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Analyzing Austria's forest disturbance regime as basis for the development of climate change adaptation strategies

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Kurzfassung

Störungsfrequenz und –magnitude haben in Österreichs Wäldern in den letzten Jahrzehnten deutlich zugenommen, wobei sowohl Klimawandel als auch Änderungen in Waldstruktur und –zusammensetzung zu diesem Anstieg beigetragen haben. Wind, Borkenkäfer und Schnee sind die bedeutendsten Störungsursachen in Österreich. In den Jahren 2002 - 2010 verursachten sie Schäden von jeweils durchschnittlich 3,1 Mio. m³, 2,2 Mio. m³ und 0,6 Mio m³ pro Jahr (i.e. in Summe 33,7 % des durchschnittlichen Holzeinschlages der gleichen Periode). Darüber hinaus lassen Szenarioanalysen eine weitere, klimabedingte Intensivierung von Waldschäden in Zukunft erwarten. Eine derartige Entwicklung würde nicht nur die nachhaltige Holz-produktion beeinträchtigen, sondern auch Ökosystemleistungen wie z.B. den Schutz vor Naturgefahren oder die Sequestrierung von Kohlenstoff gefährden.

Ziel der vorliegenden Studie war es, durch ein verbessertes quantitatives Verständnis des Störungsregimes in Österreich zur Entwicklung von Anpassungsstrategien in der Waldbewirtschaftung beizutragen. Analysiert wurde dazu die räumliche und zeitliche Variation von Wind-, Borkenkäfer- und Schneeschäden in Österreich auf der Ebene von Forstbezirken (n=72) für die Periode 2002 - 2010. Die Ergebnisse der Studie zeigen, dass ein bedeutender Teil der räumlichen Variation (21,1 – 44,0%) von Störungsschäden in Österreich durch prädisponierend wirkende Faktoren erklärt werden kann. Ein Großteil dieser Faktoren ist durch Waldbewirtschaftung entweder unmittelbar (z.B. durch waldbauliches Steuern von Waldzusammensetzung und -struktur) oder mittelbar (z.B. durch Verringerung von Stammschäden, geänderte Waldbausysteme) beeinflussbar. Den höchsten Einfluss auf alle drei Schadarten hatte die Baumartenzusammensetzung (Fichten- bzw. Koniferenanteil).

Im Gegensatz zu prädisponierenden Faktoren zeigte die Analyse von kurzfristigen, auslösende Faktoren (weitere 11.1% - 23.1% der Variation in Österreichs Störungsregime), dass diese vor allem mit Wettervariablen und Wechselwirkungen im Störungsregime assoziiert sind, und daher nur geringfügig durch Anpassungsmaßnahmen beeinflussbar sind. In Hinblick auf die Klimasensitivität des österreichischen Störungsregimes lässt sich auf Basis der vorliegenden Analysen schlussfolgern, dass steigende Temperaturen sowie höhere Variation in der Wasserversorgung mit großer Wahrscheinlichkeit zu einem weiteren Anstieg von Störungsschäden führen werden. Diese beträchtliche Klimasensitivität unterstreicht die Bedeutung von Anpassungsmaßnahmen im Bereich des Störungsmanagements, um Waldfunktionen auch in Zukunft nachhaltig zur Verfügung stellen zu können. Die vorliegende Studie zeigt diesbezügliche mögliche (räumliche sowie methodische) Ansatzpunkte auf. Sie dokumentiert das große Potential des Waldbaus im Störungsmanagement (z.B. durch die Förderung von diversen, an die standörtlichen Gegebenheiten angepassten Beständen), unterstreicht aber auch die Notwendigkeit, die diesbezüglich langen Vorlaufzeiten zu berücksichtigen.

Abstract

Disturbance frequency and magnitude have increased considerably in Austria's forests in recent decades. Both climatic changes as well as changes in forest structure and composition have contributed to this intensification. Wind, bark beetles and snow are the most important disturbance agents in Austria, damaging 3.1 Mill. m^3, 2.2 Mill. m^3, and 0.6 Mill. m^3 on average per year, respectively, in the period 2002 to 2010 (i.e., in total 33.7% of the total harvest level in the same period). In addition, scenario analyses point towards a further increase of disturbance damage under changing climate conditions, with the potential to negatively impact important ecosystem services such as timber production, the protection against gravitational hazards, and the sequestration of carbon.

The objectives of this study were to improve the quantitative understanding of Austria's disturbance regime in the context of developing adaptation strategies in forest management. We analyzed the spatio-temporal variation of wind, bark beetle, and snow damage at the level of forest districts (n=72) for the years 2002 to 2010. Results show that a considerable portion (21.1% - 44.0%) of the spatial variation in disturbance damage in Austria could be explained by predisposing factors. Many of these factors can be either directly (e.g., through managing stand structure and composition) or indirectly (e.g., via a reduction of stem damage and alternative silvicultural systems) influenced by forest management. The most important factor for all three disturbance agents was tree species composition (i.e., the proportion of Norway spruce and/ or conifers).

In contrast to predisposing factors, management was found to have only a minor potential influence on inciting factors of disturbance damage, which explained an additional 11.1% and 23.1% of the variation and were mainly related to weather indicators and disturbance interactions. The findings of the current study suggest that rising temperatures and an increasing variation in precipitation could further intensify disturbance regimes. This climate sensitivity underlines the importance of disturbance-focused climate change adaptation measures in order to sustainably fulfill important ecosystem functions and services also in the future. The current study highlights spatial as well as methodological hotspots in this regard, and documents the considerable potential of silvicultural measures in disturbance management (e.g., via the promotion of diverse and site-adapted stands), but also underlines the importance of considering the long lead times of adaptation in forest management.

