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Changes of forest cover and disturbance regimes in the mountain forests of the Alps

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ABSTRACT

Natural disturbances, such as avalanches, snow breakage, insect outbreaks, windthrow or fires shape mountain forests globally. However, in many regions over the past centuries human activities have strongly influenced forest dynamics, especially following natural disturbances, thus limiting our understanding of natural ecological processes, particularly in densely-settled regions. In this contribution we briefly review the current understanding of changes in forest cover, forest structure, and disturbance regimes in the mountain forests across the European Alps over the past millennia. We also quantify changes in forest cover across the entire Alps based on inventory data over the past century. Finally, using the Swiss Alps as an example, we analyze in-depth changes in forest cover and forest structure and their effect on patterns of fire and wind disturbances, based on digital historic maps from 1880, modern forest cover maps, inventory data on current forest structure, topographical data, and spatially explicit data on disturbances. This multifaceted approach presents a long-term and detailed picture of the dynamics of mountain forest ecosystems in the Alps. During pre-industrial times, natural disturbances were reduced by fire suppression and land-use, which included extraction of large amounts of biomass that decreased total forest cover. More recently, forest cover has increased again across the entire Alps (on average +4% per decade over the past 25–115 years). Live tree volume (+10% per decade) and dead tree volume (mean +59% per decade) have increased over the last 15–40 years in all regions for which data were available. In the Swiss Alps secondary forests that established after 1880 constitute approximately 43% of the forest cover. Compared to forests established previously, post-1880 forests are situated primarily on steep slopes (>30°), have lower biomass, a more aggregated forest structure (primarily stem-exclusion stage), and have been more strongly affected by fires, but less affected by wind disturbance in the 20th century. More broadly, an increase in growing stock and expanding forest areas since the mid-19th century have - along with climatic changes - contributed to an increasing frequency and size of disturbances in the Alps. Although many areas remain intensively managed, the extent, structure, and dynamics of the forests of the Alps reflect natural drivers more strongly today than at any time in the past millennium.

1. Introduction

Mountain forests globally are undergoing major changes driven by factors related to climate, land-use, and natural disturbances (Dale et al., 2001; Kulakowski et al., 2012). While the understanding of all three of these driving forces has greatly increased, interactions between them are still difficult to disentangle. Natural disturbances such as fire, wind, insect outbreaks and avalanches are strongly affected by forest cover, forest structure, climate, and land-use (Kulakowski and Veblen, 2002; Seidl et al., 2011a; Kulakowski et al., 2011; Puerta-Piñero et al., 2012; Liu et al., 2015; Flatley et al., 2013). Especially in mountainous areas, which form a complex biophysical template for these disturbances

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and their drivers, the spatiotemporal complexities of associated dynamics are not yet well understood.

Forest cover has substantially increased since the 19th century in several mountain ranges of the world (Wear and Bolstad, 1998; Bunce, 1991; Kozak, 2003), mainly as a result of reduced or abandoned agricultural areas (Baldock et al., 1996; Gellrich et al., 2007). As past land-use can have multiple and long-term impacts on forest soils and successional pattern (Foster, 1992; Körner et al., 1997; Dambrine et al., 2006; Spohn et al., 2016), we can expect important differences between post-agricultural forests compared to areas that have long been forested (Flinn and Vellend, 2005; Foster et al., 2003). In addition to forest expansion, changes in climate and forest management have contributed to widespread changes in forest structure and biomass stocks. Across large parts of Europe, these changes have contributed to increased disturbances by wind, bark beetles, and wildfires over the past decades (Seidl et al., 2014; Wastl et al., 2013). However, in the specific context of the Alps it is not clear whether recent trends in disturbance regimes are primarily related to successional dynamics in newly established secondary forest, or to increasing biomass levels in previously established forests, and how strongly these changes are mediated by ongoing climatic changes. It is thus helpful to examine long-term trends to obtain better insights into the drivers of mountain forest dynamics.

Reliable data on forest cover changes and disturbance history is much more limited before the 19th century than for recent periods in the Alps, but several lines of evidence can provide insights into forest development and species shifts over longer time periods (Kaplan et al., 2009). In particular paleoecological data provide evidence of how forest composition and extent has changed during periods of increasing pressure of human land-use, and how fire regimes have changed in response to climate and land-use (Tinner and Kaltenrieder, 2005; Conedera et al., this issue). Evidence of past forest development and the historic variation of different disturbances regimes is often provided by dendroecological reconstructions of disturbance regimes (e.g. Janda et al., in press; Panayotov et al., this issue), but in some regions the influence of human management over past centuries was strong, obscuring the evidence of natural disturbances (Kulakowski and Bebi, 2004). Empirical data can be complemented with simulation models that can help to elucidate current and future patterns and composition of mountain forests, and how they are affected by climate, land-use and natural disturbances (e.g. Temperli et al., 2013; Thom et al., 2016). In contrast to the forest history since the 19th century, which has been characterized by increasing biomass and disturbances (cf. Usbeck et al., 2010a, 2010b, Appendix, Table A1), we have a relatively fragmentary picture of the processes that contributed to the massive decreases of forest cover and biomass prior to the 19th century (Kaplan et al., 2009; Küster, 2010). Consequently, our long-term understanding of the variability in disturbance regimes remains cursory for forest ecosystems such as those in the European Alps, which have a long and intensive management history (Bätzing, 2003; Mathieu et al., 2016). As a result, no long-term and broad-scale overview on natural disturbance regimes of the Alps exists to date.

