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Research article

# Harnessing landscape heterogeneity for managing future disturbance risks in forest ecosystems

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ABSTRACT

In order to prevent irreversible impacts of climate change on the biosphere it is imperative to phase out the use of fossil fuels. Consequently, the provisioning of renewable resources such as timber and biomass from forests is an ecosystem service of increasing importance. However, risk factors such as changing disturbance regimes are challenging the continuous provisioning of ecosystem services, and are thus a key concern in forest management. We here used simulation modeling to study different risk management strategies in the context of timber production under changing climate and disturbance regimes, focusing on a 8127 ha forest landscape in the Northern Front Range of the Alps in Austria. We show that under a continuation of historical management, disturbances from wind and bark beetles increase by +39.5% on average over 200 years in response to future climate change. Promoting mixed forests and climate-adapted tree species as well as increasing management intensity effectively reduced future disturbance risk. Analyzing the spatial patterns of disturbance on the landscape, we found a highly uneven distribution of risk among stands (Gini coefficients up to 0.466), but also a spatially variable effectiveness of silvicultural risk reduction measures. This spatial variability in the contribution to and control of risk can be used to inform disturbance management: Stands which have a high leverage on overall risk and for which risks can effectively be reduced (24.4% of the stands in our simulations) should be a priority for risk mitigation measures. In contrast, management should embrace natural disturbances for their beneficial effects on biodiversity in areas which neither contribute strongly to landscape-scale risk nor respond positively to risk mitigation measures (16.9% of stands). We here illustrate how spatial heterogeneity in forest landscapes can be harnessed to address both positive and negative effects of changing natural disturbance regimes in ecosystem management.



## 1. Introduction

The decoupling of human development from the use of fossil resources in order to halt climate change is a major challenge of the 21st century. In response to this challenge political programs increasingly foster a bio-based and circular economy, aiming to reduce overall resource use, and substitute fossil resources with sustainably sourced renewable materials (Pülzl et al., 2014; Staffas et al., 2013). Forest ecosystems cover more than 30% of the global land area and are a primary source of renewable resources for humans. Consequently, the demand for timber and fiber from forests is increasing (FAO, 2017). Outlook studies for the forest sector project a further increase in the demand for biomass from forests for the near- to mid-term future (UNECE and FAO, 2011). At the same time the land base for sustainable forest management is decreasing (Hansen et al., 2013), due to the land-use changes resulting from a growing human population. Furthermore, the efforts to combat biodiversity loss, another crucial planetary challenge of the 21st century (Steffen et al., 2015), require an increasing amount of land to be set aside for conservation purposes (Belote et al., 2017). This land is henceforth no longer available for the provisioning of renewable resources to society. Finally, there is an increasing recognition that the wellbeing of a growing human population depends on a variety of ecosystem services beyond the provisioning of timber and fiber, including regulating, cultural, and supporting services (MA, 2005). Managing ecosystems for a wide

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range of different ecosystem services can reduce the provisioning of individual services such as biomass production, as trade-offs between ecosystem services are common (Lafond et al., 2017; Langner et al., 2017). Consequently, while the demand for biomass from forests is growing, ongoing societal changes make its provisioning increasingly complex.

In addition to societal changes also environmental stressors complicate the sustainable provisioning of biomass from forests, and thus pose risks for an emerging bioeconomy. Factors such as anthropogenic climate change or the human alterations of the global nitrogen cycle have profound impacts on the natural dynamics of ecosystems (Steffen et al., 2015). In past decades, biomass production has largely benefitted from environmental changes in areas such as Central Europe, with longer growing seasons, $CO_2$ fertilization, and N deposition accelerating forest growth (Pretzsch et al., 2014). While these positive effects are expected to continue in the short term, increases in natural disturbances such as extended drought periods, wildfires, insect outbreaks, and windstorms could compensate or even reverse such positive effects of global change (Nabuurs et al., 2013; Reyer et al., 2017). The impact of natural disturbances has already increased in forests around the globe, and is expected to further intensify in the coming decades in response to ongoing changes in the climate system (Seidl et al., 2017a). Both scientists and forestry professionals expect alterations in the disturbance regime to be among the most profound impacts climate change will have on forest ecosystems (Lindner et al., 2010; Seidl et al., 2016a).