B-1 Introduction

B-1.1 The imperative to adapt to climate change in forest management

Forests ecosystems cover roughly 30% of the global land area, store approximately the same amount of carbon as the earths' atmosphere, are hotspots of biodiversity, and provide a multitude of ecosystem services to society. Currently, close to 4 million hectares of Austria (48%) are covered with forests, which provide approximately 20 million m³ of timber to the market annually, create 6.45 billion Euros in production value per year, and employ more than 6,700 people in forestry (and 290,000 people in the overall forest-wood-chain) (BMLFUW 2012a). However, forests are not only a source of renewable timber, fiber, and bioenergy, but also provide a number of important ecosystem services, such as the protection against natural hazards, to society. Many mountainous parts of Austria would be virtually uninhabitable without the protection function of forests (Mayer and Ott 1991). More than 20% of Austria's forests mainly protect against natural hazards such as soil erosion, rockfall, avalanches or mudflows. Other important ecosystem services include the storage of carbon (Hasenauer 2011), which has a pivotal role in climate change mitigation, recreational values, as well as the provisioning of drinking water to society (Vacik and Lexer 2001).

Recent studies have shown that many of these ecosystem services are considerably threatened by climate change (Schröter et al. 2005). In cooperation with the Austrian Federal Forests (ÖBf) and based on state-of-the-art simulation modeling and multi-criteria decision analysis, Seidl et al. (2011a) showed that 39.6% of the ÖBf forests might be highly vulnerable to the climatic changes expected for the second half of the 21st century. This assessment, which considered the climate sensitivity of a variety of ecosystem goods and services from timber production and C storage to the conservation of biological diversity, highlights the importance and need for adaptation in forest management in order to cope with the challenges of climate change and ensure a sustainable provisioning of ecosystem services also under drastically changing environmental conditions (see also Millar et al. 2007). A *timely* implementation of measures to reduce climate change impacts and strengthen adaptive capacity is of particular importance in forestry, due to the strong inertia in forest dynamics and the long lead times adaptation measures take to become effective (Seidl et al. 2009). This imperative to adaptation in forestry is also recognized by the recently presented national climate change adaptation strategy of Austria, which, in its action plan, proposes eight concrete adaptation measures for Austria's forests (BMLFUW 2012b).

A major concern in forest management with regard to climate change are intensifying natural disturbance regimes, i.e., a climate-related increase in intensity and frequency of widespread tree mortality events caused by agents such as insects and wildfire, or extreme weather events such as drought and strong wind. Concern about intensifying disturbance regimes has led the Ministerial Conference on the Protection of Forests in Europe to ask for *"urgent action […] to minimize risks of damage from events such as storms, floods, fire, drought, pests and diseases in order to protect European forests and their functions"* in their recently adopted Oslo Ministerial Decision (Forest Europe 2011). Also the Austrian climate change adaptation policy focuses one of its proposed adaptation measures on the *"adaptation and improvement of disturbance management"* (BMLFUW 2012b). This political attention to disturbances comes in direct response to the observation of increasing disturbance damage, both at country- and continental scales (Schelhaas et al. 2003, Tomiczek et al. 2011).

B-1.2 After the storm is before the storm: disturbance regimes are intensifying

Damages from wind and bark beetles are the by far most important natural disturbances in central Europe (Tomiczek et at. 2011), and they have already intensified considerably throughout the continent in recent decades (Schelhaas et al. 2003). Disturbances are strongly climate sensitive processes, and the observed increase in frequency and severity of disturbances has in part been attributed to recent changes in the climate system (Seidl et al. 2011b). For instance, insect reproductive success and survival have strongly increased due to rising temperatures (Battisti et al. 2005). Furthermore, decreasing periods of soil frost have already increased the susceptibility of forests to winter windstorms due to decreased anchorage (Usbeck et al. 2010). Future climate changes are expected to continue this already observable trend towards more disturbances. For central Europe, for instance, damage from bark beetles is projected to quadruple by the end of the 21st century (assuming only a moderate warming of 2.4°C, Seidl et al. 2009). Vulnerability to wind damage is also predicted to increase in Europe and expected to double in some areas by 2100 (Schelhaas et al. 2010). In general, there is growing evidence that disturbances will intensify further in the future (see e.g., Lindner et al. 2010).

B-1.3 Potential impacts of intensifying disturbance regimes

The potential for drastic changes in the disturbance regime could have considerable impacts on ecosystem services and functions. Through a devaluation of wood, the need to harvest prematurely, and negative market effects from large pulses of salvaged timber, disturbances can have a strong disrupting effect on timber production and the timber-based economy. For instance, a single wind event in southern Sweden in January 2005 was estimated to have caused an overall economic damage of 2.4 billion Euros in forestry (Skogsstyrelsen 2006). Furthermore, disturbance events can turn forests acting as a carbon (C) sink to the atmosphere into a C source (Kurz et al. 2008, Seidl et al. 2008). They thus have the potential to strongly interfere with objectives to mitigate climate change through forest management (Canadell and Raupach 2008). In mountain forest ecosystems, where the protection against gravitational natural hazards such as rockfall, avalanches and mudflows is an ecosystem service of considerable importance, a continuous forest cover is essential to ensure a sustainable provisioning of this protection function (Brang et al. 2006). Increasing disturbance frequency and severity can thus be expected to also have dire consequences in the context of natural hazards protection. However, not only ecosystem services but also biodiversity will be affected by changing disturbance regimes: More and bigger disturbances can result in a higher portion of species-rich early seral habitat on the landscape (Swanson et al. 2011). However, intensifying disturbances can also negatively impact species depending on late-seral habitats, and disturbed areas are particularly prone to the colonization of invasive alien species (With 2002).

