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Projektübersicht

1 Kurzfassung

Der globale Wandel stellt zunehmend eine Herausforderung für Ökosysteme sowie deren Bewirtschafter dar. Um dieser Herausforderung zu begegnen zeigt sich zunehmend, dass eine integrierte Sicht auf ökologische und soziale Systeme (Ansatz der gekoppelten Mensch-Umwelt-Systeme, „coupled human and natural systems approach“, CHANS) notwendig ist. Das theoretische Verständnis derartiger Systeme ist in den letzten Jahren stark gestiegen. Die operationale Umsetzung des CHANS Ansatzes hinkt jedoch noch hinter den theoretischen Entwicklungen hinterher, nicht zuletzt aufgrund von fehlenden Werkzeugen für eine integrierte Abschätzung der Entwicklung von CHANS unter sich wandelnden Umweltbedingungen. Weitere Unsicherheiten in der Interaktion zwischen Mensch und Umwelt im globalen Wandel liegt in der bisher noch schlecht quantitativ beschriebenen adaptiven Kapazität von ÖkosystemmanagerInnen. Werden jedoch diese Aspekte in Analysen zur Auswirkung des Klimawandels vernachlässigt, kann dies entweder zu einer Überschätzung von Klimafolgen führen (z.B. wenn die soziale Anpassungsfähigkeit des Systems ignoriert wird), oder aber auch fälschlich Stabilität suggerieren (z.B. wenn dynamische und zum Teil abrupte ökosystemare Änderungen in sozialen Modellen nicht berücksichtigt werden).

Um die Robustheit von zukünftigen Klimafolgenabschätzungen im Wald zu erhöhen, waren die Ziele dieses Projekts
(i) wichtige Interaktionen zwischen Mensch und Umwelt zu operationalisieren, indem ein agenten-basiertes Modell der Waldbewirtschaftung entwickelt wurde, welches in ein bestehendes dynamisches Waldlandschaftsmodell integriert wurde,
(ii) die Anpassungskapazität von WaldbewirtschafterInnen in Österreich durch eine Umfrage unter aktuellen und zukünftigen ManagerInnen besser zu beschreiben und
(iii) zu untersuchen, wie alternative Bewirtschaftungsentscheidungen und Einstellungen zur Anpassung der Bewirtschaftung zukünftige Trajektorien in Waldlandschaften beeinflussen.

Das Hauptergebnis des Projektes besteht in dem neu entwickelten Modell ABE (Agent-Based model of forEst management), welches ManagerInnen als individuelle Agenten abbildet, welche autonom und räumlich explizit in einem multi-skaligen Entscheidungsraum Bewirtschaftungsentscheidungen treffen. Dieses neue Modell wurde dynamisch in das Waldlandschaftsmodell iLand (the individual-based forest landscape and disturbance model) integriert, wodurch dynamische Interaktionen zwischen Änderungen im Ökosystem und der Bewirtschaftung simuliert werden können. Diese Modellkombination war in Tests autonom in der Lage, Waldlandschaften unter gängigen Bewirtschaftungsverfahren realistisch über lange Zeiträume zu simulieren. Weiters zeigten Tests gegen unabhängige Daten aus Durchforstungsversuchen, dass das Modell die ökosystemare Reaktion auf eine weite Bandbreite an Bewirtschaftungseingriffen realistisch abzubilden vermag.

Eine wichtige Basis für die Parameterisierung des Modells ABE war eine eingehende Untersuchung der Einstellungen und Absichten von WaldbewirtschafterInnen in Bezug auf Klimawandelanpassung. Unsere Untersuchungen zeigten das WaldbewirtschafterInnen in Österreich stark an den Klimawandel glauben (94.7% der Befragten), wobei sich kein signifikanter Unterschied zwischen aktuellen BewirtschafterInnen und zukünftigen ManagerInnen (i.e., StudentInnen der Forstwissenschaften) feststellen ließ. Basierend auf den beabsichtigten Reaktionen auf mögliche zukünftige Änderungen in Wäldern konnten folgende vier Gruppen unterschieden werden: Sehr sensitive, anpassungsfreudige BewirtschafterInnen (27.7%), jene ManagerInnen, welche sich vor allem an Änderungen in Waldwachstum und –verjüngung anpassen (46.7%), BewirtschafterInnen welche ausschließlich sensitiv auf geänderte Verjüngungsdynamik reagieren (11.2%), sowie ManagerInnen welche nicht vorhaben, sich an klimabedingte Änderungen im Wald anzupassen (14.4%). Wichtige Einflussfaktoren auf diese unterschiedlichen Einstellungen zur Anpassung waren vor allem persönliche Erfahrungen sowie Erwartungen in Bezug auf zunehmende Waldschäden durch Störungen, wobei auch demographische Faktoren sowie individuelle Bewirtschaftungsziele von Bedeutung waren.

Simulationsexperimente mit unterschiedlichen Anpassungsszenarien zeigten, dass passives Verhalten (i.e., das Reagieren auf bereits manifestierte Klimafolgen) nicht ausreicht, um die Entwicklung von Waldökosystemen im Klimawandel zu stabilisieren. Nur durch die Kombination von passivem und aktivem (i.e., vorausschauendem) Anpassungsverhalten der BewirtschafterInnen konnten in der Simulation die im Vergleich zur Walddynamik sehr rasch ablaufenden klimatischen Änderungen entsprechend abgefedert werden. Für Landschaften mit vielen ManagerInnen zeigte sich in der Simulation, dass die Heterogenität in den Anpassungsentscheidungen zwar die Anpassung des Systems verzögert, aber auch die landschaftliche Diversität des Ökosystems erhöht, was sich wiederum positiv auf die zeitliche Stabilität des Systems auswirkt. Abrupt und uniform implementierte Anpassungsmaßnahmen beschleunigen zwar den Anpassungsprozess, können jedoch auch zu ungewollten strukturellen Effekten (wie z.B. einer unausgeglichenen Altersklassenverteilung) führen. Diese Simulationsergebnisse suggerieren, dass die Vielzahl an Bewirtschaftungsentscheidungen, wie sie für eine kleinteilige Besitzstruktur typisch sind, nicht notwendigerweise nur negative für die Klimaanpassung von Waldlandschaften sein muss.

Auf der Bestandesebene konnte durch eine simulationsgestützte Reanalyse von Durchforstungsversuchen in Österreich gezeigt werden, dass verstärkte Durchforstungen vor allem auf warmen und trockenen Standorten negative Klimaauswirkungen auf die Baumart Fichte abmindern können. Auf Standorte wo diese Baumart vom Klimawandel profitiert (z.B. in höheren Lagen) konnte jedoch kein zusätzlicher, über den unter aktuellen Bedingungen hinausgehender Durchforstungseffekt nachgewiesen werden. Diese Analysen unterstreichen das Durchforstungen ein wichtiges Werkzeug im waldbaulichen Portfolio der Klimaanpassung sein können. Sie zeigen aber auch, dass Durchforstungen kein Allheilmittel darstellen und Durchforstungsentscheidungen – so wie alle anderen Anpassungsmaßnahmen auch – im speziellen Kontext des jeweiligen Standorts und Bestandes beurteilt werden müssen.

Zusammenfassend kann festgehalten werden, dass im Projekt MOCCA ein neuer, agenten-basierter Ansatz zur dynamischen Simulation von Waldbewirtschaftung entwickelt und getestet wurde, welcher in Zukunft eine verbesserte Analyse von Wald als CHANS erlaubt. Diese Entwicklungsarbeit wird in zukünftigen Klimafolgenstudien eine robustere Abschätzung der Klimavulnerabilität von Österreichs Wald fördern. Basierend auf den hier durchgeführten initialen Szenarioanalysen sollte in zukünftigen Arbeiten vor allem auf die Bewirtschaftungsheterogenität in durch Kleinwaldbesitz geprägten Landschaften weiter eingegangen werden, um besser zu verstehen unter welchen Bedingungen diese Heterogeneität die Resilienz gegen Klimawandel erhöht bzw. reduziert.

2 Executive Summary

Global change poses increasing challenges for ecosystems and their managers. To address these challenges it is increasingly clear that a coupled human and natural systems (CHANS) perspective is needed. And while the science of CHANS has advanced greatly in recent years, its mainstreaming into operational ecosystem management has proven to be difficult. One aspect complicating the application of the CHANS approach has been the lack of tools that are simultaneously able to accommodate the complexities of ecological and social systems. A further issue is the still limited understanding of the adaptive capacity of ecosystem managers. However, neglecting these aspects could lead to either an overestimation of the CHANS′ vulnerability to global change (e.g., where the social adaptive capacity is disregarded in assessments based solely on ecosystem models), or to the pretense of stability (e.g., where the dynamic responses of ecosystem processes to environmental changes are neglected in models of the social system).

In order to improve the robustness of assessments of future forest CHANS trajectories, our objectives here were
(i) to operationalize the coupling of human and natural systems in the context of landscape-scale forest ecosystem management by developing an agent-based model of forest management and implementing it in a dynamic forest landscape modeling framework,
(ii) to better describe and quantify social adaptive capacity of forest managers in Austria via conducting a questionnaire study among current and future forest managers (i.e., active managers and forestry students), and
(iii) to investigate the effect of how alternative management decisions and attitudes towards adaptation influence forest ecosystem trajectories under climate change.

The main result and outcome of the project is the model ABE (Agent-Based model of forEst management), which is an agent-based model featuring a spatially explicit multi-scale decision making framework, fully interacting with the forest landscape model iLand (the individual-based forest landscape and disturbance model). We showed that the newly developed model is autonomously able to reproduce meaningful trajectories of ecological and social indicators over the extended period of multiple centuries. We furthermore tested the model against independent data from thinning trials and showed that the ecosystems response to a wide range of management decisions is well captured in the simulation.

Forming the baseline for parameterizing the model was an investigation of the attitudes and intentions for adaptation among forest managers. Forest managers in Austria were found to strongly belief in climate change (94.7% of respondents), and no significant difference was found between current and future managers (i.e., active managers and forestry students). Based on intended responses to climate-induced ecosystem changes we distinguished four groups of managers: highly sensitive managers (27.7%), those mainly sensitive to changes in growth and regeneration processes (46.7%), managers primarily sensitive to regeneration changes (11.2%), and insensitive managers not responding to climate-induced changes in the forest (14.4%). Experiences and beliefs with regard to disturbance-related tree mortality were found to particularly influence a manager’s sensitivity to climate change. In addition, also demographic factors (age, education) as well as individual management goals influenced a manager’s sensitivity to climate-induced changes in the forest.

In experimenting with different decision attitudes of managing agents in the newly developed simulation framework we found that both passive (reactive) and active (prospective) adaptive behavior is necessary to successfully stabilize system trajectories under environmental changes that progress at a high rate (relative to the long time horizons of forest dynamics). Furthermore, investigating multi-agent landscapes we found that diversity in managerial responses to environmental changes resulted in slower adaptation of crucial variables, but also increased the variation on the landscape. This heterogeneity in turn contributed to increasing the temporal

stability of landscape trajectories over time. Uniform and abrupt implementation of a management regime sped up the adaptation process, but also created long-term structural legacies that might also be problematic in the context of future management (e.g., a highly unbalanced age class distribution). This finding suggests that variation in management responses on the landscape, as typically found in multi-ownership landscapes, is not necessarily a bad thing for climate change adaptation, as it creates heterogeneity on the landscape which in turn fosters resilience.

At the stand-level, re-analyzing three Norway spruce thinning trials across Austria under climate change using the newly developed forest management model showed that at warm and dry sites increasing thinning intensity and/ or frequency can reduce growth losses from climate change. Yet, at sites benefiting from a warmer climate (e.g., at higher elevations) thinnings were not found to further improve the performance of forests under climate change beyond the thinning effect also observed under current climate. This underlines that thinnings are an important tool in the adaptation portfolio of forest managers. However, it also highlights that no "one-size-fits-all" adaptation solutions exists in forest management, and that adaptation measures need to be considered in the context of specific site and stand conditions.

In conclusion, we have developed and tested an agent-based model of forest ecosystem management and integrated it into the forest landscape model iLand. This new tool, which is flexible in its design and has been tested with regard to a variety of system behaviors in this study, can improve future assessments of forest ecosystems under climate change. The project MOCCA has thus delivered an important methodological advance for future climate impact research in Austria and beyond. Based on our initial analyses, future research could use this tool to further investigate the effects of managerial heterogeneity in multi-ownership forest landscapes, in order to determine under which conditions social response diversity fosters resilience, and under which conditions resilience is reduced due to delayed transitions to adapted conditions.

3 Background and objectives

Ecosystems around the globe are increasingly under pressure from environmental changes, a loss of biological diversity, and rising societal demands on ecosystem services (Rockström et al., 2009). Climate change is expected to profoundly alter the composition, structure, and functioning of ecosystems, e.g., through a facilitation of disturbance events such as wildfires and bark beetle outbreaks (Seidl et al., 2014). Furthermore, changes in the global nitrogen cycle and the eutrophication resulting from excessive nitrogen input into ecosystems are increasingly threatening freshwater systems (Gruber and Galloway, 2008). Changes in climate alongside with land-use changes contribute to the ongoing loss of biological diversity (Butchart et al., 2010), and threaten to lead to drastic (and possibly irreversible) impacts on the earth system.

To address these emerging challenges in the stewardship of our planet in general and in the management of ecosystems in particular the concept of resilience has been proposed recently (Biggs et al., 2012). In this context, resilience has been defined as the capacity of a system to retain desired structures, processes, and functions in the face of disturbance and change (Folke, 2006; Liu et al., 2007). While the conceptual idea of resilience has been proposed already some decades ago (Holling, 1973) a key finding of more recent research was that an integrated consideration of social and ecological systems is required to understand and successfully address the complexities of global change and biodiversity loss in the stewardship of ecosystems (Liu et al., 2007). And while considerable advances have been made in recent years in developing a sound conceptual framework for such a coupled human and natural systems (CHANS) science (Biggs et al., 2012; Chapin et al., 2010), it's mainstreaming into specific aspects of ecosystem management has proven to be challenging (Spies et al., 2014).

Challenges are particularly profound in the context of forest ecosystems, where the effects of human interactions with the ecosystem prevail for decades to centuries, and a temporal decoupling between management decisions and their implications on a rapidly changing society can frequently be observed. One factor that is currently restricting a wider application of a CHANS perspective in forest ecosystem management is the lack of appropriate tools for addressing the dynamic interactions between social and ecological systems over extended time horizons. A variety of models for simulating and projecting the dynamics of forest ecosystems have been presented and are being used to study the ecological responses to global change (Evans, 2012; Mäkelä et al., 2000). And while these models incorporate an increasing level of ecological process understanding, they frequently are limited in addressing the interactions of ecosystems with humans. This limitation arises inter alia from a scale mismatch between the typically considered entity in forest models (i.e., trees to stands) and the scale at which stewardship decisions are made and resilience can be assessed (i.e., the watershed, landscape, and beyond) (Seidl et al., 2013). Theory suggests that scales both above and below the focal scale need to be considered in order to assess and manage for resilience (Walker et al., 2004), yet most tools currently available are not able to accommodate such a multi-scale perspective. Furthermore, the overwhelming majority of forest models approximate human interaction with the biosphere in the form of static, pre-defined interventions. These can be prescriptions (i.e., which management action to implement where and when (Rasche et al., 2011)), or they can include a priori defined if-then rules to study alternative management scenarios (Seidl et al., 2011a). Most of these approaches do, however, fall short in embracing the complex and dynamic responses of managers to a changing environment.

