REPORT

The sensitivity of current and future forest managers to climate-induced changes in ecological processes

Rupert Seidl, Filip Aggestam, Werner Rammer,
Kristina Blennow, Bernhard Wolfslehner

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Abstract Climate vulnerability of managed forest ecosystems is not only determined by ecological processes but also influenced by the adaptive capacity of forest managers. To better understand adaptive behaviour, we conducted a questionnaire study among current and future forest managers (i.e. active managers and forestry students) in Austria. We found widespread belief in climate change (94.7 % of respondents), and no significant difference between current and future managers. Based on intended responses to climate-induced ecosystem changes, we distinguished four groups: 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 (14.4 %). Experiences and beliefs with regard to disturbance-related tree mortality were found to particularly influence a manager's sensitivity to climate change. Our findings underline the importance of the social dimension of climate change adaptation, and suggest potentially strong adaptive feedbacks between ecosystems and their managers.

Keywords Climate change adaptation · Beliefs and experiences · Forest management · Growth change · Disturbance change · Regeneration change

INTRODUCTION

Forest ecosystems and the services they provide for society are increasingly under pressure from climate change

(Lindner et al. 2010). Recent research has shown that future climate change is likely to profoundly alter all main processes of forest dynamics, i.e. tree growth, mortality, and regeneration. Growth, for instance, is generally expected to increase in higher latitudes and altitudes (due to extended growing seasons and the effect of CO₂ fertilization), while a reduction from increasing water limitations can be expected in warmer and drier regions of the globe (Reyer et al. 2014). Increased mortality from drought and disturbances such as wildfires and insect outbreaks is furthermore expected under climate change (Seidl et al. 2014). Due to climate-induced shifts in species' niches, a changing dynamic of forest regeneration is also likely, possibly leading to altered forest composition in the future (Hanewinkel et al. 2013).

Globally, the vast majority of forest ecosystems are managed (with only approximately 13 % currently under legal protection (FAO 2010)), providing important ecosystem goods and services for society (MA 2005). In managed forests, human interventions are the primary drivers of forest structure, composition, and functioning, which means that aspects of management can modulate (or override) the response of ecosystem processes to climate change (Rasche et al. 2013). In order to understand how forests will react to changes in the global climate system, it is thus essential to consider both ecological sensitivities and social responses to these changes (Seidl and Lexer 2013). Consequently, to address climate change impacts on managed forest ecosystems, a coupled human and natural systems perspective is needed (cf. Liu et al. 2007). However, hitherto the large majority of climate change research in forest ecosystems has focused on understanding climate change impacts on ecological processes. Managers responses to a changing environment and the potential feedbacks on ecosystems through changes in management still remain poorly understood (e.g. Grothmann and Patt 2005).

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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; Wagner et al. 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.

However, while many recent assessments of the climate vulnerability of forests incorporate detailed responses of ecosystem processes to climatic changes (e.g. via the application of process-based ecosystem models), management responses to climate change are either prescribed a priori (i.e. managers change their behaviours at a predefined point in time) or a continuation of past management regimes is assumed (e.g. Seidl et al. 2011a; Elkin et al. 2013). Currently, the dynamic response of managers to changes in the environment is rarely taken into account in climate change vulnerability studies. Consequently, they underestimate the social adaptive capacity and response diversity of managed forest ecosystems, which may lead to unrealistic results and can bias scenario analyses of future forest trajectories.

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. To address these questions, we conducted a questionnaire study among current forest managers in the Austrian province of Styria. 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.

MATERIALS AND METHODS

Materials

Questionnaire design

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 contained a total of 24 questions, whereof 16 were relevant for the objectives of the current study. 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). In line with the primary study question, the main focus of the questionnaire was on changes in growth, mortality, and regeneration. 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 (cf. Seidl et al. 2011a). 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). Questions were designed as closed-answer questions, but eleven of the questions gave the respondents the opportunity to add further comments and provide alternative answers. All questions were formulated in German, with English translations given in Table 1 and Tables S1–S2 (Appendix S1). The information gathered from specific questions is referred to by the letter Q throughout the manuscript.