B-1.4 Approaches for accounting for disturbances in forest management

These expected changes in the disturbance regime, and their potential impacts on ecosystem services to society, are a growing concern for the sustainable management of forest ecosystems. The adaptation of forest management to these expected changes in is, however, hampered by the fact that disturbances are considerably less studied and understood than other processes in forest ecosystems (Turner 2010). Despite the growing understanding of how management can alleviate disturbance pressure (e.g., Jactel et al. 2009) there are still information gaps particularly related to questions of implementing large-scale adaptation strategies (such as the one presented for Austria by BMLFUW 2012b). For one thing, while our process-understanding of individual disturbance processes, such as the mechanisms of uprooting and breakage from wind (Gardiner et al. 2008) or the population dynamics and climate sensitivity of important insect species (Netherer and Schopf 2010) has been increasing rapidly in recent years, how these complex processes scale to larger areas such as forest districts (i.e., the primary entities for the implementation of policy-level adaptation strategies) is still difficult to assess, since scaling of highly nonlinear ecosystem processes is not trivial (Wiens 1989). Also, the development of process-based simulation models harnessing these findings for silvicultural decision support is gathering steam (e.g., Seidl et al. 2012), but is still in its infancy with regard to addressing disturbance interactions and larger spatial scales (see the review by Seidl et al. 2011c).

Thus, as a complementary approach to process-based analyses, expert systems have been developed and successfully applied at various scales (Führer and Nopp 2001, Netherer and Nopp-Mayer 2005). Such approaches, based strongly on expert assessment and weighting of individual drivers of disturbance regimes, can be scaled to, for instance, district levels, as recently demonstrated by Tomiczek and Schweiger (2012). However, they are rarely explicitly climate-sensitive (they use e.g., coarse-filter proxies such as elevation as a stand-in for climate variables) which limits their inferential potential and applicability in the context of changing environmental conditions. Furthermore, their foundation in expert opinion can be a strength, e.g., in accounting for disturbance factors for which only limited data exist, but can also be a weakness, considering inherent limitations of human beings in assessing complex, multi-dimensional problems.

A third approach is empirical, data-driven analysis to identify the drivers and dynamics of disturbance regimes in order to deduce important information to address them in forest management (e.g., Hanewinkel et al. 2008). Empirical analyses can be conducted at a variety of scales, i.e. they frequently rely on implicit scaling assumptions (cf. Bugmann et al. 2000). They furthermore can be very computationally efficient in addressing large study areas (e.g., Littell et al. 2009), and accepted methodological approaches to disentangling complex problems exist (e.g., Seidl et al. 2011b). An additional advantage compared to many process-based models (focusing on the assessment of damage probabilities, e.g., Blennow et al. 2010) and expert systems (yielding relative rankings of disturbance risk, e.g., Netherer and Nopp-Mayer 2005) is the ability to address disturbance damage (i.e., the variable of main concern to managers) explicitly. This in many cases allows a more direct link to affected ecosystem services to be established, which increases the utility in the context of silviculture and management decision making. Ultimately, however, the quality of such statistical approaches depends on the underlying data, and good disturbance data are in many areas still scarce to date.

B-2 Objectives

With the main motivation to aid climate change adaptation in Austria's forests, in particular with regard to the possibility of intensifying natural disturbance regimes, we here analyzed the spatio-temporal variation in Austria's disturbance regime in order to

(i) identify drivers of decadal-scale disturbance intensification in Austria,

(ii) assess major determinants of predisposition to disturbances, and how (strongly) they can be influenced by management,

(iii) identify spatial hotspots of disturbance predisposition to aid efficient resource allocation in adaptation endeavors, and

(iv) identify inciting factors and evaluate their potential to serve as early warning indicators in disturbance management.

Since Austria has one of the best and longest-running disturbance monitoring systems in Europe, we used data from this monitoring program in combination with a statistical approach to address our objectives. The main spatio-temporal resolution of the study was the forest district level (n=72) analyzed at annual time step for the period 2002 to 2010 (objectives ii to iv), while large-scale trends (1958-2001) were analyzed at country scale (objective i).

B-3 Methods and materials

B-3.1 Study design

In analyzing Austria's disturbance regime we follow the general concept of tree decline and death proposed by Manion (1981). With regard to drivers of tree death, this approach separates predisposing factors from inciting factors (Fig. B-1). A similar distinction between factors contributing to disturbance susceptibility and those influencing their occurrence was recently proposed also by Seidl et al. (2011c) in the context of a process-based analysis framework for modeling disturbance regimes. The key aspect of this analysis framework is - in line with recently emerging ecological theory (see e.g., Holling and Gunderson 2002) - that factors at different scales influence disturbance processes.