This latter aspect is the domain of agent-based models (ABMs), i.e., a class of models that explicitly accounts for the fact that managerial decisions are an emerging property of the intentions, beliefs, and interactions between agents and their environment (Gilbert, 2008). ABMs have been applied widely in a variety of fields, e.g. in land use change modeling (Kelley and Evans, 2011), policy analysis (Smajgl and Bohensky, 2013), and value chain assessments (Schwab et al., 2009). Examples in the context of forest management include analyses on the influence of information flow between land managers (Satake et al., 2007) and the impact of socio-ecological change on harvesting patterns (Leahy et al., 2013). While ABMs are a powerful means to capture the social dynamics of resource management decisions, they are often limited with regard to the representation of ecological processes. Frequently, the ecosystem trajectories underlying the simulated management decisions of agents assume static or unlimited resource supply, or are derived from empirical models (Bone and Dragićević, 2009; Kostadinov et al., 2013), rather than being based in ecological process understanding. Other ABM approaches have relied on detailed process models but used them to derive a predefined set of external inputs (Bolte et al., 2006; Gaube et al., 2009), limiting their application in the context of dynamically changing environmental conditions.

Recent efforts to bridge this gap between the ecological and social realms in modeling have been made in fields such as the dynamic simulation of land-use changes (Filatova et al., 2013). However, in the context of management decisions within a given land-use in general and forest ecosystem management in particular the dynamic coupling of human and natural systems remains a challenge for existing simulation approaches (Bousquet and Le Page, 2004; Filatova et al., 2013). One key issue here is also the parameterization of such coupled CHANS models, particularly with regard to the social response parameters. Consequently, recent research has focused on improving our understanding of how forest managers perceive climate risks, aiming to determine the factors and barriers associated with adapting forest management to climate change (Moser and Ekstrom, 2010). Generally, recent studies point to a low risk awareness among forest managers (Eriksson, 2014), and a limited belief in the need for climate change adaptation (Lawrence and Marzano, 2014). This appears to be the result of short-term economic considerations, a perceived impotence to influence natural phenomena, and prevailing uncertainties about future conditions (Lidskog and Sjödin, 2014). However, there is also a high diversity in the perceptions of risk in general and climate change risks in particular (Petr et al., 2014), related to – in part – the general differences in attitudes and motivations for managing forests (Hogl et al., 2005; Ingemarson et al., 2006). Yet, Blennow et al. (2012), in a study spanning a wide social and ecological gradient from Portugal to Germany and Sweden, showed that the propensity to adapt is strongly related to believing in and experiencing local effects of climate change. This suggests strong interactions between the ecosystem and its management, and highlights that individuals and their decisions are important constituents of the social adaptive capacity of managed forests.

Currently, coupling social and ecological systems in models and parameterizing these models meaningfully remain key limitations of our ability to make robust predictions on the adaptive capacity of CHANS, and quantify their resilience to global change. In MOCCA, we addressed this issue by
(i) developing a novel agent-based model of forest management and coupling it with a process-based forest landscape model,
(ii) researching managers attitudes and responses to a changing environment as a prerequisite to parameterize the model (i.e., the ecosystem → man influence),
(iii) test the response to simulated management interventions against independent data from thinning trials (i.e., the man → ecosystem influence), and
(iv) conduct first experiments under climate change to assess CHANS dynamics in a changing world.

4 Results

The overarching aim of MOCCA was to improve the dynamic simulation of interacting human and ecological systems in forests, in order to increase the robustness in climate change vulnerability assessments. To operationalize this objective we've further decomposed the social-ecological interactions into (a) the effects of changes in forest ecosystems on managers and their decisions, and (b) the effects of forest managers' decisions on ecosystems. The central element of the project is the development of an agent-based model of forest management, which ties these two aspects together and allows the investigation of their dynamic interactions over time (see part B, section 6 for details). As final step, the effect of social-ecological feedbacks on ecosystem trajectories under climate change was evaluated (see Figure 1).

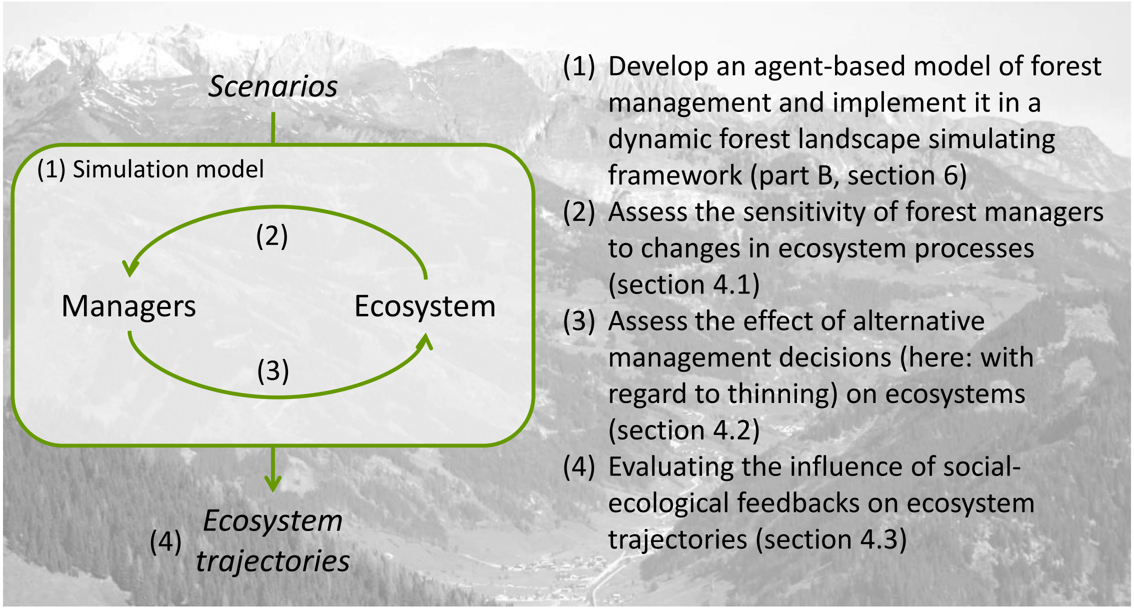

Figure 1: Overview of the MOCCA approach and the four main tasks addressed in the project as well as the sections of this document reporting on them (in parenthesis).

4.1 The effect of changes in forest ecosystems on managers and their decisions

4.1.1 Methods and materials

Here, we address the question of how sensitive forest managers are to climate-induced changes in ecological processes. Our specific objectives were to understand (i) if and how possible changes in forest growth, mortality, and regeneration lead to changes in management, (ii) how climate change beliefs and experiences influence this sensitivity of managers, and (iii) whether individual management objectives, education, and demographic parameters can explain differences in the sensitivity of managers to environmental changes.

In order to consistently address a large and diverse population of managers we used an online questionnaire as our approach to gather information. The questionnaire was structured into three sections, designed to obtain information on (i) the attitudes towards forests and their management, (ii) how respondents perceive and adapt to climate change, and (iii) their demographic data (e.g. age, gender, educational background). Questions were formulated to determine whether the respondents believed they had already experienced changes in these processes that they attribute to climate change, and whether they expected such changes for the future (Table 1). The process of mortality was here represented specifically by disturbance-induced losses, i.e. abrupt pulses of tree mortality from e.g., bark beetle outbreaks or windthrow, as these are expected to be particularly sensitive to climate change (Seidl et al., 2014). Subsequently, questions on the intention of managers to adapt to such changes in ecological processes were posed. Here we aimed to elucidate the tolerance thresholds of managers with regard to these changes in order to determine if and when changes in the environment are likely to lead to changes in management decisions (Seidl et al., 2011b). To determine this managerial sensitivity we defined five levels of change for each process (SL0-SL4) and asked which of these levels of change would make respondents adapt their management (Table 1).

The questionnaire study was implemented in cooperation with the forestry section of the chamber for agriculture in the Austrian province of Styria. It was sent out from a chamber mailing address to all chamber members and employees (a parent population of approximately 4,000 people, subsequently referred to as "current managers") on June 6th, 2014. The link to the questionnaire was active for 12 weeks, and within that time frame 182 individuals responded. Of the respondents, 58.7% identified themselves as farmers owning forest, while 21.7% either own or work for a forest enterprise. A further 9.8% of the respondents stated that they own forest but are not themselves professionally involved in forest management. The size of the forest owned or managed by the respondents was predominately small, with 42.4% having less than 11 ha under their stewardship. Only 12.0% owned or managed more than 100 ha of forest. This strongly skewed forest area distribution is representative for Austria's forest ownership structure (Anonymous, 2009).

However, especially in forestry, where management cycles considerably exceed the professional life of individual managers, it is important to account for inter-generational differences in values and sensitivities to change (Adger et al., 2009). We thus also tested if and how current, experienced forest managers differ from future (well-educated yet less experienced) managers. To that end we replicated our questionnaire study with forestry students at the University of Natural Resources and Life Sciences Vienna, Austria (subsequently referred to as "future managers"). In particular, students enrolled in the master-level courses "mountain forest silviculture" and "management of protective forests" in the spring term of 2014 were invited to respond in class and via email. Of the 97 students enrolled in these two courses 64 responded to the questionnaire. Of these respondents, 23.1% had already experience in practical forest management (i.e., either own forest or have worked in forest management previously).

First, we analysed the beliefs and perceived personal experiences (henceforward referred to simply as experiences) of respondents with regard to climate change and its impact on ecological processes. After an exploratory analysis we tested for differences in beliefs and experiences between current vs. future managers using X^2 tests. Furthermore, we analysed the intended response of managers to changes in ecological processes, testing how sensitive managers were to climate-induced changes in tree growth, disturbance, and regeneration. This analysis was based on the generic sensitivity levels defined in the questionnaire (SL0-4), allowing us to compare sensitivities across processes. Subsequently, we ran a correlation analysis to examine if individual beliefs and experiences explained the intention of managers to adapt. To determine if managerial sensitivities to changes in ecological processes were significantly influenced by beliefs and experiences we used X^2 tests. We first tested the effect of general beliefs and experiences (e.g. whether respondents believed that climate change in general will impact them, Q06 and Q08), and subsequently investigated these variables specifically for the three processes growth, disturbance, and regeneration (Q10-12). Due to often observed issues of asymmetry and framing when using positive (gains) versus negative (losses) terminology (Tversky and Kahneman, 1981) we here focused solely on managers experiencing or believing in negative climate-related outcomes.

Table 1: Beliefs, experiences, and sensitivity of forest managers to climate change (pooled for current and future managers). n = number of responses per question. SL= sensitivity level.

Question	Answer	Response
Q05: How likely do you consider climate change (n=189)	*Very likely*	54.0%
	Rather likely	40.7%
	Rather unlikely	3.2%
	I dont believe in climate change	2.1%
	No opinion	0.0%
Q06: Have you already experienced climate change impacts in the forest (n=189)	*Yes*	54.0%
	Not sure	29.6%
	No	16.4%
Q07: If so, which changes have you observed (multiple answers possible) (n=246)	*Growth decline*	1.6%
	Growth increase	4.1%
	Increase in abiotic damage	46.3%
	Increase in biotic damage	45.9%
	Increasing problems in forest regeneration	5.7%
	Improved forest regeneration	6.9%
	Other	3.7%
Q08: Do you belief that climate change will substantially affect your management in the future (n=189)	*Yes, highly likely*	19.6%
	Yes, possibly	43.9%
	Not sure	18.0%
	Rather unlikely	16.9%
	Definitely not	1.6%
Q09: If yes, what kinds of changes are you expecting (multiple answers possible) (n=246)	*Growth decline*	7.3%
	Growth increase	6.9%
	Increase in abiotic damage	55.7%
	Increase in biotic damage	54.9%
	Increasing problems in forest regeneration	15.9%
	Improved forest regeneration	8.1%
	Other	1.2%
Q10: Would you adapt your management if growth would decline by (n=189)	*>50% (SL1)*	5.3%
	>33% (SL2)	18.0%
	>20% (SL3)	36.5%
	>10% (SL4)	19.6%
	Changes in growth have no effect on my management (SL0)	20.6%
Q11: Would you adapt your management if disturbances of a magnitude that have occurred only once in the last 50 years would return every (n=189)	*33 Years (SL4)*	13.8%
	25 Years (SL3)	15.3%
	10 years (SL2)	38.1%
	5 Years (SL1)	18.0%
	Changes in disturbance have no effect on my management (SL0)	14.8%
Q12: Would you adapt your management if a certain percentage of your target tree species would fail to regenerate (n=188)	*>10% (SL4)*	13.3%
	>25% (SL3)	52.7%
	>50% (SL2)	18.6%
	>75% (SL1)	1.1%
	Changes in regeneration have no effect on my management (SL0)	14.4%

After analysing the intended responses to climate-induced changes in ecosystem processes individually, we subsequently also investigated them jointly, asking if there are consistent patterns of sensitivities within our group of respondents. This analysis was designed to identify types of managers with regard to their intention to adapt. We conducted a cluster analysis of the respondents' sensitivities to changes in the three study variables (Q10-Q12) using partitioning around medoids (Kaufman and Rousseeuw, 1990), a more robust variant of k-means clustering. The number of clusters most supported by the data was determined by running the algorithm over a range of k from 2 to 20, and analysing cluster silhouettes and isolation. The thus determined grouping into manager types was further explored by means of the machine learning algorithm Random Forest (Breiman, 2001). In this final step of the analysis we aimed at determining which factors influenced the different types of responses. Here we again considered experiences and beliefs as explanatory variables, but also included demographic variables, education level, and management goals. Random Forest was used as it is able to address complex and non-linear classification problems with non-independent predictors (such as beliefs and experiences of climate change), while at the same time providing a robust, permutation-based estimate of variable importance (Cutler et al., 2007).

4.1.2 Results

A large majority of the respondents believed in climate change, with only 5.3% across both groups considering climate change to be unlikely or not believing in it at all (Q05). Furthermore, 54.0% believed that they had already experienced effects of climatic changes in the forest (Q06). When asked at the level of individual ecosystem processes, 46.3% of the respondents reported that they had already experienced increasing abiotic disturbances, while only 1.6% had already observed growth declines that they attribute to ongoing climate change (Q07). In the future, respondents primarily expect to see further changes in the disturbance regime (55.7% for abiotic agents), while a growing number of respondents also expect negative impacts of climate change on forest growth (7.3%) and regeneration (15.9%) (Q09). Interestingly, current and future managers did not differ significantly in their beliefs and expectations, both with regard to climate change in general as well as concerning its current and potential future effects on individual ecosystem processes. We thus pooled the two groups for the subsequent analyses.

Most of the respondents were sensitive to negative climate impacts on growth (79.4%), regeneration (85.6%), and disturbance (85.2%), with sensitivity here referring to an intended adaptation of management in response to a future change in these ecological processes (Q10-12). In particular, a considerable number of respondents reported to be highly sensitive to changes in growth (19.6%), intending to already adapt their management if growth losses would exceed 10% (SL4). With regard to negative changes in regeneration and disturbances, 13.3% and 13.8% of the respondents were in the most sensitive category (SL4). With regard to changes in growth and regeneration, the largest share of respondents generally reported low tolerance thresholds (SL3), i.e., they were highly sensitivity to changes in these processes. For disturbance changes, the median sensitivity was lower (SL2), and a considerable proportion of the responders indicated that only a very drastic decrease in the disturbance return interval (i.e., a reduction by a factor of 10, SL1) would make them reconsider their current management strategy (Figure 2).

