses. A review by Thom and Seidl (2016) compiling 25 observations of disturbance impacts on timber production reports mostly negative disturbance effects on this ecosystem service.

The two indicators for climate regulation, carbon storage and Net Ecosystem Production, showed a more differentiated picture than the indicators for timber production. Carbon storage had largely similar trends to standing timber volume, with PIAB and AFF storing the highest levels of carbon under both baseline conditions and climate change. NEP, on the other hand, was highest under PNV and FSUA, which also remained the best performing strategies under climate change, despite a strongly reduced NEP in selected periods. Carbon storage under PNV and FSUA was more stable than under PIAB and AFF, while the opposite was the case for Net Ecosystem Productivity. The increased stability in C uptake under PIAB and AFF despite an increase in disturbance susceptibility can be attributed to the increased abundance of younger forests on the landscape. Stand-replacing disturbances lead to an unintended reduction in the rotation period, resulting in younger forests which generally have a higher rate of carbon uptake (Hudiburg et al., 2009; Williams et al., 2014). Overall, a reduction of climate regulation services is evident under climate change, regardless of management strategies. Irauschek et al. (2015) also found a negative impact on carbon storage for a forest landscape in western Austria under climate change, while Zlatanov et al. (2015) report more differentiated impacts with both negative and positive developments of carbon storage under climate change, depending on the management alternatives applied. The impacts of climate change on forest NEP have not been investigated in depth so far. However, drawing on data from experimental sites in different ecosystem types, Shaver et al. (2000) found a decrease in NEP under climate change, as heterotrophic respiration increased more strongly than NPP. In a simulation study investigating the climate effects on the functioning of terrestrial ecosystems using different vegetation models, Cramer et al. (2001) found negative impacts of climate change on NEP. However, this effect was mostly driven by changes in the vegetation dynamics of tropical ecosystems and the study did not investigate disturbance effects. Kobler et al., (2015) compared sites disturbed by wind and clear-felling to undisturbed forest (on experimental sites close to the study area of this thesis) finding a clear reduction of NEP after disturbance. One point that warrants discussing in the context of climate mitigation is the negative impact of climate change on the soil carbon pool in the simulations. While soil carbon increased under baseline climate, climate change strongly dampened this increase. Frank et al. (2015) suggest strong impacts of climatic extremes on soils, both through erosion processes and through impacts on microbial activity. For example, in soil-warming experiments on forest sites in western Austria, Schindlbacher et al. (2012) found an increased release of carbon through soil respiration in warmer soils, especially when soil moisture content was not lowered. Impacts of climate change on soils, both direct and indirect, and the feedback between vegetation and soil therefore require more attention when considering the climate regulation function of forests.

In the context of site protection only one of the investigated indicators, Leaf Area Index, showed a noticeable reaction to forest management. Here, PIAB performed best under baseline conditions, but suffered a reduction under climate change, while all the other strategies increased their LAI under climate change.

The water runoff indicator was influenced only marginally by the different management strategies investigated. Strategies with a higher conifer share had slightly lower runoff, which is consistent with previous research showing that broadleaved forests generally have higher runoff than coniferous forests (Komatsu et al., 2011). As precipitation is very high in the area and considerably exceeds potential evapotranspiration, runoff is high as well, regardless of management strategy. Under climate change, runoff increased slightly for all strategies, which was partially related to an increase in precipitation in some of the climate change scenarios. Another factor contributing to this increase was increased disturbances, resulting in reduced evapotranspiration. A major shortcoming here is that there is no distinction between groundwater outflow and surface runoff within the iLand water cycle module. A comparison of surface runoff would most likely yield clearer differences between managements, and would be of higher relevance in the context of erosion protection. Overall, based on the two indicators assessed here, the provisioning of site protection is stable under climate change, with a slight overall increase under FSUA, PNV and AFF. Interestingly, while the indicators used where different, Irauschek et al. (2015) also found the protection service (against avalanches and landslides) to be indifferent to climate change. Zlatanov et al. (2015) and Mina et al. (2016), on the other hand, both found decreasing service for landslide and rock fall protection under climate change. Elkin et al. (2013) reported both increases and decreases in rock fall protection for two Swiss landscapes, depending on elevation.