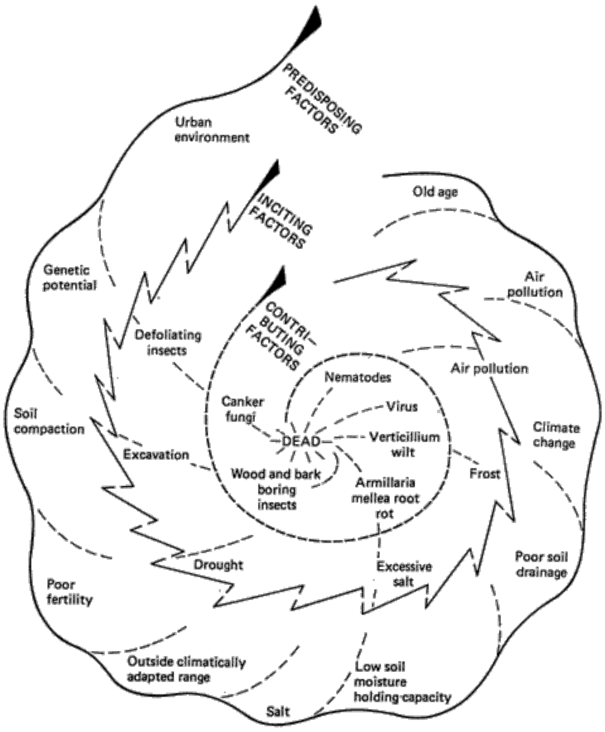


Fig. B-1: The "tree decline spiral" (Source: Manion 1981)

Within our framework, predisposition summarizes factors that are (for all practical purposes) temporally invariant or change only very gradually. It thus describes "slow" variables such as vegetation structure and composition, climate, and societal aspects of forest stewardship (e.g., ownership). In contrast, inciting factors, i.e., triggers for the occurrence of disturbance, are characterized by a high inter- and even intra-annual variability. Examples for these "fast" variables are weather phenomena or the interactions within the disturbance regime. These factors are, however, conditional on large-scale predisposing factors, which is why we chose a sequential study design, in a first step analyzing the spatial variation in predisposing factors, and in a subsequent step, i.e., after controlling for the effect of varying predisposition in space, analyzing the role of inciting factors with regard to the temporal variation in disturbance damage (Fig. B-2). Factor groups of major drivers of predisposition and occurrence processes were identified, with the aim to aid the interpretation and analysis towards supporting forest management and adaptation (Fig. B-2). The individual indicators defining these factor groups are described in detail in section B-3.2.2 below.

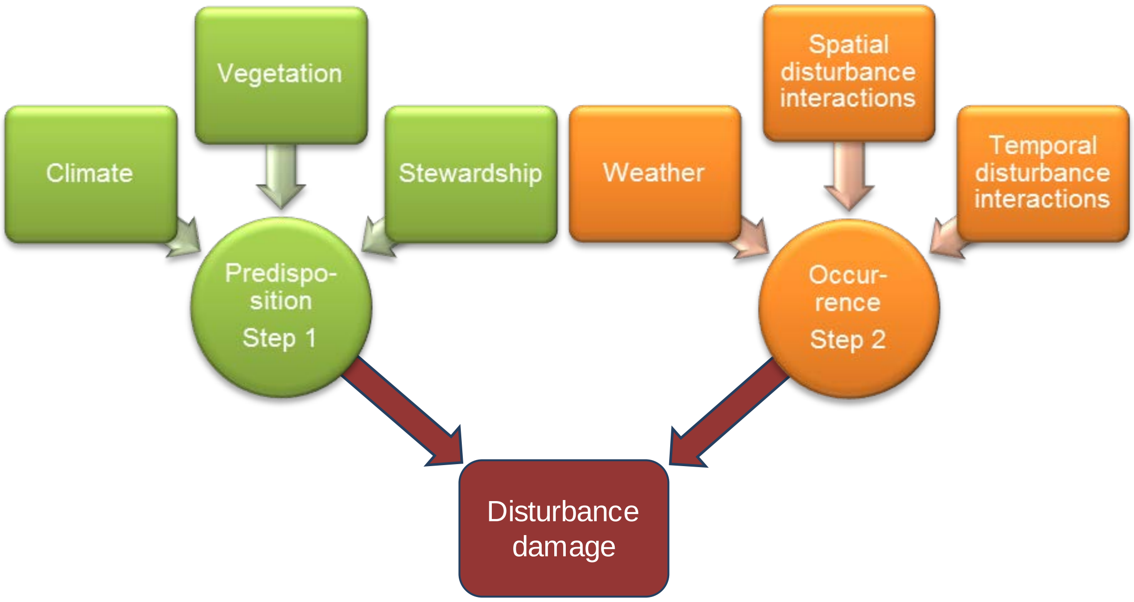


Fig. B-2: A process-driven framework for analyzing the spatio-temporal variation in Austria's disturbance regime.

B-3.2 Material

B-3.2.1 Disturbance data

A data set comprising damaged timber from wind, bark beetles and snow was available from the Austrian Forest Damage Database of the Federal Research and Training Centre for Forests, Natural Hazards and Landscape (BFW) (Tomiczek et al. 2011). Its spatial grain is the forest district level with coverage for the whole of Austria (see Fig. B-3). The data set comprises annual damage in the period 2002 – 2010. With regard to “bark beetles” we focused on the most important species on conifers, i.e. *Ips typographus* , *Ips amitinus*, *Pityogenes chalcographus*, *Dendroctonus micans*, *Pityokteines curvidens*, *Pityokteines spinidens*, *Pityokteines vorontzowi*, *Cryphalus piceae*, *Tomicus piniperda*, *Tomicus minor*, *Pityogenes bidentatus*, *Ips acuminatus*, *Ips sexdentatus*, *Ips cembrae*. Bark beetles on broadleaved trees were not included in order to increase specificity and inferential power of the analysis. Their contribution to damaged timber volume in Austria is, however, comparatively small (e.g. Tomiczek et al. 2009). In addition, a longer time series from 1958-2001 was included in the analysis to investigate (drivers of) long-term trends. This data was, however, only available at country-resolution.