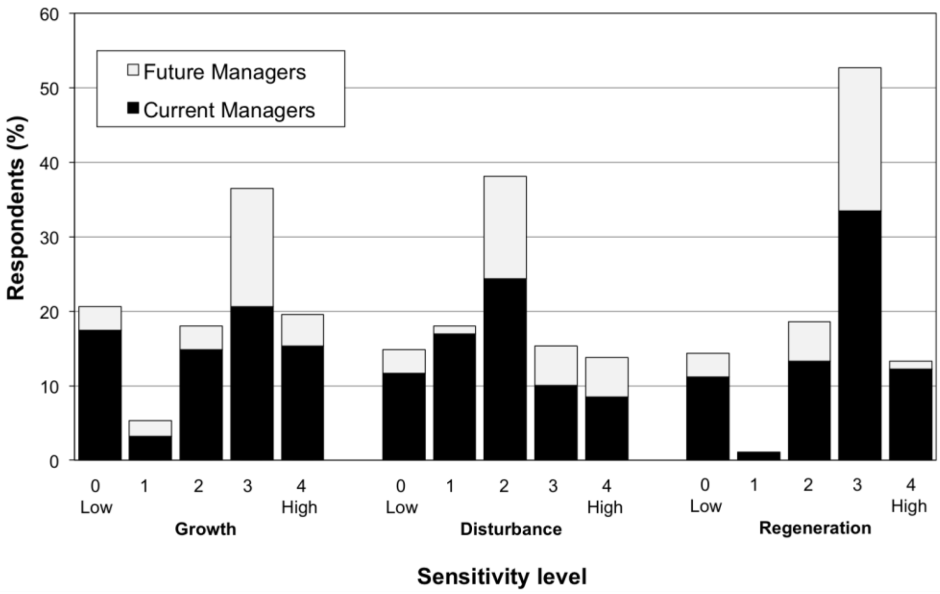

Figure 2: The sensitivity of forest managers to climate-induced changes in growth, disturbance, and regeneration. For a description of the sensitivity levels see Table 1.

We did not find a significant relationship between the general belief in climate change (Q05) and the intention to adapt to climate-induced changes in growth and regeneration processes (Q10, Q12). Furthermore, also the perceived experience of climate-induced changes and the expectation to see more of these changes in the future (Q06, Q08) did not significantly alter a manager's intention to adapt to changes in growth and regeneration. Only with regard to disturbance (Q11), a general belief in climate change and the expectation of future climate-induced changes had a significant influence on intended adaptive response of managers towards changing disturbance regimes. A similar pattern emerged when analysed at the level of beliefs and experiences regarding specific ecological processes (Q07, Q09), indicating that the respondents were consistent in their general and specific beliefs and experiences of climate change. Of the three ecological processes analysed, only beliefs and experiences regarding climate-induced changes in disturbances were significantly related to the intention of managers to adapt to disturbance changes.

Based on correlation analysis we found that a person's sensitivity towards climate-driven changes in individual ecological processes was not independent, i.e. the intended responses to changes in growth, disturbance, and regeneration (Q10-12) were found to be associated across respondents. We thus conducted a cluster analysis to identify different types of managers with regard to their sensitivity to environmental changes. A grouping into four clusters was found to best address the trade-offs between low within-cluster dissimilarity and high between-cluster separation. The largest group (46.7%) were managers that were sensitive to changes in growth and regeneration, but less so to changes in disturbance (Controllers). The second largest group (27.7%) were managers highly sensitive to changes in all three processes (Early adapters). The remaining respondents were either primarily sensitive to regeneration processes (Nurturers, 11.2%) or did not intend to respond at all to changes in ecosystem processes (Non-adapters, 14.4%) (Table 2).

Table 2: Types of responses to negative environmental changes among respondents, and their sensitivity to changes in ecological processes. Sensitivity levels (SL) and tolerance thresholds are indicated for the cluster medoids, i.e., those data points that best represent the cluster.

Type	Percent of respondents	Sensitivity to changes in			Description of sensitivity to climate-induced changes in ecological processes
		Growth	Dist-urbance	Regener-ation	
Early Adapters	27.7%	SL:3 (high: adapt if changes >20%)	SL:3 (high: adapt if frequency changes >2-fold)	SL:3 (high: adapt if changes >25%)	Early Adapters are sensitive to changes in all three ecological processes. They are equally sensitive to changes in growth, disturbance, and regeneration.
Controllers	46.7%	SL:3 (high: adapt if changes >20%)	SL:2 (moderate: adapt if frequency changes >5-fold)	SL:3 (high: adapt if changes >25%)	Controllers are sensitive to changes in growth and regeneration processes (i.e., those processes they can influence fairly directly through management), but are less sensitive to changes in disturbance processes (often perceived as force majeure and beyond the influence of management).
Nurturers	11.2%	SL:0 (none: not sensitive to growth changes)	SL:1 (low: adapt if frequency changes >10-fold	SL:3 (high: adapt if changes >25%)	Nurturers are mainly sensitive to changes in regeneration processes, but do not react at all to changes in growth, and only to very drastic changes in disturbance regimes.
Non-adapters	14.4%	SL:0 (none: not sensitive to growth changes)	SL:0 (none: not sensitive to disturbance changes)	SL:0 (none: not sensitive to regeneration changes)	Non-adapters do not respond to changes in growth, disturbance, and regeneration processes in their management.

To investigate if demographic factors (i.e., age and gender), education level, management goals, beliefs, and experiences explained differences in manager types we used the machine learning algorithm Random Forest. The algorithm was moderately able to explain the differences of the four types of managers based on the considered explanatory values (classification error rate: 37.22%), and confirmed beliefs and experiences of disturbances as the most influential variables. A more detailed analysis showed that the managers perceiving to already experience climate-induced changes in the disturbance regime were more likely to be found in the Controllers group (Figure 3a). This suggests that being exposed to disturbances led them to focus on regeneration and growth processes, rather than to a higher sensitivity towards future changes in the disturbance regime. A second factor of high influence proved to be education. Particular differences were evident here for the group of Nurturers, comprising managers mainly adapting their management to changes in regeneration. Of all groups they had the highest number of respondents who had received a higher education (high school or university degree). Interestingly, also Non-adapters had on average a higher level of general education than Early adapters (Figure 3b). Furthermore, the main objective of the managers in their stewardship was another important factor influencing their sensitivity to climate change. While timber production was the main management objective over all four groups (69.7% of respondents), the Early adapters featured the highest share of people currently not actively involved in forest management. Finally, the Random Forest analysis showed that also age was a factor associated with different sensitivities towards changes in ecosystem processes. Specifically, respondents in the Nurturers and Non-adapters groups were significantly older than those in the Early adapters group (Figure 3d).

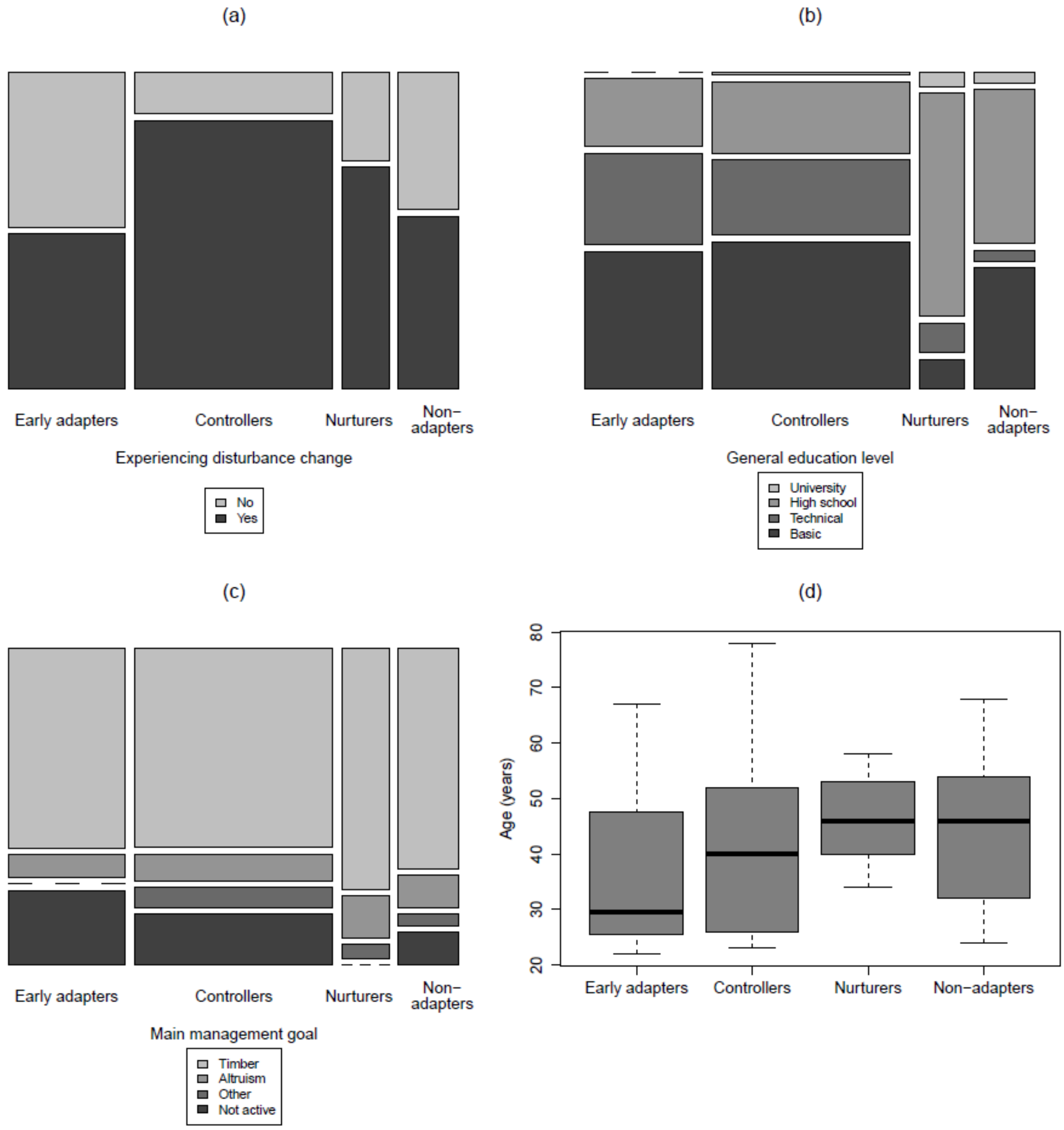

Figure 3: Relationship of the most influential (a) experience variable, (b) educational variable, (c) management objective, and (d) demographic variable on the four response groups determined by means of cluster analysis (cf. Table 4). In the mosaic plots of panels (a) to (c) the size of the respective compartment is proportional to the number of observations in the respective category. In panel (d) boxes denote the interquartile range, and whiskers extend to the minimum and maximum data points while the bold horizontal line indicates the median.

4.1.3 Discussion

We investigated the beliefs and intended responses of current and future forest managers to climate-induced changes in ecological processes. In general, we found high awareness about climate change among the respondents of this study. With only 5.3% not believing in climate change the awareness was considerably higher than in previous analyses of forest managers across Europe (Blennow et al., 2012; Eriksson, 2014). We also found that beliefs and experiences of managers determine their sensitivity to a changing environment, which is well in line with previous analyses (Blennow and Persson, 2009; Blennow et al., 2012; Weber, 2006). However, considering individual ecological processes explicitly we could show that the significance of beliefs and experiences for management decision making varies strongly with ecological process. While seeing and believing changes in growth and regeneration had little influence on the adaptive responses of managers, seeing and believing in changing disturbance risks was highly influential. This finding suggests that being exposed to abrupt, event-type impacts has a stronger effect on decision makers compared to gradual changes (e.g., in tree growth and regeneration). This conclusion is in line with behavioural decision research suggesting that the factors most strongly associated with fear or worry are most likely linked to result in visceral reactions towards risk (Weber, 2006).

One factor limiting the interpretation of these findings is the low response rate obtained from current forest managers. This might be the result of time constraints of the recipients of the questionnaire, as the summer months during which the questionnaire campaign was held are typically a busy time for farmers. Furthermore, it can also partly be explained by not all of the recipients of the questionnaire being forest owners or managers, and thus the questions not being relevant for them. Nonetheless, the high belief in climate change might partly also result from only managers concerned about this issue responding to the questionnaire (i.e., response bias (Fowler, 2009)). Despite this potential problem, our sample size (consisting of 182 currently active managers from a single province in Austria) is in the same range of that of a recent European questionnaire study on climate change beliefs and experiences at the country level (Blennow et al., 2012).

Furthermore, care needs to be exercised in interpreting questionnaire results on experiences and intentions (Podsakoff et al., 2003). For instance, a large number of respondents (46.1%) state that they have already experienced climate-induced changes in the forest disturbance regime. However, due to the inherently stochastic nature of disturbance regimes such changes are hard to detect at the spatial and temporal scales of forest management decision making (i.e., years to several decades and hectares to a few square kilometres). Furthermore, despite the fact that disturbance damage has indeed increased in Europe recently, not all of these changes can be attributed to climate change (Seidl et al., 2011c). This illustrates the broader problem of attribution and scale in dealing with climate change in forestry, which contributes to a slow response of managers to this challenge (Weber, 2006). Another issue that needs to be considered in the interpretation of our results is the possibility of a disparity between intended responses and actions of managers. In other words: Real-world decisions of managers might deviate from the answers they provided in the questionnaire due to desirability bias (Podsakoff et al., 2003). In addition, questions on tolerance thresholds are difficult to assess and answer. Structured interviews and workshops with managers could be used in future efforts to corroborate our results, obtaining more detailed insights into manager’s behaviours and allowing to better test for inconsistencies in responses. Generally, we did find high consistency in the statements of individual respondents between questions, e.g., with regard to their general and process-specific beliefs and experiences of climate change.

An interesting result from our analysis is the apparent similarity in beliefs and expectations between current and future managers. Notwithstanding the differences in the response rates between these two groups, this suggests that the education students are currently receiving does not substantially alter their views on climate change from those prevailing among seasoned forest managers. In turn, this finding implies that the views of managers do not change significantly after taking over responsibility in practical decision making (with its economic and social constraints). This consistency is noteworthy as previous analyses indicated that ecological theory frequently fails practitioners, e.g. due to its limited value in planning and predictive power (Driscoll and Lindenmayer, 2012). This finding furthermore suggests that behavioural and decision modelling based on student responses (Janssen and Ostrom, 2006) might also be applicable in the broader context of practical decision making, despite the apparent demographic and socio-economic differences between students and other groups in society (Bello et al., 2009). However, notwithstanding the similarities in beliefs and expectations of current and future managers, we also found that factors such as age and education of respondents significantly determined their sensitivity and intended responses to climate change. Also, the largest share of respondents currently not actively involved in forest management was found to be the most responsive to climate change (i.e., the Early adapters cluster), suggesting that decisions to adapt might be easier to take on paper than in practice. However, it is important to note that considerable variation remains also within clusters, and that individual behaviour might deviate from the broad typology described here. Furthermore, an important aspect of adaptive behaviour is learning, which is why neither these categories nor their associated response thresholds should be seen as static over time.

Almost half of the respondents are best characterized as Controllers, i.e., being highly sensitive to changes in growth and regeneration processes, and less so to climate-induced disturbance changes. Interestingly, while many respondents state that they experience and expect climate-induced changes in the disturbance regime, the thresholds for adapting their management to these very changes appear to be higher than for other processes. Notwithstanding the reservation that changes in the disturbance return interval might be harder to gauge than percent changes in growth, this finding suggests that a large group of managers base their adaptation decisions on processes that they feel are more under their control, compared to the highly stochastic nature of natural disturbances. More broadly this suggests that a command and control attitude to ecosystem management (Holling and Meffe, 1996) is also prevalent when considering whether to respond to environmental changes. This finding, however, also implies that managers – implicitly or explicitly – consider the uncertainties in impacts and their ability to mitigate them when making decisions about climate risks (Lidskog and Sjödin, 2014; Seidl, 2014).