Natural disturbances abruptly and lastingly alter forest structures, and have largely negative impacts on the sustainable and continuous provisioning of ecosystem services (Thom and Seidl, 2016). Consequently, forest risk management has long sought to prevent the occurrence of natural disturbances, or to reduce their impacts (Hanewinkel et al., 2011). However, traditional approaches of risk management have been of only limited success, as evidenced by a steady increase in the timber damaged by natural disturbances over past decades, e.g. in Europe (Seidl et al., 2014b). Furthermore, natural disturbances fulfill a number of important functions in forest ecosystems, such as contributing to their adaptive capacity (Thom et al., 2017b) and fostering biodiversity (Beudert et al., 2015; Wermelinger et al., 2017). Consequently, natural disturbances are increasingly seen as an integral part of ecosystem management (Kulakowski et al., 2017). For operational forest planning this poses the question of how to integrate natural processes such as disturbances into management while meeting an increasing level of biomass demand. The complexity of addressing disturbances in management is further increased by the fact that natural disturbance regimes are changing rapidly, possibly transgressing their natural range of variability in coming decades (Kulakowski et al., 2017; Seidl et al., 2017a). Consequently, an improved management of disturbance risks is needed in forestry, incorporating natural disturbances processes into management while at the same time safeguarding a continuous biomass provisioning for society.

As a result of the long history of considering disturbance risks in forest management a wide variety of risk management tools exist today. Predisposition assessment systems have, for instance, been used to identify areas at particular risk within a landscape, based on site classification and stand attributes (Hanewinkel et al., 2011; Netherer and Nopp-Mayr, 2005). Such systems are widely used in operational forest management today. They, however, assume forest ecosystems to be static, and are not able to address changing environmental conditions and their effects on disturbance risk. A second set of tools widely used for forest risk management are simulation models (Hanewinkel et al., 2011; Seidl et al., 2011). These approaches address disturbance risks more dynamically, e.g., quantifying the possible impact of wind disturbances on timber resources (Albrecht et al., 2015; Blennow et al., 2010). Yet, most approaches to date have focused on the stand scale (but see e.g., Cairns et al., 2008; Zeng et al., 2010), making landscape dynamics and heterogeneity important frontiers of forest risk research (Turner et al., 2013).

Here, we propose that the spatial heterogeneity within a managed forest landscape can be utilized to stratify risk management approaches, and unify the different management perspectives on natural disturbances (prevent vs. embrace). Specifically, we investigate (i) the spatial variation in the contribution of individual stands to landscape-scale risks and goals in the context of timber production, as well as (ii) the spatially variable response of stands to risk management strategies. Our analysis specifically addresses the question of how priority areas for different management responses to disturbance (e.g., actively reduce disturbance risk in management vs. let natural disturbance processes develop unimpeded) can be identified on the landscape. We hypothesized that (1) disturbance risk will increase substantially with climate change, but (2) that the contribution of individual stands to the overall risk at the landscape scale (and thus their leverage in risk management) is not uniform. Furthermore, we expected that not only risk varies spatially on the landscape, but that (3) also the response of individual stands to risk mitigation measures is not uniform (i.e., different levels of risk control exist on the landscape).

## 2. Methods and materials

### 2.1. Study landscape

Questions of spatial variation in disturbance and risk management were addressed for the Weissenbachtal landscape, located in the Northern Front Range of the Alps in Austria (N 47.78°, E 13.59°). The geology of the region is dominated by calcareous bedrock consisting mainly of limestone and dolomite. Common soil types are Chromic Cambisols and Rendzic Leptosols with Moder and Tangel humus types (Mayer et al., 2017). The Weissenbachtal landscape extends over 8127 ha, of which 5716 ha are stockable forest area. It is representative for managed forests in Central Europe in several ways: First, it is characterized by considerable environmental heterogeneity, extending over an elevational gradient from 490 m to 1400 m. Mean annual temperature is 7.5 °C, with temperatures decreasing sharply with elevation (from 9.6 °C to 5.5 °C). Precipitation is ample and increases with elevation (1,207 mm to 2,071 mm, with a landscape mean of 1,503 mm), with 57.5% of the precipitation occurring between April and September. Second, the natural vegetation of the landscape is dominated by Norway spruce (*Picea abies* (L.) Karst.), silver fir (*Abies alba* Mill.), and European beech (*Fagus sylvatica* L.), which are the three most important late-seral tree species in Central Europe above ca. 500 m in elevation. Specifically, the natural vegetation <800 m asl. is dominated by beech at Weissenbachtal. In mid elevations spruce and fir increase in competitiveness, with areas >800 m asl. being characterized by a mixed forest type of spruce, fir and beech (Kilian et al., 1994). Third, the landscape has a long and intensive management history, and was primarily used to provide fuel wood for the production of salt from a nearby mine. Densities of wild ungulates were historically high, due to the area being a favored hunting ground of the Austrian imperial family throughout the 19$^{th}$ and early 20$^{th}$ century. Reflecting this management history, the current vegetation structure and composition differs substantially from natural conditions. Spruce was historically favored for timber production, and 48.9% of the growing stock on the landscape are currently spruce. Fir, on the other hand, suffered considerably from clear-cut management and high game densities, and currently only makes up 2.2% of the growing stock on the landscape. Stand