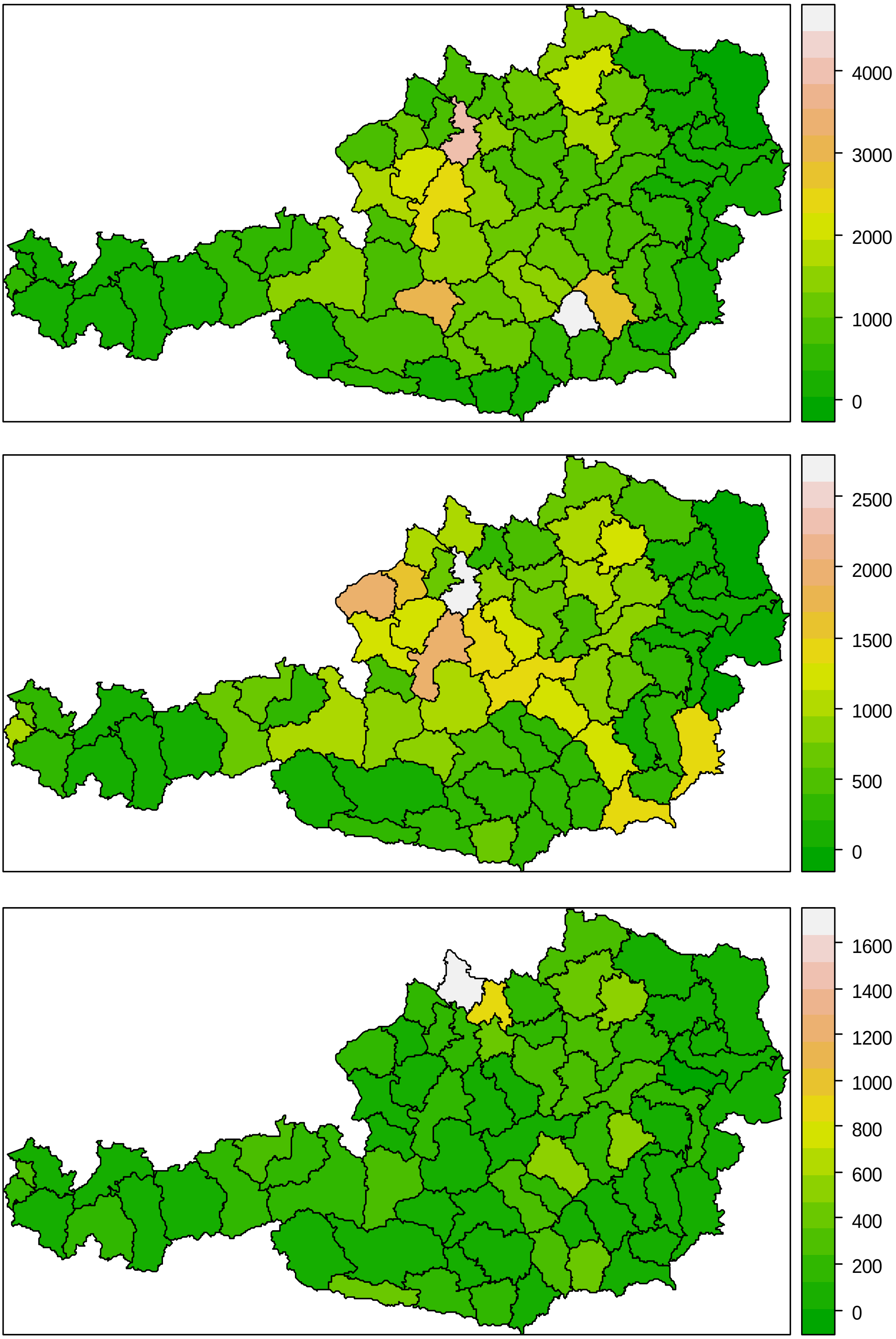


Fig. B-3: Spatial distribution of mean disturbance damage intensity (m³ per 1,000 ha) in Austria in the period 2002-2010. Top panel: wind. Center panel: bark beetles. Lower panel: snow. Note the different scales for every disturbance agent. Source: Austrian Forest Damage Database.

B-3.2.2 Potential drivers of disturbance predisposition

In order to investigate the influence of a variety of predisposing (i.e., slow) factors on disturbance, district-level data on potential predictors were compiled from different sources, grouped into three broad categories (cf. Fig. B-2). Data on vegetation, with selected indicators describing species composition, the deviation from the potential natural vegetation, stand age and growing stock, were gathered from the Austrian Forest Inventory (AFI 2012, inventory period 2007-2009). Also variables describing forest stewardship, such as ownership, the prevalence of different harvest systems (e.g., clear-cut harvesting), and stem damage (bark peeling and harvest damage) were derived from AFI. In order to prevent circular reasoning, however, the latter indicator was extracted for the inventory period 2000-2002, i.e. we here were interested in the effect of previous stem damage on subsequent stability and disturbance damage. In addition, the accessibility (as described by the density of the forest road network) and the level of district forest personnel (ÖFJ 2009) were extracted as additional stewardship-related factors potentially influencing disturbance predisposition (see Tomiczek and Schweiger 2012).