Our findings on how climate-induced changes in ecosystem processes might lead to changes in ecosystem management are an important step towards an improved understanding of the interactions between social and ecological systems (Schou et al., 2015). They, for instance, document that decision makers are highly individualistic with regard to how they perceive and respond to environmental changes, which is contradictory to a top-down, policy-driven perspective on climate change adaptation. We showed that individual beliefs and experiences – in addition to demographic factors, education, and management objectives – are important for distinguishing broad types of decision makers, especially for non-industrial, small-scale, private forest owners (Boon and Meilby, 2007; Dayer et al., 2014; Hogl et al., 2005; Ingemarson et al., 2006). These insights can help to tailor policy instruments and incentives towards better addressing forest managers' needs in the future, and thus support the implementation of climate change adaptation measures. However, while the specific beliefs and value systems of forest professionals might differ (Pregernig, 2001), it is important to recognise that also professional norms, habits, and traditions play an important role for management responses (Primmer and Karppinen, 2010), as does their institutional environment (Zivojinovic and Wolfslehner, 2015).

In the context of climate vulnerability the high sensitivity of managers to changes in ecosystem processes found here suggests that adaptive behaviour is common in managed forests, and must not be neglected when considering future system trajectories (Elkin et al., 2013; Seidl et al., 2011b). In this regard the response types identified here and their specific tolerance thresholds for taking action can be used to better characterize forest managers in future studies, e.g. using agent-based modelling (Filatova et al., 2013; Janssen and Ostrom, 2006). This could increase the robustness of climate change vulnerability assessments of managed forests, as it fosters an explicit consideration of the individualistic response of managers to changes in the ecosystem, and thus supports an empirically-based quantification of the diversity of social responses in the system, which is a crucial component of socio-ecological adaptive capacity.

4.2 The effects of forest managers' decisions on ecosystems: Thinning as an example

4.2.1 Methods and materials

The specific aims of this part of the project were to assess whether the newly developed management model (see part B, section 6) was able to realistically reproduce the effects of one of the most important forest management interventions, i.e. thinnings. To that end we ran the model for three different thinning trials and compared the simulation results against the independent long-term observations of these trials. Subsequently, we reanalyzed the thinning experiments under different climate change forcings, in order to assess the climate change adaptation capacity of thinnings.

The three thinning trials studied here are implemented and managed by the Austrian Research Center for Forests (BFW), who courtesy provided their data for this study. All three trials focus on Norway spruce, which is currently the economically most important tree species in Austria. The first trial site is St. Oswald ob Eibiswald, located in the ecoregion 5.4 "Weststeirisches Bergland", at an average altitude of 1250 meters asl (BFW, 2013a). The observation period ran from runs from 1968 to 2013, with a tree age of 40 years in the beginning of the trial. Four different thinning variants were implemented, with thinning intensities (here expressed as mean annual timber volume removal percentage) ranging from 0% to 1.4% yr^{-1}. The mean annual temperature during the trial period was 5.1°C, and the mean annual precipitation sum was 1394mm. The second thinning trial was located at Karlstift, in the ecoregion 9.2 "Waldviertel" at an elevation of 930 m asl (BFW, 2014). The trial was started in 1964 and was last remearsured in 2010. At the beginning of the trial the trees were between 15 and 20 years old. Four different thinning variants were studied at Karlstift, with thinning intensities ranging from 0% to 4.0% yr^{-1}. The mean annual temperature during the trial period was 5.9°C, and the average annual precipitation sum amounted to 831 mm. The third trial included in our analyses was also located in ecoregion 9.2 (near Ottenstein), but at a considerably lower elevation of 540 m asl. Conditions are warmer and drier at the Ottenstein trial, with a mean annual temperature of 7.1°C and an annual precipitation sum of 633 mm. The trial was implemented in 1970 in a 59-year old stand, and last remeasured in 2014 (BFW, 2013b). Five different thinning variants were studied at Ottenstein, with thinning intensities ranging from 0% to 5.5% yr^{-1}.

To assess the potential of thinning as climate change adaptation measure, the thinning trials were reanalyzed under three regionally downscaled climate change scenarios, representing different combinations of global and regional circulation models under A1B forcing: CNRM-RM4.5 driven by the global climate models (GCM) ARPEGE and MPI-REMO as well as ICTP-RegCM3 driven by the GCM ECHAM5. The climate data were downscaled and supplied by H. Formayer, BOKU Meteorology. For each of the three scenarios, we focused on the climate expected for two future time periods, 2040-2060 and 2080-2100, and drew years randomly from these periods in the reanalysis simulations (i.e., time slice approach). The respective changes relative to baseline climate are given in Table 3.

Table 3: Changes in important climate parameters relative to the baseline period at the three thinning trial locations (columns) for the three climate scenarios and two time periods (rows). VPD= vapor pressure deficit.

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

4.2.2 Results and discussion

In comparing the observed thinning response to the model results, we found that the newly developed management model was well able to simulate a wide range of thinning regimes at the three study sites across Austria. With regard to the diameter at breast height (dbh), a crucial indicator of stand development, the model was well able to reproduce the wide range of observed diameters at the end of the trials (Figure 4). This is particularly noteworthy, as dbh is a parameter highly sensitive to changes in stand density, suggesting that the ecosystems response to a wide range of management interventions was well captured by the model. Across sites, adjusted R^2 of observed versus predicted dbhs ranged between 0.436 and 0.621. The bias in the simulated dbhs at the end of the simulation period was between -10.0% and +11.5% (-3 cm to +4 cm) and thus suggests satisfactorily accuracy of the model in the context of management applications.

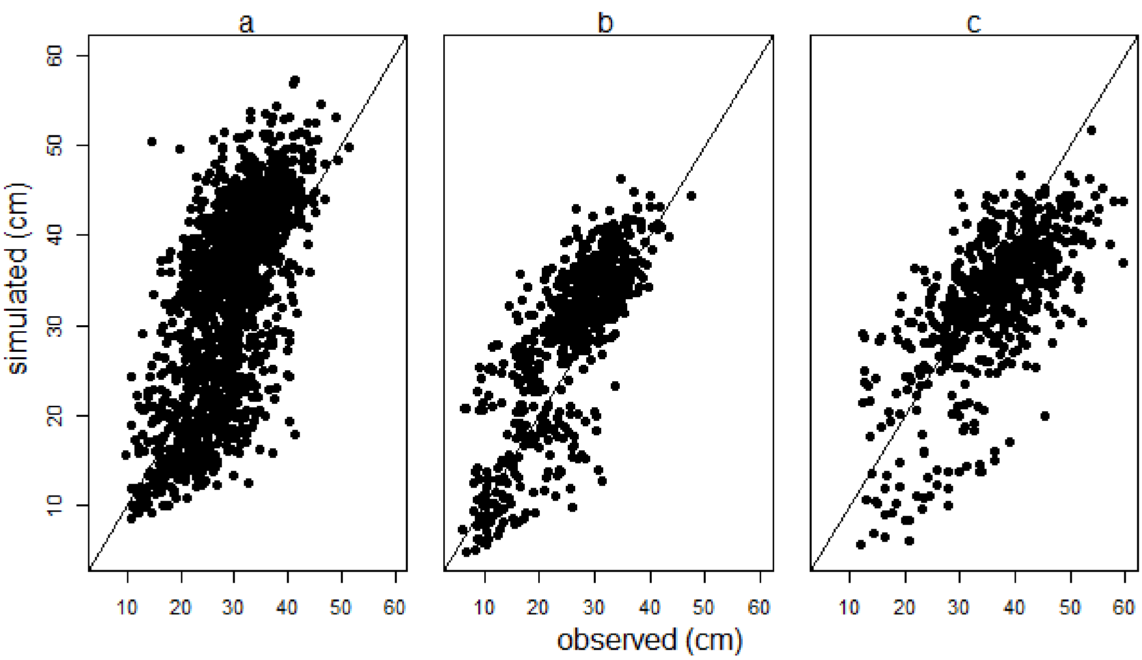

Figure 4: Simulated versus observed diameter at breast height of individual trees at the end of the 40+ year study period for the thinning trials (a) Eibiswald, (b) Karlstift, and (c) Ottenstein.

Climate change scenarios resulted in both positive and negative effects on forest productivity, depending on the combination of scenario and site. Forests responded most strongly positively at the high elevation site Eibiswald, where warmer temperatures extended the growing season and CO2 fertilization allowed for increased C uptake and growth. The maximum simulated increase in the mean annual timber increment (MAI) was +20% at Eibiswald under the ICTP scenario. Most strongly negatively affected by climate change was the already under current climate warm and dry site Ottenstein. Warmer and partially also drier climate periods in the future resulted in simulated decreases in MAI by as much as -15% (REMO scenario). The effect of CO2 fertilization was here offset by increasing environmental limitations.

At Ottenstein, thinnings were able to reduce the negative climate change impacts. Simulation results showed that increasing thinning intensity lead to a decreasing reduction in timber and diameter growth. In other words, thinnings are able to compensate negative climate effects, particularly under warm and dry site conditions (Figure 5). The other sites showed a less clear thinning signal under climate change.

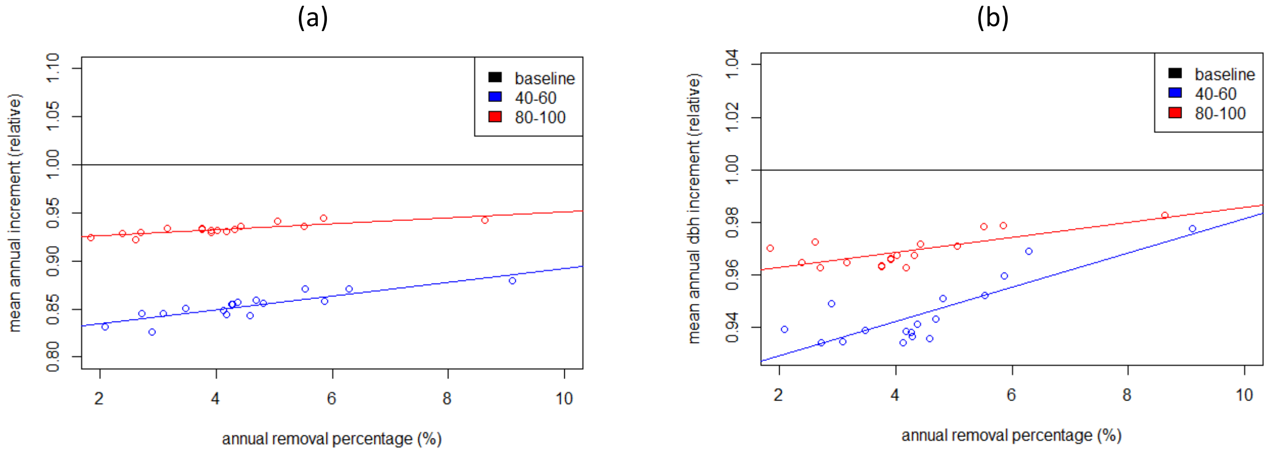

Figure 5: The effect of climate change on (a) mean annual timber increment and (b) mean annual diameter increment relative to baseline climate at the site Ottenstein (climate scenario: A1B, REMO). Increasing thinning intensity (expressed here as the mean annual volume removal percentage over the trial period) reduces the reduction in increment relative to baseline climate.

We here showed that the newly developed forest management model integrated into the iLand simulation platform is well able to reproduce the ecosystem response to a wide range of thinning interventions. The results are well in line with previous model evaluation studies, and, considering that iLand is a process-based model (simulating responses to changing density based on first principles of plant competition and ecophysiology), can be deemed highly successful. These tests against independent data increase the confidence in the newly developed management model and underline it's suitability for future studies of forest management under climate change. Also the particular findings on thinning effects under climate change are well in line with the literature and theoretical understanding. Thinning particularly alleviates a trees competitive situation by removing neighboring trees and increasing the resource availability for the remaining trees. Thinning is thus particularly effective to reduce negative climate change impacts where resources, and particularly water, are already limiting (D'Amato et al., 2013; Gebhardt et al., 2014). As such our findings show that thinning is an important measure of climate change adaptation in forestry, but also highlight that it is not universally effective. Further studies should thus investigate under which site and climate conditions thinnings can be particularly helpful to mitigate negative climate change impacts.

4.3 Social-ecological feedbacks on ecosystem trajectories under climate change

4.3.1 Methods and materials

In order to test the behavior of the newly developed model at the landscape scale, and study the trajectories emerging from a dynamic coupling of human and natural systems we set up a suite of simulation experiments. All experiments are conducted for a 1,170 ha forest landscape situated in the northern Front Range of the Eastern Alps (province of Upper Austria, Austria) and under the stewardship of the Austrian Federal Forests. As we were primarily interested in the spatial patterns created by the management decisions taken by the agents in our experiments, we've imputed homogeneous climate and soil conditions to the landscape (Table 4), controlling for an interference of environmental heterogeneity with managerial heterogeneity. Furthermore, in order to control for legacy effects of past forest management (e.g., via an uneven distribution of stand age) we populated the landscape randomly with even-aged stands according to a "normal forest" assumption (i.e., with all age-classes being equally represented on the landscape). All simulation experiments were run for a period of 400 years in order to capture the long-term dynamics of the coupled human and natural system. Natural disturbances were omitted in all simulations in order to reduce the stochasticity in the simulations and aid the comparison between the different simulation experiments with regard to the effects of different agent populations and decisions.

Table 4: Characteristics of the generic forest landscape used for the simulation experiments

Attribute	Value
Mean annual temperature (1981-2010)	4.8° ± 0.7 °C
Annual precipitation sum (1981-2010)	1,409 mm ± 119 mm
Soil type	eutric Cambisol
Soil depth	1.6 m
Total forest area	1,170 ha
Number of stands	364
Mean stand area	3.2 ha ± 2.5 ha
Tree species	*Picea abies* (L.) Karst.
Site index (mean annual increment at age 100 years)	6.2 m³ ha-1 yr-1
Initial standing stock	266 m³ ha-1
Initial rotation length	110 yrs

The main objective of the agents in all experiments was sustainable timber production. To that end, their decision heuristic was set up to follow the primary aim of producing the maximum amount of timber possible given the ecological conditions, while observing the constraints that (i) periodic harvests should not exceed the increment level (sustainable yield criteria), and (ii) a balanced distribution of stand ages should be maintained at the management unit (MU). Beyond this simple decision heuristic the effects of differences in agent architecture and adaptive behavior on CHANS trajectories were tested in the three experiments as described in the following paragraphs.

Experiment 1: One vs. multiple managers. While the study landscape investigated here is under the stewardship of a single forest owner and managed by a single manager, the large majority of forest landscapes in Central Europe feature a multitude of forest owners (and thus also multiple management decision makers). Austria, for instance, has approximately 145,000 forest owners, and 59% of the country's forest area is held by owners of less than 200 ha. In Experiment 1 we tested the effect of a single vs. multiple managers on the dynamic behavior of the CHANS. To that end we distributed existing stand polygons randomly into 30 management units (mean ± sd: 39 ha ± 14 ha), and assigned each unit a separate managing agent. Each of these agents was, however, set up to be identical in their operational and strategic decision making. With the goal of sustainable timber production the stand treatment program implemented by the agents consisted of planting 2,500 trees per hectare, followed by moderate thinnings at age 40 and 60, and a clear-cut at the rotation age of 110 years. Comparing a landscape managed by a single vs. multiple agents we tested the hypothesis that more (yet identical) agents lead to a more variable forest structure over time, as smaller management units under sustainable yield imply a less temporally balanced cutting schedule. Deviations between harvest and increment levels were tested by means of Wilcoxon's signed rank sum tests, and stand age distributions were analyzed using the Gini coefficient. Linear regression was used to determine trends over time. While accounting for inter- and intra-annual variability in climate in the simulated ecosystem dynamics, no change in environmental conditions was simulated in Experiment 1.