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 (<i>n</i> = 189)	Very likely	54.0
	Rather likely	40.7
	Rather unlikely	3.2
	I don't believe in climate change	2.1
	No opinion	0.0
Q06: Have you already experienced climate change impacts in the forest (<i>n</i> = 189)	Yes	54.0
	Not sure	29.6
	No	16.4
Q07: If so, which changes have you observed (multiple answers possible) (<i>n</i> = 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 (<i>n</i> = 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) (<i>n</i> = 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 (<i>n</i> = 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 (<i>n</i> = 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 (<i>n</i> = 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

Participants

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). Information on the demographics of the respondents can be found in Table 2.

To test for inter-generational differences in sensitivity to climate change (Adger et al. 2009) and address the question whether future forest managers differ from current managers with regard to their intended responses to climate change, we ran a second campaign among graduate students at the University of Natural Resources and Life Sciences Vienna (subsequently referred to as “future managers”) using the same questionnaire. 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).

Methods

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. Since no clear hierarchy of influence between beliefs and experiences of climate change could be established in previous work (Myers et al. 2012), we here used these two variables independently (see also Blennow and Persson 2009; Blennow et al. 2012), but accounted for their possible interactions via a statistical approach that is robust to such covariation (see below). After an exploratory analysis, we tested for differences in beliefs and experiences between current and 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 were related to 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,

Table 2 Demographic structure and highest level of completed forestry education of questionnaire respondents (questions Q13 and Q16, see Appendix 1)

	Gender	Age	No forestry education	Applied forestry education	Forest warden	Forester	Academic degree in forestry	Total
Current forest managers	Male	<30	3	2	5	4	–	14
		30–50	17	23	2	5	10	57
		50>	14	10	6	2	10	42
	Female	<30	1	–	1	1	1	4
		30–50	5	1	–	1	1	8
		50>	4	–	–	–	–	4
Future forest managers	Male	<30	12	2	–	6	16	36
		30–50	2	2	–	–	2	6
		50>	–	–	–	–	–	–
	Female	>30	2	–	–	–	8	10
		30–50	–	–	–	–	–	–
		50>	–	–	–	–	–	–
Total			60	40	14	19	48	181

disturbance, and regeneration (Q10–12). A graphical outline of our analysis approach is given in Fig. 1. Due to often observed issues of asymmetry and framing when using positive (gains) versus negative (losses) terminology (e.g. Tversky and Kahneman 1981), we here focused solely on managers experiencing or believing in negative climate-related outcomes. However, analysing beliefs and experiences regardless of their directionality did not change the main findings reported here (see Appendix S2 in the Electronic Supplementary Material for a joint analysis of climate risks and opportunities).

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).

RESULTS

Beliefs and experiences of managers regarding environmental changes

Analysing the 246 respondents for differences between current and future managers showed that current managers were significantly older ($P < 0.001$, Q14). They were also less likely to have received a higher general education, but a considerable share had received training as forestry worker or forest warden (Table 2, Q15, Q16). In contrast, future managers were significantly younger and had a higher level of general education ($P < 0.001$), but were less likely to having received a practical forestry-related education (see Appendix 1).

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). Correlation analyses showed that while there is no effect of age or gender, lower general education reduced the likelihood of having experienced negative effects of climate change. Most notably, however, 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

Fig. 1 Overview of the analysed variables and relationships. Q refers to the questions of the questionnaire, and # denotes the section of the paper that presents the respective results: #3.1: Beliefs and experiences of managers regarding environmental changes; #3.2: Sensitivity of managers to climate-induced changes in ecosystem processes; #3.3: How beliefs and experiences affect the climate change sensitivity of forest managers

Table 3 There was no significant difference in the beliefs and experiences between the sub-samples of current and future forest managers (χ^2 test). Q denotes the number of the question (see Table 1)

Type	Beliefs and experiences	<i>P</i> value
General (<i>n</i> = 189)	General belief in climate change (Q05)	0.576
	General experiences of climate change impacts (Q06)	0.204
Process-specific (<i>n</i> = 246)	Belief in future growth loss (Q09)	0.134
	Already experiencing growth loss (Q07)	0.232
	Belief in future disturbance increase (Q09)	0.501
	Already experiencing disturbance increase (Q07)	0.411
	Belief in future regeneration problems (Q09)	0.954
	Already experiencing regeneration problems (Q07)	0.822

future effects on individual ecosystem processes (Table 3). We thus pooled the two groups for the subsequent analyses.