Climate-related variables describing the temperature and precipitation regime (1961-1990) were compiled from the Hydrological Atlas of Austria (HAÖ, Fürst and Nachtnebel 2007), and aggregated to the polygons of forest districts (accounting for the spatial distribution of forest area within districts). In addition, to describe the long-term wind climate over Austria, topographic indices (topex-to-distance, Hannah et al. 1995) as well as a coarse-scale windiness record (50 year return-intervall 2-second gusts at 10m height) resampled from ZAMG (2012a) were aggregated to the level of forest districts. All potential driver variables used in the analysis of predisposition are described in Tab. B-1.

B-3.2.3 Potential inciting factors of disturbance

For computation of inciting variables, related to the occurrence of disturbance events, data for 81 ZAMG weather stations for the years 2001 - 2010 were utilized. Variables extracted from weather station data included daily mean, maximum and minimum temperatures, maximum daytime precipitation, number of days with precipitation greater than 1 mm, as well as the sum of precipitation per month. Monthly anomalies were calculated relative to the station climatology for 1961-1990. After finding considerable spatial correlation between anomalies in an exploratory analysis we used ordinary kriging (Bivand et al. 2008) with individual variogram-models for every month of every year (thus accounting for different monthly spatial patterns dependent on the general synoptic situation) to spatially interpolate weather station anomalies to the district centroids. For further analysis, monthly anomalies were aggregated to seasonal averages.

While this approach of spatially aggregated anomalies was deemed suitable for temperature- and precipitation-related variables, the high local variability in wind data as well as the limited information of weather station data with regard to peak winds prevented the use of the same data source also to characterize wind events (H. Formayer, pers. communication). We thus reverted to a simple dummy variable of storm occurrence based on qualitative information of the ZAMG extreme weather events reports (ZAMG 2012d).

A further important group of inciting factors, particularly in the context of bark beetle damage, relate to spatio-temporal interactions of the disturbance regime. We used both spatial (the neighboring district with the highest damage) as well as temporal (one- and two-year lag) disturbance interactions as potential predictors in the analysis. Furthermore, wind damage (one- and two-year lag) was included as potential interaction variable inciting bark beetle disturbance. All potential variables used in the second analysis step of inciting factors are described in Tab. B-2.

Tab. B-1: Potential drivers of disturbance predisposition investigated in this study.

Factor group	Acronym	Description	Unit	Source
Vegetation	V_S	Proportion of Norway spruce on commercial forest area	%	AFI (2012)
	V_C	Proportion of conifers on commercial forest area	%	AFI (2012)
	V_{SM}	Proportion of pure Norway spruce stands on commercial forest area	%	AFI (2012)
	$V_{PNV\text{-}S}$	Ratio of current Norway spruce area to the area of the species expected in the potential natural vegetation (PNV)	%	AFI (2012); Starlinger (in Lexer 2001)
	$V_{PNV\text{-}C}$	Ratio of current area of coniferous forests to the area of conifers expected in the potential natural vegetation (PNV)	%	AFI (2012)
	V_{GS}	Growing stock	m³ per ha	AFI (2012)
	V_{SSA}	Skewness of age class distribution	dimensionless	AFI (2012)
	V_{MA}	Mean age	years	AFI (2012)
Stewardship	S_{LFE}	Share of district standing stock managed by large forest enterprises	%	AFI (2012)
	$S_{ÖBf}$	Share of district standing stock managed by the ÖBf	%	AFI (2012)
	S_{CC}	Share of clear-cut harvesting on total final harvest	%	AFI (2012)
	S_{BP}	Share of growing stock damaged by bark peeling	%	AFI (2012)
	S_{HD}	Share of growing stock affected by harvest damage	%	AFI (2012)
	S_{FSS}	Commercial forest per forest service staff (foresters + academics)	ha	AFI (2012); ÖFJ (2009)
	S_{RD}	forest road network density	m per ha	AFI (2012)
Climate	C_{SF}	frost, defined as proportion of days cooler than 0°C in winter	%	Fürst & Nachtnebel (2007)
	C_{TTD}	Topex-to-distance (d=500, 1000, 2000, 3000 m)	Index	this study
	C_W	Windiness	Km/h	ZAMG (2012a)
	C_T	temperature, annual and seasonal mean	°C	Fürst & Nachtnebel (2007)
	C_{GDD}	degree-days (threshold >8.3°C)	°C	Fürst & Nachtnebel (2007)
	C_{WS}	variation in water availability (standard deviation of precipitation in the vegetation period)	mm	Fürst & Nachtnebel (2007)
	C_P	precipitation, annual and seasonal sum	mm	Fürst & Nachtnebel (2007)
	C_{WSC}	potential wet snow days (temperature range from 1°C to -3°C) in winter	days	Fürst & Nachtnebel (2007)

Tab. B-2: Potential inciting factors of disturbance damage investigated in this study.