In terms of biodiversity, both indicators agreed with regard to the effects of forest management and climate change. The tree species rich management strategies FSUA and PNV not only performed best for the indicator tree species diversity, but also improved the diversity of forest-dwelling species. An interesting development was observed for tree species diversity under climate change, where PIAB showed a clear increase, while a slight decline was recorded for all other strategies. This is mainly due to an increasing dominance of beech in the latter strategies, lowering the Shannon exponent indicator value. In this simulation study, the influence of browsing by ungulates (mainly red deer and roe deer) was not included. Browsing pressure can have a strong influence on tree specis composition, favouring especially spruce and resulting in reduced tree species diversity (Clasen and Knoke, 2009; Kittredge et al., 1995).

Forest-dwelling species diversity clearly increased under climate change, especially for the strategies which were initially less diverse. On the one hand this is a response to ensuing tree species changes in these management strategies. On the other hand it also clearly demonstrates the positive impact of disturbances on biodiversity, which is consistent with the analyses by Thom et al. (2016a) and Thom and Seidl (2016).

Overall, the impact of climate change on biodiversity found here is in line with other studies such as Irauschek et al. (2015) and Mina et al. (2016), who reported generally positive impacts of climate change on forest biodiversity.

5.3. Implications for forest management

No clear "best practice" management could be identified, i.e., no single strategy performed best regarding all ecosystem services investigated. Ecosystem service indicators responded very differently to alternative management strategies, resulting in a complex picture of ecosystem services provisioning even under baseline climate.

Notably, the strategy based on the current management of the Austrian Federal Forests (AFF) showed a balanced performance across ecosystem services under baseline climate. However, it suffered a noticeable decrease in performance under climate change in several indicators, suggesting only moderate robustness to changing future conditions. The age structure of the forest as well as its species composition were important influences in determining the landscapes sensitivity to changing climate and disturbance regimes. This suggests that a diversification of forest management in terms of species and structures can help to avoid risks and increase the robustness of ecosystem services provisioning. Shortening rotation periods to reduce risks has also been proposed in previous studies on climate change adaptation (for example by Seidl et al. (2011b)), and is beneficial also in the case investigated here.

Finally, it is important to note that the best management will always depend on the values and preferences for each service by managers, forest owners, and local stakeholders. Here, all services have been evaluated assuming equal importance. However, in reality some services might be considerably more important to managers and owners than others, which needs to be considered in the design of locally adapted management plans. Also, there is a trade-off between a high absolute performance and stability over time for some services, such as timber production. In this case, risk-averse managers might prefer a lower overall performance coupled with a more predictable provisioning of services over time, while risk-taking managers might opt for a management alternative which delivers an overall higher performance even though it might, for example, be much more affected by disturbance (c.f. Blennow and Sallnäs, 2002; Seidl et al., 2016a).

5.4. Outlook and further research needs

Here, all ecosystem services have been assessed individually. An important next step will be to analyse the services in relation to each other, identifying potential trade-offs between services (see also Mina et al., 2016) and how these trade-offs are affected by climate change. This could be done, for instance, by applying the framework proposed by Bradford and D'Amato (2012).

While management strategies have here only been compared in relation to each other, it could additionally be interesting to establish absolute minimum thresholds of service provisioning which must not be crossed, in order to more strongly reflect the local demands for services. From the current assessment – focusing purely on the supply side and ignoring demands – it remains unclear whether all strategies would in fact be able to satisfy such minimum levels of provisioning.

Over the course of the project, a dialogue with stakeholders was established and their feedback on the results was collected in a final workshop. One interesting point raised by the stakeholders was the possibility of a spatially explicit analysis of the provisioning of ecosystem services and specifically the expected impacts of climate change. Such an analysis could help managers to identify areas at risk, where management would need to actively counteract negative trends, as well as highlight areas with high robustness, which would allow increased degrees of freedom in management also under climate change.

6 Conclusions

The objective of this thesis was to investigate the effects of forest management and climate change on the provisioning of a selected set of ecosystem services by simulating different management strategies and climate scenarios using a process-based forest landscape model. The design and implementation of the management strategies was successfully able to produce realistic trajectories of four management strategies with different age structures and tree species compositions.

