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Assessing the resilience of Norway spruce forests through a model-based reanalysis of thinning trials

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ABSTRACT

As a result of a rapidly changing climate the resilience of forests is an increasingly important property for ecosystem management. Recent efforts have improved the theoretical understanding of resilience, yet its operational quantification remains challenging. Furthermore, there is growing awareness that resilience is not only a means to addressing the consequences of climate change but is also affected by it, necessitating a better understanding of the climate sensitivity of resilience. Quantifying current and future resilience is thus an important step towards mainstreaming resilience thinking into ecosystem management. Here, we present a novel approach for quantifying forest resilience from thinning trials, and assess the climate sensitivity of resilience using process-based ecosystem modeling. We reinterpret the wide range of removal intensities and frequencies in thinning trials as an experimental gradient of perturbation, and estimate resilience as the recovery rate after perturbation. Our specific objectives were (i) to determine how resilience varies with stand and site conditions, (ii) to assess the climate sensitivity of resilience across a range of potential future climate scenarios, and (iii) to evaluate the robustness of resilience estimates to different focal indicators and assessment methodologies. We analyzed three long-term thinning trials in Norway spruce (*Picea abies* (L.) Karst.) forests across an elevation gradient in Austria, evaluating and applying the individual-based process model iLand. The resilience of Norway spruce was highest at the montane site, and decreased at lower elevations. Resilience also decreased with increasing stand age and basal area. The effects of climate change were strongly context-dependent: At the montane site, where precipitation levels were ample even under climate change, warming increased resilience in all scenarios. At lower elevations, however, rising temperatures decreased resilience, particularly at precipitation levels below 750–800 mm. Our results were largely robust to different focal variables and resilience definitions. Based on our findings management can improve the capacity to recover from partial disturbances by avoiding overmature and overstocked conditions. At increasingly water limited sites a strongly decreasing resilience of Norway spruce will require a shift towards tree species better adapted to the expected future conditions.

1. Introduction

Climate change is increasingly altering forest ecosystem dynamics, yet the impacts of warming vary strongly between ecosystems. While some areas benefit from a prolonged growing season and CO_2 fertilization (Reyer et al., 2014), others are experiencing an increase in drought stress (Allen et al., 2015) as a result of the ongoing climatic changes. The vulnerability to climate is expected to be particularly high in areas that are exposed to disproportionally large changes in the climate system (Lindner et al., 2010). An example are the European Alps, which have warmed twice as much as the northern hemisphere over the past decades (Auer et al., 2007). Furthermore, particular vulnerability is expected for species that are at the margins of their natural range, or have been cultivated outside their realized niche (Hanewinkel et al., 2013; Seidl et al., 2011). Here, a prominent example is Norway spruce (*Picea abies* (L.) Karst.): The species is natural to Europe's mountain forests (Bebi et al., in press) and high latitudes, but has been planted widely also in low elevation areas of Central Europe, where it is expected to be particularly vulnerable to climate change (Boden et al., 2014; Hlásny and Turčáni, 2013; Lindner et al., 2010).

In response to growing concerns about climate change the resilience of forest ecosystems has received increasing attention

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recently, and has been proposed as an important factor for addressing future uncertainties in ecosystem management (Biggs et al., 2012; Seidl, 2014). Resilience can broadly be defined as the ability of a system to recover from disturbance and persist in the face of perturbations (Carpenter et al., 2001). The theory of resilience in ecosystems has made considerable progress recently (Reyer et al., 2015; Scheffer et al., 2015). Yet, the operational assessment and quantification of resilience in real world systems has remained challenging. One reason for why applications lag behind theory developments is that many indicators of resilience require long-term data over a wide gradient of perturbations that are not commonly available in forest ecosystems. To address the need for long time-series in determining resilience, dendroecological analyses have recently been used to assess the resilience to climatic extremes (Boden et al., 2014; Lloret et al., 2011). While allowing important insights into the plasticity and response of trees to changes in climate, these studies rely on past extremes for inferring resilience, and thus are not necessarily representative for the conditions that are expected for the future (Radeloff et al., 2015). Furthermore, the individual tree resilience inferred from tree rings might differ substantially from stand- to landscape level resilience, with the latter being the primary focal scales of forest management.

While no long-term stand-level resilience experiments exist to date, forest research has accumulated a wealth of experimental data over the past decades. An important category of such existing long-term experiments are thinning trials. These are experiments that have been designed to understand how different thinning regimes influence the growth, stability, timber quality, and mortality of trees (Pretzsch, 2005; Zeide, 2001). They usually span a wide gradient of removal levels and intervention intervals, and include replications as well as untreated control plots in order to deduce thinning effects with a high degree of statistical rigor. Over the last decades these trials have provided important information on improving the productivity, structure, and composition of forest ecosystems through management. More recently, these studies have also been used to inform management responses to a changing climate (D'Amato et al., 2011; Kerhoulas et al., 2013; Neill and Puettmann, 2013), particularly focusing on the question whether reduced tree density can alleviate increasing drought stress (D'Amato et al., 2013; Elkin et al., 2015; Gebhardt et al., 2014).