Factor group	Acronym	Description	Unit	Source
Weather	W_t	Mean daily temperature anomalies per season (reference period 1961 - 1990)	°C	ZAMG (2012b,c)
	W_{MTMAX}	Daily maximum temperature anomalies per season (reference period 1961 - 1990)	°C	ZAMG (2012b,c)
	W_{MTMIN}	Daily minimum temperature anomalies per season (reference period 1961 - 1990)	°C	ZAMG (2012b,c)
	W_{RSUM}	Anomalies of precipitation sum per season (reference period 1961 - 1990)	ratio	ZAMG (2012b,c)
	W_{RMAX}	Anomalies in daily precipitation maximum per season (reference period 1961 - 1990)	ratio	ZAMG (2012b,c)
	W_{N1}	Anomalies in days with precipitation ≥ 1 mm per season (reference period 1961 - 1990)	ratio	ZAMG (2012b,c)
	W_{WD}	Storm events	dummy	ZAMG (2012d)
Spatial disturbance interaction	S_{DIA}	bark beetle damage in the most damaged neighboring district (spatial autocorrelation)	m³ per 1000 ha	this study
	S_{DIA-1}	bark beetle damage in the most damaged neighboring district in the previous year (spatio-temporal autocorrelation)	m³ per 1000 ha	this study
Temporal disturbance interaction	T_{DIW-1}	wind damage in previous year (disturbance interactions)	m³ per 1000 ha	this study
	T_{DIW-2}	wind damage two years ago (disturbance interactions)	m³ per 1000 ha	this study
	T_{DIB-1}	bark beetle damage in previous year (disturbance interactions)	m³ per 1000 ha	this study
	T_{DIB-2}	bark beetle damage two years ago (disturbance interactions)	m³ per 1000 ha	this study

B-3.3 Methods

B-3.3.1 Hypotheses-driven analysis

Our statistical analysis of the data is guided by hypotheses on the influence of these individual predisposing (Tab. B-3) and inciting (Tab. B-4) factors on disturbance damage, based largely on previous findings from the literature (see e.g., Missbach 1985, Peltola 1996, Nykänen et al. 1997, Schmidt-Vogt 1997, Wermelinger and Seifert 1998, Peltola et al. 1999, Führer and Nopp 2001, Schelhaas et al. 2003, Hedgren et al. 2003, Zemek et al. 2003, Wermelinger 2004, Danjon et al. 2005, Netherer and Nopp-Mayer 2005, Metsämäki and Anttila 2005, Økland and Bjørnstad 2006, Schütz et al. 2006, Baier et al. 2007, McCallum et al. 2007, Glynn et al. 2007, Hanewinkel et al. 2008, Wermelinger et al. 2008, Albrecht et al. 2009, Jactel et al. 2009, Kantor et al. 2009, Gardiner et al. 2010, Kilpeläinen et al. 2010, Usbeck et al. 2010, Hlasny et al. 2011, MacQuarrie and Cooke 2011, Kostal et al. 2011, Kautz et al. 2011, Overbeck and Schmidt 2012).

Tab. B-3: Hypothesized relationships between individual predisposing factors and disturbance damage. NA: not analyzed; MAM: spring; JJA: summer; SON: autumn; DJF: winter.

Factor group	**Potential predictor**	**Response**		
		Wind	**Bark beetles**	**Snow**
Vegetation	V_S	+	+	+
	V_C	+	+	+
	V_{SM}	+	+	+
	V_{PNV-S}	+	+	+
	V_{PNV-C}	+	+	+
	V_{GS}	+	+	+
	V_{SSA}	-	-	-
	V_{MA}	NA	NA	+
Stewardship	S_{LFE}	-	-	-
	$S_{\text{ÖBf}}$	+	+	-
	S_{CC}	+	+	NA
	S_{BP}	+	NA	+
	S_{HD}	+	NA	+
	S_{FSS}	NA	+	NA
	S_{RD}	NA	-	NA
Climate	C_{SF}	-	NA	NA
	C_{TTD}	-	NA	NA
	C_W	-	NA	NA
	C_T, MAT	NA	+	NA
	C_T, MAM	NA	+	NA
	C_T, JJA	NA	+	NA
	C_T, SON	NA	+	NA
	C_T, DJF	NA	+	+
	C_{GDD}	NA	+	NA
	C_{WS}	NA	+	NA
	C_P, DJF	NA	NA	+
	C_{WSC}	NA	NA	+

Tab. B-4: Hypothesized relationship between individual inciting factors and disturbance damage NA: not analyzed; MAM: spring; JJA: summer; SON: autumn; DJF: winter.

Factor group	Potential predictor	Response	
		Wind	**Bark beetles**
Weather	W_T, MAM	NA	+
	W_T, JJA	NA	+
	W_T, SON	NA	+
	W_T, DJF	+	NA
	W_{MTMAX}, MAM	NA	+
	W_{MTMAX}, JJA	NA	+
	W_{MTMAX}, SON	NA	+
	W_{MTMAX}, DJF	+	NA
	W_{MTMIN}, DJF	+	+
	W_{RSUM}, MAM	NA	-
	W_{RSUM}, JJA	NA	-
	W_{RSUM}, SON	NA	-
	W_{RMAX}, MAM	+	-
	W_{RMAX}, JJA	+	-
	W_{RMAX}, SON	+	-
	W_{N1}, MAM	NA	-
	W_{N1}, JJA	NA	-
	W_{N1}, SON	NA	-
	W_{WD}	+	NA
Spatial disturbance interaction	S_{DIA}	NA	+
	S_{DIA-1}	NA	+
Temporal disturbance interaction	T_{DIW-1}	NA	+
	T_{DIW-2}	NA	+
	T_{DIB-1}	NA	+
	T_{DIB-2}	NA	+

B-3.3.2 Exploratory correlation analyses

As a first analysis step, and prior to conducting more complex multi-factorial analyses, we investigated correlations between individual variables and disturbance damage. Since exploratory analysis of scatterplots did not suggest strongly nonlinear patterns we used Pearsons correlation coefficient in the analysis. The response variable with regard to predisposition was the average (2002-2010) disturbance damage per district (m^3 per 1000 ha), while annual deviation from this district-level mean was investigated with regard to inciting factors. Correlation coefficients for all individual factor correlations of Tables B-3 and B-4 can be found in the Appendix (Tab. A1-A5).