Experiment 2: Passive adaptation to climate change. In contrast, in Experiment 2 a +3.0°C warming over 150 years was imposed after an initial 100 simulation years of stationary climate, followed by a 150 year stabilization period, in order to study the dynamic adaptation of the CHANS to such an environmental change. In particular, Experiment 2 tested whether the agents are able to adapt their sustainable cutting level dynamically to a climate-driven change in increment. To that end, the simulations under a changing climate were compared to those under stable climate (both with an identical configuration of 30 similar agents, cf. Experiment 1). We hypothesized that the ecosystem will respond dynamically to changes in the climate system (enabled by the detailed process representation of iLand), which will prompt the agents to adapt their management, and will cause subsequent feedbacks on ecosystem dynamics. In particular, we expected our adaptive agents operating under a sustainable yield paradigm to dynamically adjust their harvesting levels to changing growing conditions. This experiment thus scrutinizes the ability of the coupled human and natural systems model to account for changes in the environment through passive adaptive management of the agents.

Experiment 3: Active adaptation of diverse responders. Considering the long lead times of forest management decisions, also proactive, anticipatory adaptation to climate change might be necessary in many situations. Furthermore, such active adaptation measures represent the purposeful integration of experimentation into the design of adaptive management strategies (Stankey et al., 2005). We here tested this aspect with regard to an active adaptive adjustment of the rotation period of the 30 management agents. Yet, such strategic decisions to respond to climate change can be expected to vary strongly within the agent population. Whether managers actively adapt their management strategy depends on their beliefs and experiences, as well as on their willingness to accept climate risks and their inertia to change (Blennow et al., 2012; Eriksson, 2014). In Experiment 3 we scrutinized the effect of this heterogeneity in the decision makers' responses to environmental change on the dynamics of the CHANS. To that end we compared simulations in which all 30 agents actively adapt their rotation period at the same time (after 200 simulation years) to a scenario in which every agent decides when to adapt individually. This decision is based on an agent's analysis of the emerging environmental changes (specifically, a 30-year running average over the increment trend on the landscape) against an agent-specific tolerance threshold for changes in this parameter (Seidl et al., 2011b). Agents that are insensitive towards the effects of climate change have a high tolerance threshold for growth changes (set at >50% here), while very responsive agents have a low tolerance threshold (set at a change of >1% in this experiment). Once the climate-induced ecological changes exceeded this threshold, the agents were assumed to have a probability of 0.20 to adapt their rotation period in every planning period. The agent decision heuristic thus probabilistically accounts for the fact that heterogeneity in decision makers is not only driven by different attitudes (and thus tolerance thresholds) towards change, but also includes a stochastic element. The assumed change in the rotation period (from 110 to 90 years) was the same in both sets of simulations conducted under Experiment 3 (coordinated vs. individual responders). We hypothesized that the adaptation process in a landscape of diverse responders takes considerably longer, but that it at the same time stabilizes the temporal dynamics of the CHANS at the landscape scale due to increased spatial heterogeneity (Turner et al., 2013). Since Experiment 3 includes stochastic elements, 5 replicates of the simulations were run and aggregated results are reported. With the exception of rotation period

(Experiment 3) and cutting level (Experiments 2 and 3) all other management variables remained unchanged in the experiments.

4.3.2 Results

One vs. multiple managers (Experiment 1): Under constant environmental conditions, a single agent autonomously managing the 1,170 ha study landscape was well able to fulfil the premises of sustainable timber yield while maintaining a stable forest structure at the landscape over the 400 year study period. The long term average standing volume stock was 261.1 ± 16.0 m³ ha^{-1}, and did remain within a corridor of 234.5 and 300.4 m³ ha-1 over the four simulated centuries. Likewise, the amount of timber produced from the landscape remained stable over time (p=0.170) at a level of 6.19 ± 2.17 m³ ha-1 yr^{-1}. It did not differ significantly from the mean annual increment of the simulation period (p=0.150), which documents that the management goal of sustainable timber yield was met by the autonomous actions of the agent. Furthermore, the uniform age-class distribution that served as starting value for the simulations was well preserved over the four centuries (Gini coefficient at the end of the simulation period: 0.089) by the harvesting regime implemented by the agent (Fig. 6a).

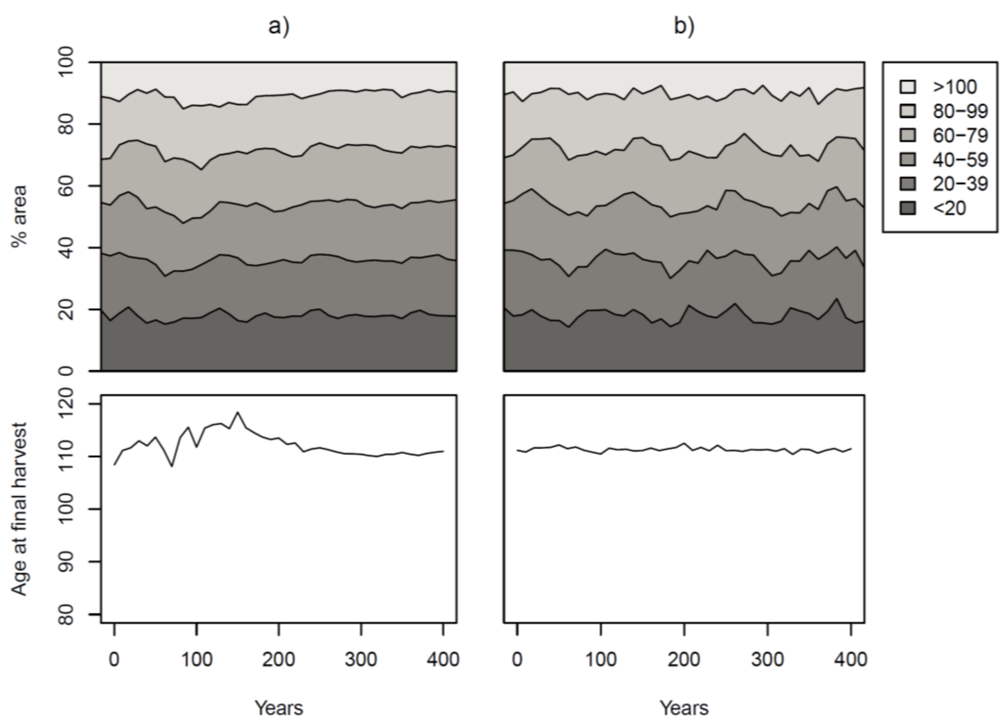

Figure 6: Development of the age class distribution (top) and mean age at which a final harvest is simulated (bottom), when a single agent (a) or 30 agents (b) are responsible for the management of the landscape.

Comparing the landscape dynamics resulting from the stewardship of one versus 30 identical agents did not reveal significant differences in these key system variables. However, the differences in the size of the respective management units (1,170 ha vs. on average 39 ha) did affect the temporal scheduling of harvesting interventions, and subsequently the development of the forest age structure in the landscape. Since a single agent on a large management unit has a much wider set of silviculturally suitable stands from which to choose from for treatments such as final harvesting, the interannual variation in the area treated every year was considerably smaller than in the landscape managed by 30 agents. Consequently, also the temporal development of the age structure of the landscape was smoother for the single vs. the multiple agent landscape (Fig.

6). However, due to the cap on annual harvest imposed by the sustainable yield premise the realized harvest age exceeded the planned rotation period quite notably in the single agent landscape, particularly in the first two rotation periods. Since the 30 agents each observe the sustainable yield criterion for their respective management unit it is less restrictive to the area of final harvest, and the realized rotation age over the landscape matches the plan more closely (Fig. 7).

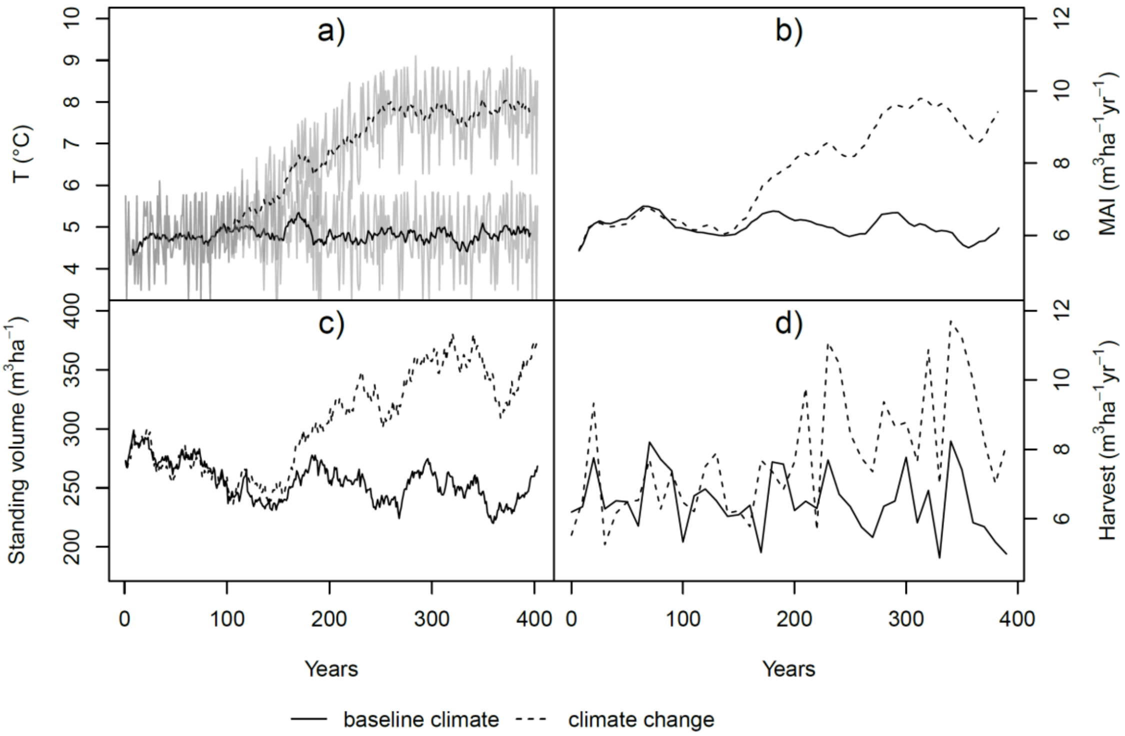

Figure 7: Comparison of simulations under baseline climate (solid line) and a climate change scenario (dashed line). a) annual (grey) and 30-year running average (black) of mean annual temperature (°C), b) mean annual timber increment (MAI,, 30-year running average), c) simulated standing timber stock (m³/ha), d) realized harvests (thinnings and final cuts) averaged for the 30 agents managing the landscape (10-year-averages).

Passive adaptation to climate change (Experiment 2): In our mountain forest landscape a warming of +3°C over 150 years (while assuming stable precipitation levels) resulted in a considerable increase in tree growth. In the last 150 years of the simulation the mean annual increment under climate change was on average 3.00 m³ ha^{-1} higher than under a continuation of past climate conditions (Fig. 7). The managing agents on the landscape autonomously detected these changes in the ecosystem, and adjusted their harvesting levels upwards accordingly. On average, the harvesting level in the last 150 years was 2.63 m³ ha^{-1} higher compared to simulations under stable climate. The agents were thus well able to passively adapt to the progressing ecological changes, and to advance their goal of sustainable timber production by acting upon the improving growing conditions. Despite an increased cutting level they did, however, observe the premise of sustainable yield, with total harvesting over the last 150 years not differing significant from the increment ($p= 0.138$). The fact that cutting remained slightly below the potential is a result of managers only adapting passively, i.e., after experiencing a change in the environment (based on the analysis of a running average of increments over the previous 30 years). Changing growing conditions did also lead to increasing standing volume stocks on the landscape (Fig. 7c). In the last 150 years of the simulation, the growing stock was on average 40.7% higher under climate change than under stable climatic conditions. From the perspective of managing agents, such an increase might not be desirable as it also increases the risk from disturbances (Thom et al., 2013). This illustrates that passive adaptation – reacting to unfolding changes after the fact – might not be sufficient to respond to climate change in forest management. Consequently, we studied the effect of agents that adapt actively and passively to environmental changes in Experiment 3.

Active adaptation of diverse responders (Experiment 3): Active adaptation through a reduction in the rotation period from 110 to 90 years was successfully able to stabilize the emerging trajectory of growing stock. In the two adaptation scenarios simulated under Experiment 3 (coordinated and individual timing of adaptation) the mean stocking levels over the full simulation period remained at 284 m³ ha^{-1} and 294 m³ ha^{-1}, respectively, and harvest levels were between 2.8% and 3.8% higher than in the passive adaptation only scenario (Experiment 2). However, the timing and pattern of adapting the rotation period among the population of agents had a strong effect on ecosystem trajectories. Despite taking approximately 50 years for the realized harvest age to approach the new rotation period (as a result of the harvesting cap imposed by the sustainable yield premise), this management impulse created a strong imbalance in the age class distribution on the landscape (mean Gini coefficient of 0.35 over the last 150 years) when all agents adapted their rotation period simultaneously in year 200. The progression of the simultaneously created large areas of young forests through stand development subsequently resulted in an oscillating standing stock level over time (Fig. 8a). Conversely, individualistic decisions to reduce the rotation period led to a much slower change of the realized harvesting age, yet also a much more even age distribution (Gini coefficient of 0.18) and stable growing stock trajectory over time. Depending on their individual tolerance thresholds for change 5% of the agents had already adapted by the simulation year 124 (i.e., only 24 years after the onset of the climate forcing), while 90% of the agents had switched to the adapted rotation period by simulation year 323 (8% of the agents did not adapt within the simulation period). This heterogeneity in management responses created variability on the landscape (Fig. 9), which in turn contributed to a temporal stabilization of the system. Nonetheless, both scenarios resulted in comparable standing stocks, increments, and harvest levels at the landscape scale. Heterogeneity and stability did thus not affect the overall management objective at the landscape scale negatively, illustrating that the early- responders compensated the effect of the late-responders in our experiment.

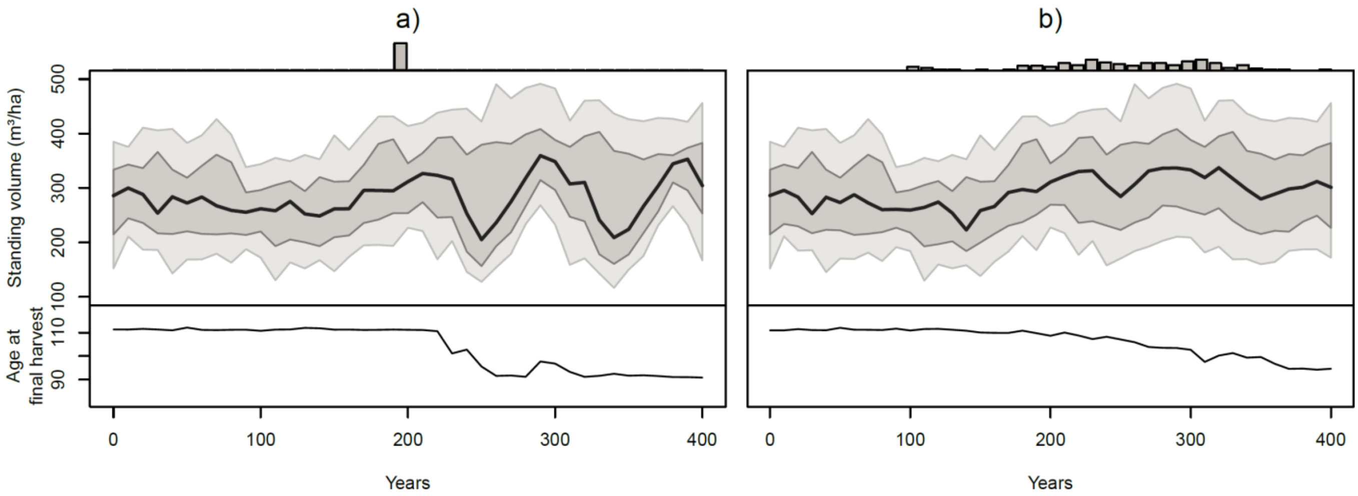

Figure 8: Comparing simulations with coordinated adaptation (i.e., all 30 agents adapt at the same point in time, (a)) with individual decisions on when to adapt based on agent-specific tolerance thresholds to the perceived environmental changes (b). The bars on the panel top indicate the decadal frequency of agents actively adapting the rotation period from 110 to 90 years. The middle panel shows the trajectory of the standing volume per management unit (light grey: 10th to 90th percentile, dark grey: 25th to 75th percentile, bold line: median). The decadal mean age of stands at final harvest is shown in the bottom panel.