Sensitivity of managers to climate-induced changes in ecosystem processes

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 only 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 (Fig. 2).

How beliefs and experiences affect the climate change sensitivity of forest managers

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 (Table S5).

Types of responders to environmental 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 who 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 4).

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 in

Fig. 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

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 (Fig. 3). 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 (Fig. 4a). 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 (Fig. 4b). 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 (Fig. 4d).

DISCUSSION AND CONCLUSION

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 (e.g. 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 (Weber 2006; Blennow and Persson 2009; Blennow et al. 2012). 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

Table 4 Types of responses to negative environmental changes among managers, 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
		Growth	Disturbance	Regeneration	
Early adapters	27.7	SL:3 (high: adapt if changes >20 %)	SL:3 (high: adapt if frequency changes >twofold)	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 >fivefold)	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 >tenfold)	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

(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).

Fig. 3 The relative importance of individual variables in explaining the membership of respondents in one of the four response types (cf. Table 4). Importance values were determined by means of the machine learning algorithm Random Forest, and indicate the percent increase in mean squared error (MSE) in the modelled data when values for that particular predictor were randomly permuted and all other predictors were left unaltered. Higher values indicate a higher importance of the variable (for details see Breiman 2001; Cutler et al. 2007)

Fig. 4 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–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

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. 2011b). 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 (cf. 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 (see also, e.g. 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 (Hogl et al. 2005; Ingemarson et al. 2006; Boon and Meilby 2007; Hujala et al. 2013; Dayer et al. 2014). 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 forestry professionals might differ (Pregernig 2001), it is important to recognize 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 (e.g. Elkin et al. 2013; Seidl et al. 2011a). 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 (Janssen and Ostrom 2006; Filatova et al. 2013; Rammer and Seidl 2015). 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.

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AUTHOR BIOGRAPHIES

Rupert Seidl (✉) is an Associate Professor at the University of Natural Resources and Life Sciences (BOKU) in Vienna, Austria. His work focuses on changing climate and disturbance regimes, and how they impact forest ecosystem management.

Address: Department of Forest- and Soil Sciences, Institute of Silviculture, University of Natural Resources and Life Sciences (BOKU), Peter Jordan Straße 82, 1190 Vienna, Austria.
e-mail: rupert.seidl@boku.ac.at

Filip Aggestam works as a researcher for the European Forest Institute Central-East European Regional Office (EFICEEC) in Vienna, Austria. He is specialized in the fields of national and international forest policy as well as stakeholder participation.

Address: European Forest Institute Central-East European Regional Office, c/o University of Natural Resources and Life Sciences (BOKU), Feistmantelstrasse 4, 1190 Vienna, Austria.
e-mail: filip.agggestam@efi.int

Werner Rammer is a senior scientist at the University of Natural Resources and Life Sciences (BOKU) in Vienna, Austria. He is interested in how forest management impact current and future ecosystem development and how management can be integrated in forest ecosystem models.

Address: Department of Forest- and Soil Sciences, Institute of Silviculture, University of Natural Resources and Life Sciences (BOKU), Peter Jordan Straße 82, 1190 Vienna, Austria.
e-mail: werner.rammer@boku.ac.at

Kristina Blennow is a Professor of Landscape Planning, directed towards Landscape Analysis in particular with respect to climate change and risk analysis. Her current research interests are in the interplay between people and their environment, through this supporting communication, planning and decision making under uncertain and changing conditions, in particular in relation to climate change.

Address: Department of Landscape Architecture, Planning and Management, Swedish University of Agricultural Sciences (SLU), Slottsvägen 5, 230 53 Alnarp, Sweden.
e-mail: kristina.blennow@slu.se

Bernhard Wolfslehner is the Head of the European Forest Institute Central-East European Regional Office in Vienna. He works on policy and decision-support for sustainable forest management and land use in Europe.

Address: Department of Forest- and Soil Sciences, Institute of Silviculture, University of Natural Resources and Life Sciences (BOKU), Peter Jordan Straße 82, 1190 Vienna, Austria.

Address: European Forest Institute Central-East European Regional Office, c/o University of Natural Resources and Life Sciences (BOKU), Feistmantelstrasse 4, 1190 Vienna, Austria.
e-mail: bernhard.wolfslehner@efi.int