Four ecosystem services were analysed by assessing two indicators per service. Both absolute performance under baseline conditions and stability (relative change) of the performance under climate change was assessed over a period of 200 years. With one exception, all indicators showed a distinct response to alternative strategies of forest management and climate change. Under baseline climate, strategies with a higher conifer share (PIAB and AFF) showed the best performance for timber production, while strategies with a higher share of broadleaved trees performed especially well regarding biodiversity. Results were more balanced for protection and climate regulation. Under climate change, there was a general reduction in timber production and carbon storage, while site protection remained stable and biodiversity increased.

The main factors influencing differences in services provisioning were the species composition and the length of the rotation period. Strategies with a higher share of broadleaves and a shorter rotation period resulted in a more stable provisioning of ecosystem services. Conifer-oriented strategies with longer rotation periods were affected more strongly by disturbances, and therefore performed less stable. In general, there was a considerable impact of disturbance on ecosystem service provisioning.

In practice, a suitable management alternative would have to be chosen according to the importance assigned to each ecosystem service and according to whether the manager would want to increase absolute performance or avoid instability. This thesis presents quantitative information which allows for assessing the impacts of changing climate and disturbance regimes and will help to design management alternatives which make forest ecosystem service provisioning more robust to these changes.

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Appendix

I Examples for Management Implementation in ABE

In the following, Java Script Code examples are given, detailing the setup of one single Stand Treatment Program and the associated activities for the AFF management strategy in order to give an idea of the information that is necessary to implement management within the model. More detailed information can be found on the model webpage (iland.boku.ac.at.at)

1) Defining the activities:

Planting

An activity of the type "planting" is set up and defined to take place in year 1 of a rotation period. The species shares for the saplings to be planted are defined using either fractions or patches of fixed sized and shape. In this case, a fixed share is used for spruce and beech and rectangular patches of a size of 10x10 pixels (200 m²) for larch. As 10 % of a hectar are equal to 5 patches, 15 patches make up the 30 % share planned for larch. Saplings are all uniformly planted with a height of 0.5 m.

```
var a_planting = { type: "planting",
      schedule: 1,
      items: [ { species: "piab",  fraction: 0.3,  height: 0.5},
              { species: "lade", pattern: "rect10", random: true,
                n: 15, h:0.5},
              { species: "fasy", fraction: 0.4,  height: 0.5}] };
```

Tending and Thinning

To define tendings (during the thicket stage) and thinnings, the activity "thinning" is used, always with the "custom" setting which allows for a detailed definition of the thinning. For the tendings, an optimal time of ten years after the establishment of the stand is specified with a timeframe from five to fifteen years after establishment. Within this time frame, the scheduler chooses the optimal time for the execution of the activity, 30 % removal of stems across all DBH-classes ("targetVariable" and "targetValue") are removed. Note that the function “calculatespeciesprobabilities” (code not shown) checks the current species composition of the stand, compares it to the target composition as defined in the Stand Treatment Program (see below) and accordingly calculates a probability for trees to be removed in order to adjust the species composition of the stand towards the target.

```
var a_tending = { type: 'thinning',
      schedule: { min: 5, opt: 10, max: 15, absolute: false },
      thinning: 'custom',
      onEvaluate: function(){ var t=
            calculateSpeciesProbabilities(stp.options.plan,
            this.targetValue, 5);
      targetValue: 30, targetVariable: 'stems', targetRelative: true,
                        classes: [100] };
```