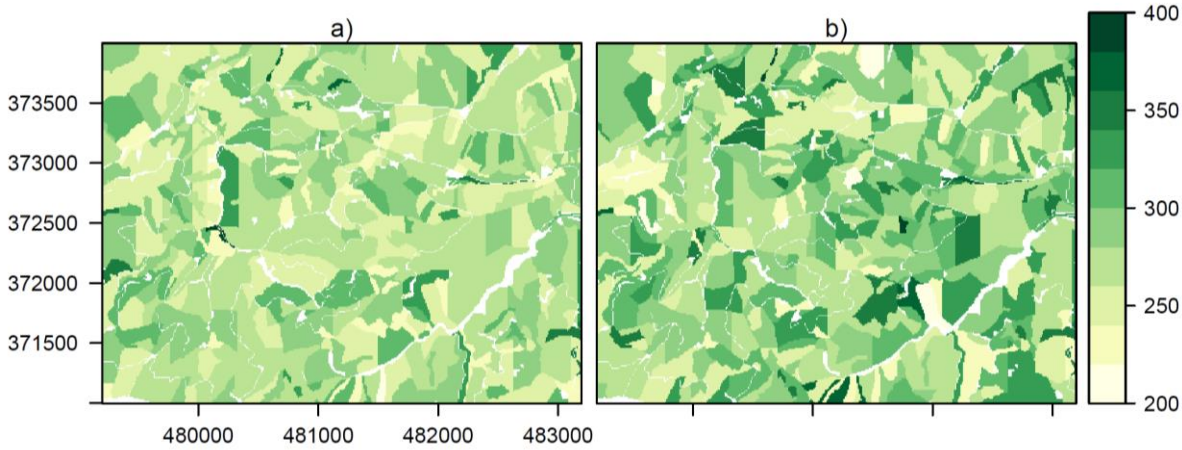

Figure 9: Mean standing volume (m³ ha^{-1}) over 400 years for simulations where all 30 agents coordinate their adaptation decision (a), and for individual decisions on when to adapt based on agent-specific tolerance thresholds (b).

4.3.3 Discussion

We here demonstrate that an interaction of a dynamic ecosystem response with agents capable of passively and actively responding to ecological changes is able to produce realistic CHANS trajectories. Our approach of implementing autonomous adaptive agents within a dynamically changing landscape based on process modeling thus has the potential to increase the robustness of future assessments of forest dynamics under global change. Tools such as the one presented here can help to mainstream a CHANS perspective into the management planning and impact assessment for forests under global environmental change (Parrott et al., 2012). Furthermore, they enable the extension of post hoc analyses on the multi-scale dynamics of CHANS (Moen and Keskitalo, 2010) to quantitative scenario analyses of potential future system trajectories.

In order to demonstrate the behavior and utility of our approach to couple an ABM with a process-based forest landscape model we here employed a simplified agent architecture. Furthermore, we have restricted our analysis to study responses to a single global change forcing under a sole management objective. Future applications should account for the considerably more complex reality of ecosystem management under global change. The response of management agents should, for instance, be specified in more detail based on empirical analyses of the perceptions and responses of decision makers to environmental changes (Blennow et al., 2012; Eriksson, 2014). Furthermore, communication and learning between agents (Satake et al., 2007) could be an important factor accelerating the diffusion of adaptation decision on the landscape (with an emerging CHANS dynamic hypothesized somewhere between the two bracketing cases studied in Experiment 3), and should thus be considered in future developments. Also the demographic structure in the agent population could be a factor that either fosters or hinders adaptive responses to change. In addition to a greater variety of agent responses also the diversity in their management objectives on the landscape needs to be addressed in more detail in future studies (Hengeveld et al., 2015; Kelley and Evans, 2011). Furthermore, the complexities of changes in multiple ecosystem processes in response to global change (e.g., also accounting for impacts on regeneration and mortality) and their joint effects on spatially heterogeneous landscapes require consideration in the future.

Consequently, the current study and its findings need to be interpreted in the light of the above described simplifications and limitations. The trajectories of the experiments designed primarily to demonstrate the effects of incrementally complex agent structures and environmental changes (i.e., especially Experiments 1 and 2) are not necessarily representative for the response of managed forest landscapes to climate change. However, our analysis showed that even the relatively simple managerial responses considered here can result in complex landscape-scale trajectories when coupled with dynamically changing ecosystems. In this regard one interesting finding is that not only diversity in the ecosystem (Mori et al., 2013; Silva Pedro et al., 2015; Turner et al., 2013) but also diversity in managerial responses contributes to system-level stability and resilience. Hitherto a weakly organized, small-scale ownership structure has been widely perceived to be an obstacle for the mainstreaming of climate change adaptation into forest management due to a delayed progress of implementation. While our simulations confirm this hypothesized delay, our results also indicate that such a diverse social structure has the advantage of creating heterogeneity on the landscape, which can stabilize system trajectories over time. We also demonstrate that a uniform and abrupt implementation of an adaptation strategy over an entire landscape can have undesired consequences in the form of long-term structural legacies in forest ecosystems. As many current simulation-based adaptation studies in forestry explore management responses in such an a priori imposed manner (Bu et al., 2008; Duveneck et al., 2014; Seidl et al., 2011a; Temperli et al., 2012) we suggest that the structural consequences resulting from such designs should be addressed more explicitly in the future.

While these findings on response diversity and the effect of long-term structural legacies are likely to be of broader applicability beyond the specific domain of our analysis (i.e., mountain forest systems in Central Europe managed by a group of autonomously operating small-scale forest owners) other outcomes might be less transferable to different systems. Our analysis, for instance, focuses primarily on changes in timber production and stocks, which are simulated to increase under climate warming. This positive response of mountain forest ecosystems is well in line with observations and simulations with other models under similar conditions (Elkin et al., 2013; Seidl et al., 2011b; Temperli et al., 2012). In systems where different focal variables are of prime concern for ecosystem management results may vary. Furthermore, in addition to such gradual changes also abrupt responses to global change are possible, such as an increase in disturbances from bark beetles (Seidl et al., 2014). Consequently, future studies should also address abrupt and severe events such as large-scale forest disturbances and their effect on CHANS dynamics.

In conclusion, we here demonstrate how to couple management agents operating with a complex, multi-level decision structure with a spatially explicit forest landscape model, improving the tools available for a quantitative and prospective analysis of CHANS. While the theoretical developments in the science of CHANS have advanced greatly in recent years (Biggs et al., 2012; Chapin et al., 2010; Folke, 2006), the integration of the two spheres in quantitative assessment tools has remained challenging particularly in the context of land management. We here bridge the gap between the modeling of forest ecosystems and their managers, and demonstrate dynamic interactions and dampening system-level feedbacks between adaptive agents and changing ecosystems. A suite of experiments with the newly developed tool suggests (i) that both passive (reactive) and active (prospective) adaptation of forest management might be necessary in order to adapt to environmental changes that progress at a high rate (relative to the long time horizons of forest dynamics), and (ii) that diversity in managerial responses to environmental changes (e.g., as a result of a multitude of diverse managing agents) increases the heterogeneity on the landscape. This could dampen the temporal fluctuation of key indicators of ecosystem services provisioning and positively influence the continuous provisioning of ecosystem services to society at the landscape scale. Our findings thus suggest that policies and incentives that favor active adaptation of forestry to global change should be intensified, but that panacea solutions should be avoided to maintain the heterogeneity and response diversity of forest landscapes.

5 Conclusions and recommendations

(i) Social-ecological interactions matter in climate change impact assessments
Most ecosystems in Austria are directly or indirectly affected by humans. Yet, assessments of the impacts of climate change on ecosystems have to date largely focused on the ecological implications, while disregarding the interactions with humans. Here we show that these interactions are highly relevant, and that disregarding them will likely lead to unrealistic assumptions on future trajectories of CHANS. To address this issue we have developed an agent-based model of forest ecosystem management and integrated it into the forest landscape model iLand. This new tool, which is flexible in its design and has been tested with regard to a variety of system behaviors in this study, can improve future assessments of forest ecosystems under climate change. The project MOCCA has thus delivered an important methodological advance for future climate impact research in Austria and beyond.

(ii) Austrias forest managers belief in climate change
We have found a high belief in climate change among forest managers in Austria – 94.7% of the respondents to two questionnaire campaigns stated that they consider climate change very likely or rather likely. A majority (54.0%) also believed that they are already experiencing the impacts of climate change. An even higher share of managers furthermore beliefs it possible or likely that climate change will substantially affect their management in the future (63.5%). Interestingly, we found no difference in the beliefs on climate change between current and future forest managers. In other words: practitioners working in the field had the same beliefs as students currently enrolled at university.

(iii) The sensitivity of managers to climate-induced changes in the forest varies widely
More than one fourth of all respondents (27.7%) stated that they are highly sensitive to climate-induced changes in the forest – even relatively small changes in the growth, regeneration or mortality of the forest would be enough for them to adapt their management strategy. On the other hand, 14.4% of the respondents stated that they will not adapt their management, regardless of the climate-induced changes that might happen in the future. We found that in particular experiencing or believing in an increase of large, abrupt mortality events (i.e., disturbances) had an influence on the willingness to adapt. In addition, also demographic factors (age, education) as well as the individual management goals influenced a manager's sensitivity to climate-induced changes in the forest.

(iv) Variation in management responses is not necessarily a bad thing, as it creates heterogeneity on the landscape (which in turn fosters resilience)
Using the newly developed simulation tool we investigated the role of a variable management response to climate warming as compared to a uniform response. Managerial variation resulted in slower adaptation of crucial variables, but also increased the variation on the landscape. This heterogeneity in turn contributed to increasing the temporal stability of landscape trajectories over time. Uniform and abrupt implementation of a management regime sped up the adaptation process, but also created long-term structural legacies that might also be problematic in the context of future management (e.g., a highly unbalanced age class distribution). Future research should thus further investigate the effect of managerial heterogeneity in forest landscapes, in order to determine under which conditions social response diversity fosters resilience, and under which conditions resilience is reduced.

(v) Active adaptation is needed in forest management to address the impacts of climate change

Based on the simulation experiments conducted here, a passive adaptation strategy (i.e., a strategy in which management only changes *after* the effects of climate change have manifested themselves) is not enough to stabilize trajectories of forest landscapes in the future. As a result of the long lead-times of adaptation measures in forestry, active (i.e., prospective) adaptation is needed in which climate impacts are detected early (or are anticipated based on models) in order accommodate the high temporal rate of climate change, relative to the slow response of forest ecosystems to managerial changes. In the simulations conducted here, only runs including managers that actively adapted to climate change resulted in stable ecosystem trajectories for the future.

(vi) Thinning can reduce the vulnerability of increasingly water-limited forests

Thinning (i.e., reducing the stand density of middle-aged forests) is an important management measure of forest management also under constant climate. Yet, more recently it has also been discussed as a climate change adaptation measure, as thinning increases the resource availability for the remaining trees, and thus can potentially buffer them against increasing climate limitations. Here we re-analyzed three Norway spruce thinning trials across Austria under climate change using the newly developed forest management model. We found that at warm and dry sites increasing thinning intensity and/ or frequency can reduce growth losses from climate change. Yet, at sites benefiting from a warmer climate (e.g., at higher elevations) thinnings were not found to further improve the performance of forests under climate change beyond the thinning effect also observed under current climate. This underlines that thinnings are an important tool in the adaptation portfolio of forest managers. However, it also highlights that no "one-size-fits-all" adaptation solutions exists in forest management, and that adaptation measures need to be considered in the context of specific site and stand conditions.

B) Project details

6 Methods

Modeling the natural system: the iLand model. The individual-based forest landscape and disturbance model iLand is a process-based ecosystem model that simulates forest landscape dynamics at the level of individual trees (Seidl et al., 2012). The competition of trees for resources is simulated spatially explicitly in iLand, using an approach rooted in ecological field theory. Resource utilization is modeled based on a light use efficiency approach accounting for atmospheric (suboptimal temperatures, humidity, CO_2 availability) and soil (nitrogen and water availability) constraints. Based on their resource availability individual trees are dynamically adapting their growth strategies to their environment. Trees can either die from age-dependent chance, stress from competition or environmental limitations, or a range of natural disturbance agents (such as wind and wildfire) in the model. Regeneration is modeled spatially explicit in the landscape, taking into account the availability and distribution of seeds, the species-specific climatic limitations for establishment, and the spatial distribution of resources such as light, water, and nutrients. The model was extensively tested and evaluated across a range of ecosystems on two continents in previous studies (Seidl et al., 2012; Silva Pedro et al., 2015). It is particularly well suited to serve as the ecosystem modeling platform for the current study as (i) its individual tree resolution allows the simulation of complex silvicultural activities (such as variable density thinning regimes), (ii) its process-based architecture ensures robust responses of ecosystem processes to changing environmental conditions, and (iii) its computational efficiency and open architecture allow for an efficient integration of complex models of the human system.

Modeling the human system: the ABE model. To represent the human system we've developed and implemented ABE, an Agent-Based model of forEst management. The ABE model provides a framework to dynamically simulate adaptive forest management in multi-agent landscapes under changing environmental conditions. The main agents simulated in ABE are forest managers, i.e., the actors concerned with making silvicultural decisions. We thus consider only one class of agents sensu Smajgl et al. (2011). Different agent types (e.g., small-scale forest owners, industrial forest managers) within this agent class can be distinguished by their behavioral components (Rounsevell et al., 2012). The local environment of the agent is its management unit (MU), i.e., an a priori defined part of the landscape (e.g., via ownership boundaries, management districts within an enterprise) under the stewardship of a given agent. Every MU is dynamically parsed into a set of stand units (SU) in the simulation, which are the spatial entities for operational management decision making by the agent. Here, we focus particularly on the interaction between the agent and the emergent ecosystem dynamics (rather than on agent – agent interactions, which are here limited to indirect communication via the observation of activities on neighboring MUs). In this regard, two general classes of agent behavior are distinguished, representing operational and strategic management decisions. Operational decisions are taken with higher frequency (i.e., annually) and are specific to a SU (e.g., decisions such as whether to harvest a stand in a given year). Conversely, strategic decisions are reevaluated only periodically, and relate to the keystone variables of a silvicultural regime such as rotation age and target species composition, which are valid over the entire MU. Strategic decisions subsequently influence operational decisions (since a change in e.g., rotation period also requires the timing of final harvests of individual SU to be altered). This two-tiered architecture in agent decision making reflects the current forest management practice in Central Europe, where operational management planning is executed on annual (or shorter) time scales, while mid-term planning and strategic adjustments usually coincide with inventory cycles (carried out at approximately decadal intervals). Behaviors for both operational and strategic decisions are chosen from a library of activities supplied to the model (Table 5).

Table 5: The operational (stand-level, SU) and strategic (management unit level, MU) activities available for the agents in ABE.