From an ecological perspective, the wide range of thinning interventions implemented in thinning trials represents an experimental gradient of disturbance. Yet, to the best of our knowledge, these experimental gradients of perturbation have to date not been used to assess forest resilience. Here, we reanalyze thinning trials with the aim to quantitatively assess the resilience of forest ecosystems. In this context it is important to note that different dimensions of resilience exist: Engineering resilience describes the ability of a system to recover from disturbance (Holling, 1996), while ecological resilience refers to a system remaining within its prevalent domain and not shifting to an alternative ecological state in response to a perturbation (Gunderson, 2000). Determined by the nature of thinnings, which are non-stand replacing interventions, we here focus solely on recovery after partial disturbance, and thus address engineering resilience in this contribution (henceforward referred to resilience for the sake of readability).

The resilience of a system is not static over time but changes *inter alia* in response to a changing climate (Seidl et al., 2016). In the context of management this means that managers need to embrace the fact that resilience as a management goal is a moving target. Moreover, whether the expected future climate conditions will erode or bolster a systems' resilience needs to be factored into management considerations. Studying the effect of future no-analog conditions (Radeloff et al., 2015) on resilience requires the use of process-based forest ecosystem models. In contrast to empirical models, which have been frequently used in the analysis of thinning responses previously, process-based approaches simulate system trajectories based on ecological mechanisms, and are thus robust also under scenarios that represent novel future conditions (Gustafson, 2013). Many process-based models, however, do not operate at the appropriate scale to capture thinning responses (Petritsch et al., 2007; Seidl et al., 2013), making a process-based reanalysis of thinning trials challenging. A thorough evaluation of the applied models is thus of paramount importance. Long-term trials offer a powerful means in this regard, allowing models to be tested across a wide gradient of experimentally manipulated conditions.

Here, our objective was to assess the resilience of Norway spruce forests in Central Europe to non-stand-replacing disturbance by re-analyzing thinning trials under both historic climate and a range of climate change scenarios. Specifically, our aims were (i) to evaluate an individual-based process model of forest dynamics with regard to its ability to reproduce observed responses to thinning interventions, (ii) to demonstrate how engineering resilience can be derived from stand-level recovery after thinning at three experimental sites distributed across an elevation gradient in Austria, (iii) to assess the climate sensitivity of resilience across a range of climate scenarios, and (iv) to evaluate the robustness of resilience estimates to different focal indicators and assessment methodologies. Previous research has shown that Norway spruce is increasingly climatically limited in low elevation areas and close to the timberline, with optimal performance in the montane elevation belt (Ponocná et al., 2016; Primicia et al., 2015). We thus hypothesized resilience to decline from the montane to the submontane elevation belt, i.e. from the center of the species' niche to its warm and dry edge. Furthermore, given the increasing level of stress introduced by a changing climate, we hypothesized resilience to decrease with progressing climate change. This hypothesis is based on findings by Zang et al. (2014), among others, indicating that increased temperature and water stress negatively impacts the recovery of Norway spruce. Lastly, we hypothesized that quantitative estimates of resilience would vary strongly across different focal variables of the assessment (Carpenter et al., 2001).

2. Materials and methods

2.1. Thinning trials

We reanalyzed three thinning trials in even-aged Norway spruce forests in Austria, maintained and re-measured by the Austrian Research Center for Forests, Vienna (Table 1). They were selected for analysis here because they span a wide gradient of thinning interventions and environmental conditions, were initiated approximately at the same time, and focus on the same tree species (Norway spruce). The trial Eibiswald (46.726N, 15.048E) is situated in the montane elevation belt (1250 m asl) at the south-eastern rim of the Alps (ecoregion western Styrian mountains, (Kilian et al., 1994)). Although the coolest site studied here, temperatures are relatively mild for the elevation and precipitation is ample (Table 1), resulting in near-optimal growing conditions for Norway spruce. Consequently, Norway spruce is the dominant tree species of the natural vegetation composition at Eibiswald (Kilian et al., 1994). Six thinning variants (including an untreated control) were implemented in 1000 m^2 blocks, each replicated three times, and separated by a 5 m buffer zone that was treated but not analyzed. The initial age of the stands was 40 years in 1968, and the observation period was 45 years. The second thinning trial is located near Karlstift in northern Austria (Waldviertel ecoregion) at 930 m asl (48.575N, 14.773E). It is characterized by cool

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