For this stand treatment, two thinnings are defined. For the first one, an optimal time of 40 years after stand establishment (with a time frame from 30 to 50 years after establishment) is defined, with an additional constraint, which only allows the thinning to take place after the stand has reached a top height of at least 12 m in this example. The minimum DBH for trees to be harvested is 10 cm, and 30 % of the basal area are removed during the treatment. Five relative DBH classes are automatically generated based on the DBH distribution in the stand and the removal of stems is spread across classes with, in this case, most of the removal happening in the middle classes.
For the second thinning, the scheduling is set to an optimal execution time of the activity at 60 (50-70) years, and the minimum top height is set to 21 meters. Otherwise, the same settings as for the first thinning were used.

```
var a_thinning1 = { type: 'thinning',
      schedule: { min: 30, opt: 40, max: 50, absolute: false },
      constraint: ["stand.topHeight>12"],
      thinning: 'custom',
      onEvaluate: function(){ var t=
            calculateSpeciesProbabilities(stp.options.plan,
            this.targetValue, 5);
      targetValue: 30, targetVariable: 'volume', targetRelative:
            true,
      minDbh: 10,classes: [10, 30, 25, 30, 5] };
```

```
var a_thinning2 = { type: 'thinning',
      schedule: { min: 50, opt: 60, max: 70, absolute: false },
      constraint: ["stand.topHeight>21"],
      thinning: 'custom',
      onEvaluate: function(){ var t=
      calculateSpeciesProbabilities(stp.options.plan,
            this.targetValue, 5);
      targetValue: 30, targetVariable: 'volume',
            targetRelative: true,
      minDbh: 10, classes: [10, 30, 25, 30, 5]};
```

Final Harvest

For the final harvests, activities of the type “scheduled” where used which is the most customizable type of activity.

The final harvest was executed in two steps, with an initial cut scheduled after 90 % of the full rotation time has passed. 10 % of trees are removed and then a ten year “sleep is called for the stand which means that the final harvest can only be executed ten years later at the earliest. The final cut is then executed at the defined harvest time (end of the rotation period). If the harvest is not executed at the maximal harvest age (1.15 times the rotation period), the harvest is executed regardless of other constraints (“force: true”). Only trees with a DBH higher than 5 cm are harvested.

```
var a_regcut = { type: "scheduled",
      schedule: { minRel: 0.80, optRel: 0.90, maxRel: 1.00, force:
            true },
      onEvaluate: function(){
      trees.loadAll();
      trees.harvest("rnd(0,1)<0.1");
      return true; },
      onExecute: function() { trees.removeMarkedTrees();
      fmengine.log("calling sleep");
      stand.sleep(10);}};
```

```
var a_clearcut =  { type: "scheduled",
      schedule: { minRel: 0.90, optRel: 1, maxRel: 1.15, force: true
            },
      onEvaluate: function(){trees.loadAll();
      if (stp.options.dbh!=undefined) {
      trees.harvest("dbh>" + stp.options.dbh );
      fmengine.log("clearcut: using threshold: " + stp.options.dbh);}
      else {
      trees.harvest("dbh>5"); }
      return true; },
      onExecute: function() {
      trees.removeMarkedTrees();  },
      onCreate: function() { activity.finalHarvest=true; },
      onSetup: function() {  }};
```

Salvaging

For salvage harvests, an activity of the type “salvage” is defined. If a tree with a DBH bigger than 15 cm is killed, it is eligible for salvage harvesting. These trees are then harvested. If more than 50 m^3 of wood are killed on a hectare, the stand is evaluated regarding whether or not it should be split into new according to level of disturbance. If more than 25 % of the stand (default, other values could be defined) are gaps, new stands are created with a size of at least 0.25 ha (default). If more than 95 % (default) of the stand are gaps, the stand is completely cleared and a new rotation period started. The salvage activity can also create trap trees. If the stand is infested and there is more than one bark beetle generation, 10 % of spruce trees are used as trap trees here.

```
var a_salvager = { type: 'salvage',  schedule: { repeat: true },
      disturbanceCondition: "dbh>15",
      onExecute: function() {
            trees.loadAll();
            trees.harvest("dbh>15"); },
      debugSplit: false,
      thresholdIgnoreDamage: 50,
     onBarkBeetleAttack: function(generations, infested) {
             if (infested>1 && generations>1) {
             if (stand.flag("bbYear") !== undefined ||
            stand.flag("bbYear") < Globals.year) {
            return false;}
            if (Globals.setting('user.salvage.trap')>0) {
      stand.setFlag("bbYear", Globals.year);
                  trees.load("species=piab and dbh>15");
      trees.kill("rnd(0,1)<" + Globals.setting('user.salvage.trap'));
            }
      return true; }
      return false; } }
```