Level	Activity	Activity description
Operational (SU)	Planting	The activity allows single- and multi-species planting. The spatial distribution of planted individuals can be regular, random, or grouped within the SU.
	Thinning	The thinning activity supports several types of thinning interventions such as thinning from above (removing mainly dominant trees), thinning from below (removing predominately suppressed trees) and selective thinning (removing competitors around selected crop trees). Thinning intensities can be specified separately for relative DBH-classes per species.
	Harvesting	Activity for various kinds of final cuts (i.e., those leading to a regeneration of the stand), allowing the removal of all trees or given fractions of trees above a defined target diameter.
	Salvaging	A special activity which can be triggered after a stand is affected by disturbances (e.g., wind, fire, insect outbreaks), and in which disturbance-killed trees are harvested.
Strategic (MU)	Change rotation age	This activity changes the planned age of final harvesting of stands.
	Change target species	As an important aspect of an agent's silvicultural system, the target species composition can be adapted through this activity.
	Change thinning intensity	Agents can decide to increase their management intensity by either increasing or decreasing the default removals in a thinning (as defined at the operational level).
	Change silvicultural system	The silvicultural system here refers to the general approach towards managing the forest. Distinctly different systems include, for instance, clear-cut forestry, continuous cover forestry, or coppicing.

The combination of agent attributes and the agent's ability to sense its environment drive their decision making behavior (Rounsevell et al., 2012), and determine their adaptive responses to changes in the environment. Agents can adapt dynamically and autonomously to changes in the environment in two ways: First, through an adjustment of operational management to changing stand conditions (passive adaptation (Stankey et al., 2005)), and second by a proactive alteration of key parameters of the prevailing management strategy (active adaptation, (Stankey et al., 2005)). In the current implementation of ABE the former relies on stand conditions and the silvicultural knowledge of agents, while the latter also incorporates an agent's sensitivity towards changes in the ecosystem. Potential future extensions could also consider agent beliefs and demography here (see Blennow et al., 2012), as well as include a response to market changes, policy incentives, and subsidies. The currently implemented agents do not actively communicate and learn from each other. However, their decisions are indirectly influenced by the actions of their neighbors, e.g., with regard to observing spatial contingencies for harvesting adjacent stands. Furthermore, neither at the operational nor at the strategic level a microeconomic approach based on utility functions was used to determine agent decisions (An, 2012). However, since ABE was developed within a flexible computational framework (see below), a variety of different agent representations can easily be implemented and tested in the future.

Coupling human and natural system models. The challenge of coupling human and natural systems can be broken down into two main streams of information, (i) to provide information about the (dynamically changing) state of the natural system to the managing agent, and (ii) to translate information about the management decisions taken by the agent into implications on the natural system (Fig. 10). The following gives an account of how we achieved this reciprocal information flow in our modeling.

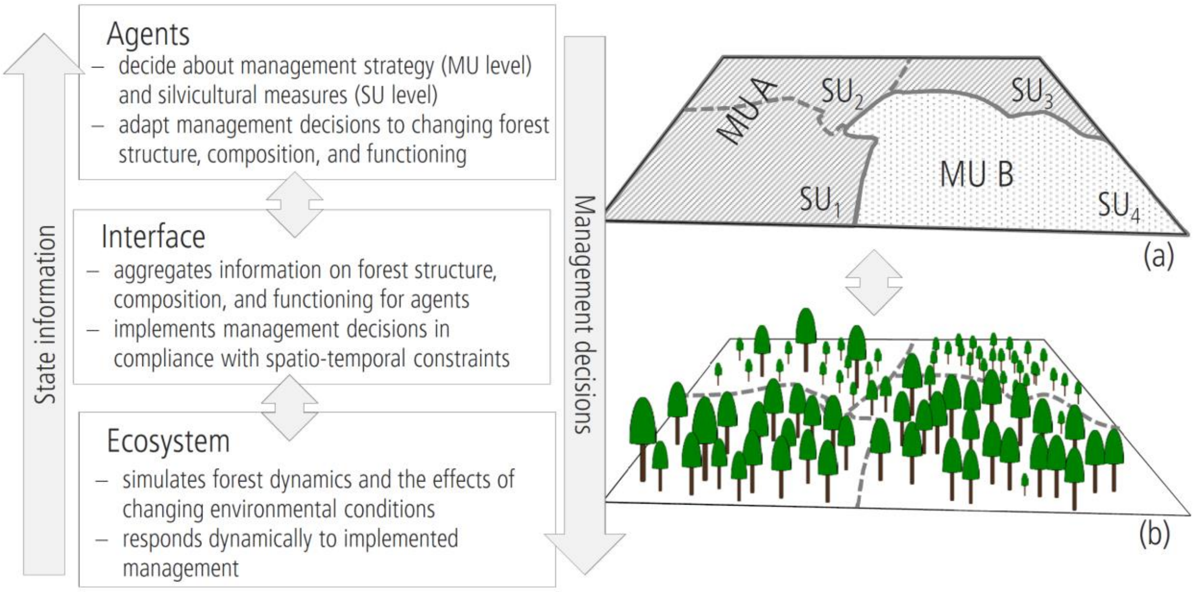

Figure 10: Conceptual overview on the coupling of the human (a) and natural systems (b). A model interface links the agents in the human system with the ecosystem, providing information about the natural world to the agent and translating and implementing agent decisions back into the ecosystem. In the human system, the landscape is divided into management units (MU A, B), and further in forest stands (SU_1 to SU_4). The ecosystem model simulates a continuous forest landscape and its response to forest management decisions and environmental changes.

Information flow from the natural to the human system: An important aspect in decision making is the availability of information on indicators of relevance for the prevailing management goals (Wolfslehner and Seidl, 2010). In silico agents thus need to be able to sense the state of their environment as dynamically simulated by the ecosystem model (Gilbert, 2008). At the level of operational planning (SU) this is achieved by annually compiling key indicators of relevance for silvicultural decisions, such as stand age, stocking level, species composition, and diameter distribution, and communicating them to the agent. Furthermore, information on long-term growth trends and disturbance frequency are available to the manager in order to be considered for stand-level decisions. Based on this information the agent consults its silvicultural strategy and knowledge (as defined by the current stand-treatment program of an agent) and identifies a suitable management action from its available list of behaviors (Fraser et al., 2013).

At the level of strategic decision making, a decision heuristic to determine decadal-scale annual allowable cut in line with criteria of sustainable timber yield is implemented, using information on mean increment and age-class structure from the dynamically simulated ecosystem. Furthermore, MU-level indicators of ecosystem change are passed on to the agent. Depending on the specification of the agent these can, for instance, include changes in growth, mortality, and the species composition relative to a specified target. These are subsequently evaluated against an agent's sensitivity towards such changes in order to determine whether the current strategy is changed. Depending on the agent architecture this sensitivity can be linked to the beliefs, experiences, education, and demographics of an agent, and is ideally underpinned by empirical data, as it forms the backbone of active adaptive behavior of agents. Should an agent decide to implement strategic changes (cf. Table 5 for a list of strategic management options), all subsequent stand-level management decisions will be affected by this decision via an updating of its stand treatment programs.

Information flow from the human to the natural system: While – based on the ecosystem information provided to the agent – a silvicultural assessment is made for each stand at every time step, not every stand is treated in every time step. The first step in translating individual human decisions back to the landscape thus entails an evaluation of all individual SU-level decisions in the context of the management unit (e.g., considering stand neighborhoods), legal constraints, and overall goals (e.g., annual allowable cut). In ABE, SU-level activities are scheduled according to their planned execution date in order to translate individual SU management considerations to a MU implementation plan for every year. An agent property decides whether the planned harvests of the upcoming decadal planning period are spread evenly over the years or scheduled as close as possible to the planned execution date, respecting the constraints at MU level (Gustafson et al., 2000). Here, not only goal constraints (e.g., annual allowable cut) but also legal constraints can be considered, e.g., by prioritizing salvage harvesting when required by law in order to prevent further spread of damages (Anonymous, 2002). The agents continuously track differences between planned and realized activities at the MU, and dynamically adapt by adjusting their year to year behavior, e.g., harvesting more than planned in a previous year is compensated by a lower cutting level in the following year. In addition to a cap on treatments the scheduling algorithm of the agent decision engine can also enforce a minimum annual harvest level, e.g., if management is required to cover the fixed costs of a forest enterprise. Furthermore, spatial constraints need to be considered by the agent in scheduling stand-level treatments. Stands that are adjacent to those being clear-cut in the current year (or which are not yet sufficiently regenerated), for instance, must not be cut in the same time step to not exceed (a legally required) maximum clear-cut size (e.g., 2 ha according to the Austrian forest act (Anonymous, 2002)). Based on agent properties and legal constraints the scheduling algorithm of the agent decision engine thus transforms the bottom-up, stand level silvicultural planning into an annual action plan for implementation in the ecological sphere. Consequently, the model interface uses this action plan of every agent to implement management measures in the ecological context of iLand, altering the forest structure in the ecosystem model by removing or planting individual trees. The applied algorithms of this implementation are based on previously developed approaches for implementing complex management interventions in individual-based forest models (Seidl et al., 2011b).

Technical implementation: The software implementation of ABE combines high-level scripting (Javascript) with a low-level core component (C++) for performance-critical parts. ABE follows the declarative paradigm (Jamil and Islam, 2009), effectively freeing model users from the necessity of programming. Declarative – in contrast to imperative – programming means to describe the desired results, instead of the steps required to accomplish those results. By facilitating a scripting approach the definition of agents and stand treatment programs is highly flexible and can be easily adapted to the particular demands of specific model applications. Activities (Table 5), on the other hand, are implemented in a lower level language (C++), allowing for a closer link to the ecological processes simulated in the ecosystem model. ABE is built upon the Qt library, an open source, cross-platform C++ library. All model code and executables developed and applied here are available under a GNU open source license from http://iLand.boku.ac.at.

References (sections 1-6)

Adger, W.N., Dessai, S., Goulden, M., Hulme, M., Lorenzoni, I., Nelson, D.R., Naess, L.O., Wolf, J., Wreford, A., 2009. Are there social limits to adaptation to climate change? Clim. Change 93, 335–354.

An, L., 2012. Modeling human decisions in coupled human and natural systems: Review of agent-based models. Ecol. Modell. 229, 25–36.

Anonymous, 2002. Bundesgesetz vom 3. Juli 1975, mit dem das Forstwesen geregelt wird, in der Novellierung vom 12. April 2002. Vienna, Austria.

Anonymous, 2009. Österreichische Waldinventur 2007-2009. Austrian Research Centre for Forests, Vienna, Austria.

Bello, D., Leung, K., Radebaugh, L., Tung, R.L., van Witteloostuijn, A., 2009. From the Editors: Student samples in international business research. J. Int. Bus. Stud. 40, 361–364.

BFW, 2013a. Durchforstungsversuchsfläche Nr. 220, St. Oswald ob Eibiswald / Stmk., Exkursionsführer. Wien.

BFW, 2013b. Europäischer Stammzahlhaltungsversuch Nr. 304, Ottenstein / NÖ, Exkursionsführer. Wien.

BFW, 2014. Durchforstungsversuch Nr. 301, Karlstift / NÖ, Exkursionsführer. Wien.

Biggs, R., Schlüter, M., Biggs, D., Bohensky, E.L., BurnSilver, S., Cundill, G., Dakos, V., Daw, T.M., Evans, L.S., Kotschy, K., Leitch, A.M., Meek, C., Quinlan, A., Raudsepp-Hearne, C., Robards, M.D., Schoon, M.L., Schultz, L., West, P.C., 2012. Toward principles for enhancing the resilience of ecosystem services. Annu. Rev. Environ. Resour. 37, 421–448.

Blennow, K., Persson, J., 2009. Climate change: Motivation for taking measure to adapt. Glob. Environ. Chang. 19, 100–104.

Blennow, K., Persson, J., Tome, M., Hanewinkel, M., 2012. Climate change: Believing and seeing implies adapting. PLoS One 7, e50182.

Bolte, J.P., Hulse, D.W., Gregory, S. V., Smith, C., 2006. Modeling biocomplexity – actors, landscapes and alternative futures. Environ. Model. Softw. 22, 570–579.

Bone, C., Dragićević, S., 2009. Evaluating Spatio-temporal Complexities of Forest Management: An Integrated Agent-based Modeling and GIS Approach. Environ. Model. Assess. 14, 481–496.

Boon, T.E., Meilby, H., 2007. Describing management attitudes to guide forest policy implementation. Small-scale For. 6, 79–92.

Bousquet, F., Le Page, C., 2004. Multi-agent simulations and ecosystem management: a review. Ecol. Modell. 176, 313–332.

Breiman, L., 2001. Random Forests. Mach. Learn. 45, 5–32.

Bu, R., He, H.S., Hu, Y., Chang, Y., Larsen, D.R., 2008. Using the LANDIS model to evaluate forest harvesting and planting strategies under possible warming climates in Northeastern China. For. Ecol. Manage. 254, 407–419.

Butchart, S.H.M., Walpole, M., Collen, B., van Strien, A., Scharlemann, J.P.W., Almond, R.E.A., Baillie, J.E.M., Bomhard, B., Brown, C., Bruno, J., Carpenter, K.E., Carr, G.M., Chanson, J., Chenery, A.M., Csirke, J., Davidson, N.C., Dentener, F., Foster, M., Galli, A., Galloway, J.N., Genovesi, P., Gregory, R.D., Hockings, M., Kapos, V., Lamarque, J.-F., Leverington, F., Loh, J., McGeoch, M.A., McRae, L., Minasyan, A., Morcillo, M.H., Oldfield, T.E.E., Pauly, D., Quader, S., Revenga, C., Sauer, J.R., Skolnik, B., Spear, D., Stanwell-Smith, D., Stuart, S.N., Symes, A., Tierney, M., Tyrrell, T.D., Vié, J.-C., Watson, R., 2010. Global Biodiversity: Indicators of Recent Declines. Science (80-.). 328, 1164–1168.

Chapin, F.S., Carpenter, S.R., Kofinas, G.P., Folke, C., Abel, N., Clark, W.C., Olsson, P., Smith, D.M.S., Walker, B., Young, O.R., Berkes, F., Biggs, R., Grove, J.M., Naylor, R.L., Pinkerton, E., Steffen, W., Swanson, F.J., 2010. Ecosystem stewardship: sustainability strategies for a rapidly changing planet. Trends Ecol. Evol. 25, 241–249.

Cutler, D.R., Edwards, T.C., Beard, K.H., Cutler, A., Hess, K.T., Gibson, J., Lawler, J.J., 2007.

Random forests for classification in ecology. Ecology 88, 2783–2792.

D’Amato, A.W., Bradford, J.B., Fraver, S., Palik, B.J., 2013. Effects of thinning on drought vulnerability and climate response in north temperate forest ecosystems. Ecol. Appl. 28, 1735–1742.

Dayer, A.A., Allred, S.B., Stedman, R.C., 2014. Comparative analysis and assessment of forest landowner typologies. Soc. Nat. Resour. 27, 1200–1212.

Driscoll, D.A., Lindenmayer, D.B., 2012. Framework to improve the application of theory in ecology and conservation. Ecol. Monogr. 82, 129–147.

Duveneck, M.J., Scheller, R.M., White, M.A., 2014. Effects of alternative forest management on biomass and species diversity in the face of climate change in the northern Great Lakes region (USA). Can. J. For. Res. 44, 700–710.

Elkin, C., Gutiérrez, A.G., Leuzinger, S., Manusch, C., Temperli, C., Rasche, L., Bugmann, H., 2013. A 2 °C warmer world is not safe for ecosystem services in the European Alps. Glob. Chang. Biol. 19, 1827–1840.

Eriksson, L., 2014. Risk perception and responses among private forest owners in Sweden. Small-scale For. 13, 483–500.

Evans, M.R., 2012. Modelling ecological systems in a changing world. Philos. Trans. R. Soc. Lond. B. Biol. Sci. 367, 181–190.

Filatova, T., Verburg, P.H., Parker, D.C., Stannard, C.A., 2013. Spatial agent-based models for socio-ecological systems: Challenges and prospects. Environ. Model. Softw. 45, 1–7.