In this contribution we briefly synthesize the available information on long-term (i.e. >100 years) forest cover changes and disturbance regimes in the Alps. We combine this information with a compilation of forest inventory and forest disturbance data for the entire mountain range of the Alps, as well as detailed data on forest cover, structure, and disturbance development since the 19th century for the Swiss Alps (Ginzler et al., 2011). Based on these sources of information we put recent forest structure and dynamics into a long-term context and we address the following main questions: (1) What are the recent trends in forest cover, structure, and disturbance regimes since the 19th century, and how do they relate to the long-term context of forest development? (2) How do secondary forests that established since the 19th century differ from pre-existing forests in terms of stand structure and natural disturbance regimes?

2. Long term forest composition and land use changes

The European Alps extend over approximately 1000 km, from the French and Italian Mediterranean coast across Switzerland, southern Bavaria, northern Italy, Austria and Slovenia, and have a total population of 14 million people (Chartré et al., 2010). The mountain peaks reach elevations of >4000 m a.s.l. and are intersected with deep valleys, some of which are >100 km long and divide the mountain range into major massifs. The Alps are a relatively young mountain system, whose "step-like" morphology was contoured by the Pleistocene glaciation. Bedrocks can be divided into calcareous and crystalline material. The climate is characterized by strong environmental gradients ranging from oceanic to dry climate. The most widespread forest types are mixed European beech (*Fagus sylvatica* L.) and silver fir (*Abies alba* Mill.), pure Norway spruce (*Picea abies* (L.) H. Karst.), and mountain pine (*Pinus mugo* Turra s.l.) in the front ranges, while European larch (*Larix decidua* Mill.), Swiss stone pine (*Pinus cembra* Mill.) and Scots pine (*Pinus sylvestris* L.) may replace them in the dry central Alps (see Conedera et al., this issue for more details).

Early changes in forest cover and forest composition since the late glacial-Holocene transition have been reconstructed based on paleoecological records (Kral, 1995; Tinner and Kaltenrieder, 2005; Conedera et al., this issue). These records show evidence of a relatively rapid invasion of pioneer species like European larch, and different pine species, occurring as early as 11,400 years before present (y BP) and extending as far as the current subalpine belt (Blarquez et al., 2009; Tinner and Kaltenrieder, 2005). Major current tree species of the Alps like silver fir (glacial refugia in the south), Norway spruce (refugia in the east), and European beech (different refugia in the south, west and east) immigrated to the Alps after 9000 y BP (Kral, 1995; van der Knaap et al., 2005).

Land-use has influenced forest dynamics at least in parts of the Alps since ca. 7500 y BP, when Neolithic herdsmen started using fire to expand pastures for grazing in mountain forests (Conedera et al., this issue; Winckler, 2012). These early human impacts and the intense use of fire have not only changed forest cover and forest density in some regions of the Alps, but have also shifted species composition. For example, anthropogenic fires combined with successive intensive browsing facilitated expansion of *P. abies* into areas formerly occupied by *A. alba*, which is more sensitive to such disturbances (Schwoerer et al., 2015; Conedera et al., this issue). A second (between 5000 and 3500 y BP) and a third (between 1200 and 700 y BP) wave of increase in the human population and human migration into the Alps led to permanent settlements in higher elevation areas, resulting in major and wide spread human impacts on mountain forests (Schuler, 1988; Winckler, 2012). Accelerated slash and burn management during this third wave reduced forest cover in central Europe, which was already below or comparable to current levels (Hauser, 1964; Bork et al., 2001).

With an increasing awareness of trade-offs between deforestation and the occurrence of natural hazards, the first written regulations against further exploitation of protection forests (i.e., forests that protect against natural hazards) were enacted in the 13th and 14th centuries (Price, 1988). In spite of such regulations, people continued to intensively exploit mountain forests and their products for energy and construction materials as well as extracting litter and pasturing over the following centuries (Mathieu et al., 2016). Deforestation and exploitation were partly slowed due to

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