2) Defining a Stand Treatment Program

This step combines selected pre-defined activities into one Stand Treatment Program with the function “addManagement”. “U” defines the length of the rotation period, in this case giving a lowest possible, an ideal and a highest possible length of the rotation period. Within the activities previously defined, the ideal length is used to schedule activities at, for example 0.9 times the planned harvest time. Then, the activities to be used in this Stand Treatment Programme are defined by using the activities which have previously been defined. “Options” provides the possibility define additional, STP-specific options and in this case is used to define the planned species composition for the stands under this STP. The values defined here are then used in the thinning activity to calculate the species removal probability.

```
fmengine.addManagement({ U: [120, 140, 160],
      planting: a_planting,
      thinning1: a_tending,
      thinning2: a_thinning3,
      regcut: a_regcut,
      clearcut: a_clearcut,
      salvage: a_salvager,
      options: {plan: {piab: 0.3, fasy: 0.5, lade: 0.2}  }} ,
            'stp03');
```

3) Defining an Agent

When creating an agent, a scheduler can be created which handles the scheduling of harvests over the whole planning unit if it is enabled. For this, a minimum and maximum amount for the scheduled harvests “minScheduleHarvest”, “maxScheduleHarvest”, defined in m³ per hectare per year for the management unit (in this case the whole landscape). The scheduler calculates the differences between the planned and the realized harvests and tries to correct for the deviations in the following years. “ScheduleRebounceDuration” defines for how long the deviations incorporated into the calculation of planned harvests for the following years, in this case 5 years. “deviationDecayRate” is a reduction rate for the deviations, e.g. each year, older deviations are discounted by this year. The scheduler also defines if the sustainable harvest option should be used (e.g. “useSustainableHarvest:1) or just a bottom-up scheduling approach. “maxHarvestLevel” indicates how much more than the amount calculated as sustainable harvest can be harvested. “harvestIntensity” can be used to simulate harvests above or below sustainable harvest and “maxHarvestLevel” defines how much more than the sustainable harvest can be harvested in one year (if for example many older stands are ready to be harvested).

Then, the Stand Treatment Programmes which the agent has as its disposal is defined and a default STP for stands where no STP is defined is assigned.

An agent with this scheduler is then added. It is possible to define agent types (for example types representing a forestry enterprise or a small private owner) and individual agents belonging to one of the agent types can be defined. In this case, only one agent (“bau”) of one agent type (“bautype”) was created, using the pre-defined agent types.

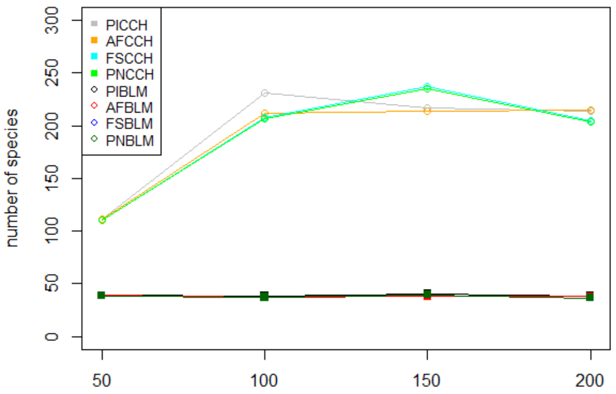
```
var base_agent = {
	scheduler: { enabled: true,
	minScheduleHarvest: 1,
	maxScheduleHarvest: 20,
	scheduleRebounceDuration: 5,
	maxHarvestLevel: 1.5,
	deviationDecayRate: 0.1,
	useSustainableHarvest: 1,
	harvestIntensity: 1},

	stp: {  'stp01': 'stp01', 'stp02': 'stp02', 'stp03': 'stp03',
		'stp04': 'stp04', 'stp05': 'stp05','stp06':
		'stp06','stp07': 'stp07','stp08': 'stp08',
		'default': 'stp01'    },
	newAgent: function() { var x= {  scheduler: this.scheduler,
	agent_updated: false };  return x; },
	run: function() { console.log('base-agent run called'); }}

fmengine.addAgentType(base_agent, 'bautype');

fmengine.addAgent('bautype', 'bau');
```