Folke, C., 2006. Resilience: The emergence of a perspective for social–ecological systems analyses. Glob. Environ. Chang. 16, 253–267.

Fowler, F.J., 2009. Survey research methods, 4th ed. Sage Publications, Thousand Oaks, USA.

Fraser, J.S., He, H.S., Shifley, S.R., Wang, W.J., Thompson, F.R., 2013. Simulating stand-level harvest prescriptions across landscapes: LANDIS PRO harvest module design. Can. J. For. Res. 43, 972–978.

Gaube, V., Kaiser, C., Wildenberg, M., Adensam, H., Fleissner, P., Kobler, J., Lutz, J., Schaumberger, A., Schaumberger, J., Smetschka, B., Wolf, A., Richter, A., Haberl, H., 2009. Combining agent-based and stock-flow modelling approaches in a participative analysis of the integrated land system in Reichraming, Austria. Landsc. Ecol. 24, 1149–1165.

Gebhardt, T., Häberle, K.-H., Matyssek, R., Schulz, C., Ammer, C., 2014. The more, the better? Water relations of Norway spruce stands after progressive thinning. Agric. For. Meteorol. 197, 235–243.

Gilbert, N., 2008. Agent-based models. Sage, Los Angeles, CA.

Gruber, N., Galloway, J.N., 2008. An Earth-system perspective of the global nitrogen cycle. Nature 451, 293–296.

Gustafson, E.J., Shifley, S.R., Mladenoff, D.J., Nimerfro, K.K., He, H.S., 2000. Spatial simulation of forest succession and timber harvesting using LANDIS. Can. J. For. Res. 30, 32–43.

Hengeveld, G.M., Didion, M., Clerkx, S., Elkin, C., Nabuurs, G.-J., Schelhaas, M.-J., 2015. The landscape-level effect of individual-owner adaptation to climate change in Dutch forests. Reg. Environ. Chang. in press, doi:10.1007/s10113–014–0718–5.

Hogl, K., Pregernig, M., Weiss, G., 2005. What is new about forest owners? A typology of private forest ownership in Austria. Small-scale For. Econ. Manag. Policy 4, 325–342.

Holling, C.S., 1973. Resilience and stability of ecological systems. Annu. Rev. Ecol. Syst. 4, 1–23.

Holling, C.S., Meffe, G.K., 1996. Command and control and the pathology of natural resource management. Conserv. Biol. 10, 328–337.

Ingemarson, F., Lindhagen, A., Eriksson, L., 2006. A typology of small-scale private forest owners in Sweden. Scand. J. For. Res. 21, 249–259.

Jamil, H., Islam, A., 2009. The power of declarative languages: A comparative exposition of scientific workflow design using BioFlow and Taverna. Serv. 2009 - 5th 2009 World Congr.

Serv. 322–329.

Janssen, M.A., Ostrom, E., 2006. Empirically based , agent-based models. Ecol. Soc. 11, 37.

Kaufman, L., Rousseeuw, P.J., 1990. Finding Groups in Data: An Introduction to Cluster Analysis. Wiley, New York.

Kelley, H., Evans, T., 2011. The relative influences of land-owner and landscape heterogeneity in an agent-based model of land-use. Ecol. Econ. 70, 1075–1087.

Kostadinov, F., Holm, S., Steubing, B., Thees, O., Lemm, R., 2013. Simulation of a Swiss wood fuel and roundwood market: An explorative study in agent-based modeling. For. Policy Econ. 1–14.

Lawrence, A., Marzano, M., 2014. Is the private forest sector adapting to climate change? A study of forest managers in north Wales. Ann. For. Sci. 71, 291–300.

Leahy, J.E., Reeves, E.G., Bell, K.P., Straub, C.L., Wilson, J.S., 2013. Agent-based modeling of harvest decisions by small scale forest landowners in Maine, USA. Int. J. For. Res. 563068, 1–12.

Lidskog, R., Sjödin, D., 2014. Why do forest owners fail to heed warnings? Conflicting risk evaluations made by the Swedish forest agency and forest owners. Scand. J. For. Res. 29, 275–282.

Liu, J., Dietz, T., Carpenter, S.R., Alberti, M., Folke, C., Moran, E., Pell, A.N., Deadman, P., Kratz, T., Lubchenco, J., Ostrom, E., Ouyang, Z., Provencher, W., Redman, C.L., Schneider, S.H., Taylor, W.W., 2007. Complexity of coupled human and natural systems. Science (80-.). 317, 1513–1516.

Mäkelä, A., Landsberg, J., Ek, A.R., Burk, T.E., Ter-Mikaelian, M., Ågren, G.I., Oliver, C.D., Puttonen, P., 2000. Process-based models for forest ecosystem management: current state of the art and challenges for practical implementation. Tree Physiol. 20, 289–298.

Moen, J., Keskitalo, E.C.H., 2010. Interlocking panarchies in multi-use boreal forests in Sweden. Ecol. Soc. 15, art.17.

Mori, A.S., Furukawa, T., Sasaki, T., 2013. Response diversity determines the resilience of ecosystems to environmental change. Biol. Rev. 88, 349–364.

Moser, S.C., Ekstrom, J.A., 2010. A framework to diagnose barriers to climate change adaptation. Proc. Natl. Acad. Sci. U. S. A. 107, 22026–22031.

Parrott, L., Chion, C., Gonzalès, R., Latombe, G., 2012. Agents, individuals, and networks: Modeling methods to inform natural resource management in regional landscapes. Ecol. Soc. 17, art32.

Petr, M., Boerboom, L., Ray, D., van der Veen, A., 2014. An uncertainty assessment framework for forest planning adaptation to climate change. For. Policy Econ. 41, 1–11.

Podsakoff, P.M., MacKenzie, S.B., Lee, J.-Y., Podsakoff, N.P., 2003. Common method biases in behavioral research: a critical review of the literature and recommended remedies. J. Appl. Psychol. 88, 879–903.

Pregernig, M., 2001. Values of Forestry Professionals and their Implications for the Applicability of Policy Instruments. Scand. J. For. Res. 16, 278–288.

Primmer, E., Karppinen, H., 2010. Professional judgment in non-industrial private forestry: Forester attitudes and social norms influencing biodiversity conservation. For. Policy Econ. 12, 136–146.

Rasche, L., Fahse, L., Zingg, A., Bugmann, H., 2011. Getting a virtual forester fit for the challenge of climatic change. J. Appl. Ecol. 48, 1174–1186.

Rockström, J., Steffen, W., Noone, K., Persson, A., Chapin, F.S., Lambin, E.F., Lenton, T.M., Scheffer, M., Folke, C., Schellnhuber, H.J., Nykvist, B., de Wit, C.A., Hughes, T., van der Leeuw, S., Rodhe, H., Sörlin, S., Snyder, P.K., Costanza, R., Svedin, U., Falkenmark, M., Karlberg, L., Corell, R.W., Fabry, V.J., Hansen, J., Walker, B., Liverman, D., Richardson, K., Crutzen, P., Foley, J.A., 2009. A safe operating space for humanity. Nature 461, 472–475.

Rounsevell, M.D.A., Robinson, D.T., Murray-Rust, D., 2012. From actors to agents in socio-ecological systems models. Philos. Trans. R. Soc. Lond. B. Biol. Sci. 367, 259–69.

Satake, A., Leslie, H.M., Iwasa, Y., Levin, S.A., 2007. Coupled ecological-social dynamics in a forested landscape: spatial interactions and information flow. J. Theor. Biol. 246, 695–707.

Schou, E., Thorsen, B.J., Jacobsen, J.B., 2015. Regeneration decisions in forestry under climate change related uncertainties and risks: Effects of three different aspects of uncertainty. For. Policy Econ. 50, 11–19.

Schwab, O., Maness, T., Bull, G., Roberts, D., 2009. Modeling the effect of changing market conditions on mountain pine beetle salvage harvesting and structural changes in the British Columbia forest products industry. Can. J. For. Res. 39, 1806–1820.

Seidl, R., 2014. The Shape of Ecosystem Management to Come: Anticipating Risks and Fostering Resilience. Bioscience 64, 1159–1169.

Seidl, R., Eastaugh, C.S., Kramer, K., Maroschek, M., Reyer, C., Socha, J., Vacchiano, G., Zlatanov, T., Hasenauer, H., 2013. Scaling issues in forest ecosystem management and how to address them with models. Eur. J. For. Res. 132, 653–666.

Seidl, R., Rammer, W., Lexer, M.J., 2011a. Adaptation options to reduce climate change vulnerability of sustainable forest management in the Austrian Alps. Can. J. For. Res. 41, 694–706.

Seidl, R., Rammer, W., Lexer, M.J., 2011b. Climate change vulnerability of sustainable forest management in the Eastern Alps. Clim. Change 106, 225–254.

Seidl, R., Rammer, W., Scheller, R.M., Spies, T.A., 2012. An individual-based process model to simulate landscape-scale forest ecosystem dynamics. Ecol. Modell. 231, 87–100.

Seidl, R., Schelhaas, M.-J., Lexer, M.J., 2011c. Unraveling the drivers of intensifying forest disturbance regimes in Europe. Glob. Chang. Biol. 17, 2842–2852.

Seidl, R., Schelhaas, M.-J., Rammer, W., Verkerk, P.J., 2014. Increasing forest disturbances in Europe and their impact on carbon storage. Nat. Clim. Chang. 4, 806–810.

Silva Pedro, M., Rammer, W., Seidl, R., 2015. Tree species diversity mitigates disturbance impacts on the forest carbon cycle. Oecologia 177, 619–630.

Smajgl, A., Bohensky, E., 2013. Behaviour and space in agent-based modelling: Poverty patterns in East Kalimantan, Indonesia. Environ. Model. Softw. 45, 8–14.

Smajgl, A., Brown, D.G., Valbuena, D., Huigen, M.G.A., 2011. Empirical characterisation of agent behaviours in socio-ecological systems. Environ. Model. Softw. 26, 837–844.

Spies, T.A., White, E.M., Kline, J.D., Fischer, A.P., Ager, A., Bailey, J., Bolte, J., Koch, J., 2014. Examining fire-prone forest landscapes as coupled human and natural systems. Ecol. Soc. 19, art9.

Stankey, G.H., Clark, R.N., Bormann, B.T., 2005. Adaptive Management of Natural Resources: Theory, Concepts, and Management Institutions, General Technical Report PNW-GTR-654. Portland, OR.

Temperli, C., Bugmann, H., Elkin, C., 2012. Adaptive management for competing forest goods and services under climate change. Ecol. Appl. 22, 2065–2077.

Thom, D., Seidl, R., Steyrer, G., Krehan, H., Formayer, H., 2013. Slow and fast drivers of the natural disturbance regime in Central European forest ecosystems. For. Ecol. Manage. 307, 293–302.

Turner, M.G., Donato, D.C., Romme, W.H., 2013. Consequences of spatial heterogeneity for ecosystem services in changing forest landscapes: priorities for future research. Landsc. Ecol. 28, 1081–1097.

Tversky, A., Kahneman, D., 1981. The framing of decisions and the psychology of choice. Science (80-.). 211, 453–458.

Walker, B., Holling, C.S., Carpenter, S.R., Kinzig, A., 2004. Resilience , Adaptability and Transformability in Social – ecological Systems. Ecol. Soc. 9.

Weber, E.U., 2006. Experience-based and description-based perceptions of long-term risk: Why global warming does not scare us (yet). Clim. Change 77, 103–120.

Wolfslehner, B., Seidl, R., 2010. Harnessing ecosystem models and multi-criteria decision analysis for the support of forest management. Environ. Manage. 46, 850–861.

Zivojinovic, I., Wolfslehner, B., 2015. Perceptions of Urban Forestry Stakeholders about Climate Change Adaptation – a Q-Method application in Serbia. Urban For. Urban Green. 14, 1079–1087.

7 Workplan

The project kick-off was in March 2013, and according to the proposed work plan the first task was to develop the algorithms for an agent-based model of forest management. To that end the literature was screened, previous models from other sectors reviewed, and an approach appropriate for the context of forest management in central Europe developed. Once the structure of the model emerged from this developmental work, we in parallel started to work on researching the information needed to parameterize the managers responses in the agent-based model. Although initially only a questionnaire among students was proposed (see proposal), we decided to extend this crucial work package to also include practitioners. After developing the questionnaire and implementing it for online dissemination we implemented the questionnaire campaign in the spring of 2014. Subsequently, we worked on interpreting the questionnaire results, as well as on implementing the management model within the landscape simulation model framework iLand. After having conducted the first tests of the model prototype we engaged in extensive testing and first scenario analyses in the last part of the project. Specifically, we tested the models ability to realistically capture a wide range of thinning responses (stand level testing). Furthermore, we tested whether the simulated management agents were able to autonomously make management decisions at the scale of a management unit (landscape level testing). Finally, we studied climate change scenarios to evaluate the potential of thinnings to mitigate climate change impacts, and to test how active and passive adaptation of a heterogeneous population of managers on the landscape affects ecosystem trajectories. The cost-neutral extension of the originally proposed project duration by two months allowed us to also complete these final scenario runs, with which we have delivered all the proposed milestones/ deliverables.

8 Publications and dissemination

Peer-reviewed papers

Author(s)	**Title**	**Publisher**
Seidl, R.	The Shape of Ecosystem Management to Come: Anticipating Risks and Fostering Resilience.	BioScience 64, 1159-1169, 2014. doi: 10.1093/biosci/biu172
Rammer, W., Seidl, R.	Coupling human and natural systems: Simulating adaptive management agents in dynamically changing forest landscapes	Global Environmental Change 35, 475-485, 2015. doi: 10.1016/j.gloenvcha.2015.10.003
Seidl, R., Aggestam, F., Rammer, W., Blennow, K., Wolfslehner, B.	The sensitivity of current and future forest managers to climate-induced changes in ecological processes	Ambio, accepted for publication. doi: 10.1007/s13280-015-0737-6

Seidl, R., Vigl, F., Rössler, G., Neumann, M., Rammer, W.	Thinning and ecosystem dynamics of Central European mountain forests under climate change: a re-analysis of long-term thinning trials using simulation modeling	In preparation; to be submitted to Forest Ecology and Management

Presentations

Author(s)	**Title**	**Conference**	**Type**
Seidl, R.	Klima und Waldschäden im Wandel – Herausforderung für den Waldbau.	Was tun, wenn's kracht? Wirkungsvolles Management von Kalamitäten. Forstliche Ausbildungsstätte Pichl, Feburary 27, 2014, Mitterdorf im Mürztal, Austria	Outreach
Rammer, W., Seidl, R.	Qt powered tools for the modelling of forest ecosystems.	Qt Developer Days 2014 Europe, October 6-8, 2014, Berlin, Germany	Science
Rammer, W., Seidl, R.	Managing change: an agent-based model of adaptive forest management at the landscape scale.	8th European Conference on Ecological Modeling, ECEM 2014 - Beyond boundaries: next generation modelling - October 27-30, 2014, Marrakech, Morocco	Science
Rammer, W., Seidl, R., Aggestam, F., Blennow, K., Wolfslehner, B.	Wie sensitiv reagieren WaldbewirtschafterInnen auf klimabedingte Änderungen in ökologischen Prozessen?	16. Österreichischer Klimatag - Aktuelle Klimaforschung in Österreich, April 28-30, 2015, Vienna, Austria	Outreach
Seidl, R., Rammer, W.	Simulation von dynamischen Rückkoppelungen zwischen Wald und seinen Bewirtschaftern unter sich wandelnden Klimabedingungen	16. Österreichischer Klimatag - Aktuelle Klimaforschung in Österreich, April 28-30, 2015, Vienna, Austria	Outreach
Rammer, W., Seidl, R.	Responding to a changing world: Modeling adaptive management agents in forest landscapes.	9th World Congress, International Association for Landscape Ecology, July 5-10, 2015, Portland, OR, USA	Science