II Species Groups used for the forest-dwelling species indicator of biodiversity

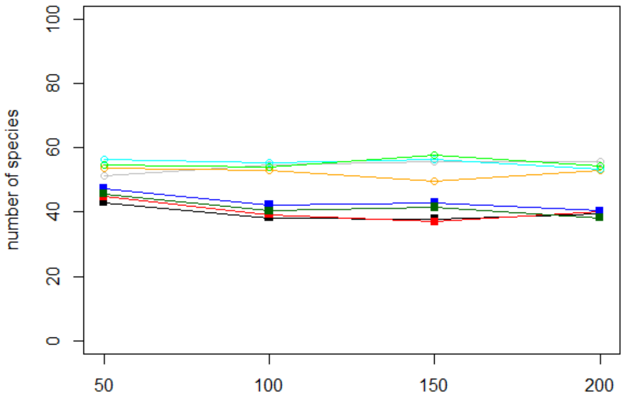
Plots show a comparison of managements under baseline conditions (BLM) and under a combination of the three climate change scenarios and the more extreme disturbance scenario (CCH). Absolute number of species within each group at the four time step (simulation years 50, 100, 150, 200) are shown.

PI=PIAB, AF=AFF, FS=FSUA, PN=PNV

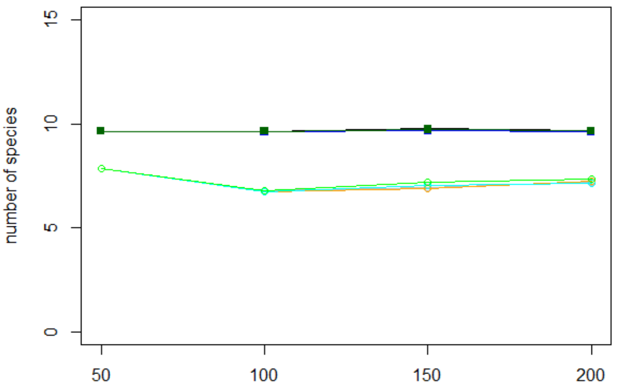
Hymenoptera



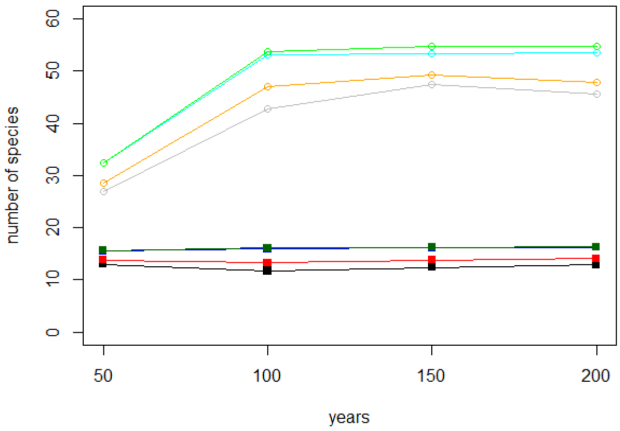
Hemiptera



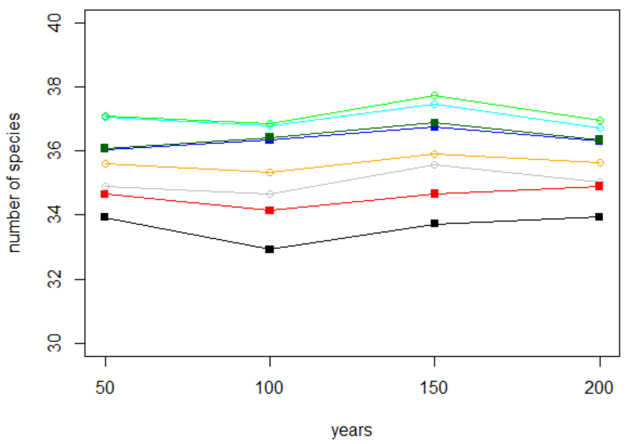
Aranae



Mollusca



Ground Vegetation



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