B-3.3.3 Predisposition: Principal component regression

Multicollinearity between predictor variables is a frequent problem in working with ecological data (Fekedulegn et al. 2002). Also in this study, the set of potential explanatory variables was highly intercorrelated. For instance, variables such as the share of spruce on total forest area and the proportion of pure spruce stands in a district are, by their very nature, highly correlated (r=0.955 in our data set). Reducing variables in order to avoid issues with multicollinearity, however, would imply the deletion of potentially important variables and a loss of their inferential capacity, and thus would reduce the overall amount of variance explained by the analysis. Since an important task in step 1 was to control for spatial variability to enable a comparative analysis of inciting factors in step 2 (cf. Fig. B-2), and thus high explanatory power was of particular importance for the subsequent analysis step, we selected principle component regression (PCR) as analysis methodology. PCR is a method to overcome problems of multicollinearity while producing stable and meaningful estimators for regression coefficients (Morzuch and Ruark 1991, Fekedulegn et al. 2002).

To that end, the independent variables were centered by subtracting their respective means, and scaled via dividing by their standard deviation. Subsequently, the correlated, original predictors were transformed into a new set of orthogonal, uncorrelated variables by means of principal component (PC) analysis. These PCs are subsequently regressed on the response variable. The full number of components, equaling the number of original variables, contains the exact same amount of information as the original data. However, as there is a trade-off between variance explained and the level of determination of individual explanatory variables, principle components have to be deleted from the full PCR model in order to achieve a parsimonious and well-determined model (similar to variable selection in multiple linear regression). In the literature, several different approaches have been presented to approach this issue. For this study, following the suggestion of Jolliffe (2002), the final model was determined by optimizing the trade-off between variance explained (R^2) and the number of significant predictors. To that end PCR models containing all possible combinations of principal components were fitted. In a first selection step, only models with a R^2 of at least 85% of the R^2 from the maximum model were retained. From this subset, the model with the highest number of significant and tractable (in terms of biological realism – cf. Tables B-3 and B-4) variables was selected as the final model of the analysis. Subsequently, the regression coefficients of the PCR were transformed back into coefficients for the original variables via the factor loadings of the PCs. These coefficients give insight into relative importance of individual standardized predictors, and express the marginal sensitivity of the mean disturbance damage to changes in a given factor.

B-3.3.4 Inciting factors: Multiple linear regression

In order to analyze the role of inciting factors on the temporal pattern of disturbances in Austria's forest districts we first controlled for the variation in predisposition to (i.e. "background levels" of) disturbances in districts. We thus calculated the deviance of the observed annual damage from the average damage expected for the district based on predisposing factors (PCR, step 1), and used the thus derived annual damage residuals as response variable in our second analysis step. Since one of our main objectives in the analysis was to aid management by identifying potential early warning indicators of disturbance occurrence (see section B-2) the approach here was particularly focused on a robust identification and selection of the most influential factors (rather than on maximizing the variance explained, cf. section B-3.3.3). We thus eliminated correlated predictor variables based on a correlation analysis, and subsequently used an information criterion approach to select the multiple linear regression (MLR) model best supported by the data (see also Marini et al. 2012). We applied backwards model selection, and used Akaikes Information Criterion (AIC) to determine the most robust model formulation. We subsequently analyzed the thus selected model in an analysis of variance to estimate the relative contribution of individual factors to the overall amount of variance explained in this second analysis step.

B-3.3.5 Drivers of long-term disturbance trends

To also analyze the drivers of long-term disturbance change and address the question of how strongly climate change as well as management-related changes in forest structure and composition have contributed to observed disturbance increases in Austria we used a second, long-term time series at country scale. The analysis approach closely followed the study by Seidl et al. (2011b), who recently addressed a similar question for continental Europe. We used the climate and forest data compiled in this previous study (Seidl et al. 2011b), but here focused on a more detailed analysis of Austria’s disturbance regime. We conducted a two-stage analysis consisting of (i) a machine learning analysis using random forest (Breiman 2001) to identify relevant driver variables, and (ii) a structural equation model analysis (Grace 2006) to determine the relative influence strength of these variables, related to the factor groups climate change and forest change. For data reasons this long-term trend analysis could only be conducted for the agents wind and bark beetles. For a detailed description of the analysis we refer to Seidl et al. (2011b).

B-4 Results

B-4.1 Analysis of long-term trends in the Austrian disturbance regime

Disturbance damage has been increasing considerably in Austria in recent years (Fig. B-4). In the ten-year period 2001 to 2010 the disturbance level (wind, snow, and bark beetles combined) was, on average, 273% higher per year than in the period 1951 to 1960, and still 100% higher than in the period 1981 to 1990. Using structural equation modeling in combination with the set of drivers described in Seidl et al. (2011b), we found that both changes in climate and in forest structure and composition had a comparable influence on this increase (Fig. B 5). In relation to results at the continental scale, the effect of changing forest structure and composition was particularly pronounced in Austria. For wind damage, particularly influential drivers of forest change were found to be an increasing stand age as well as an increasing share of conifers, while bark beetle damage was most affected by increasing forest area and growing stock. Overall, the results highlight that increasing disturbance damage can in part be seen as the flipside of the success story of Austrian forestry in recent decades. In other words, the achievement of more forest area stocked with higher volumes comes at a price of also increased disturbance damage.

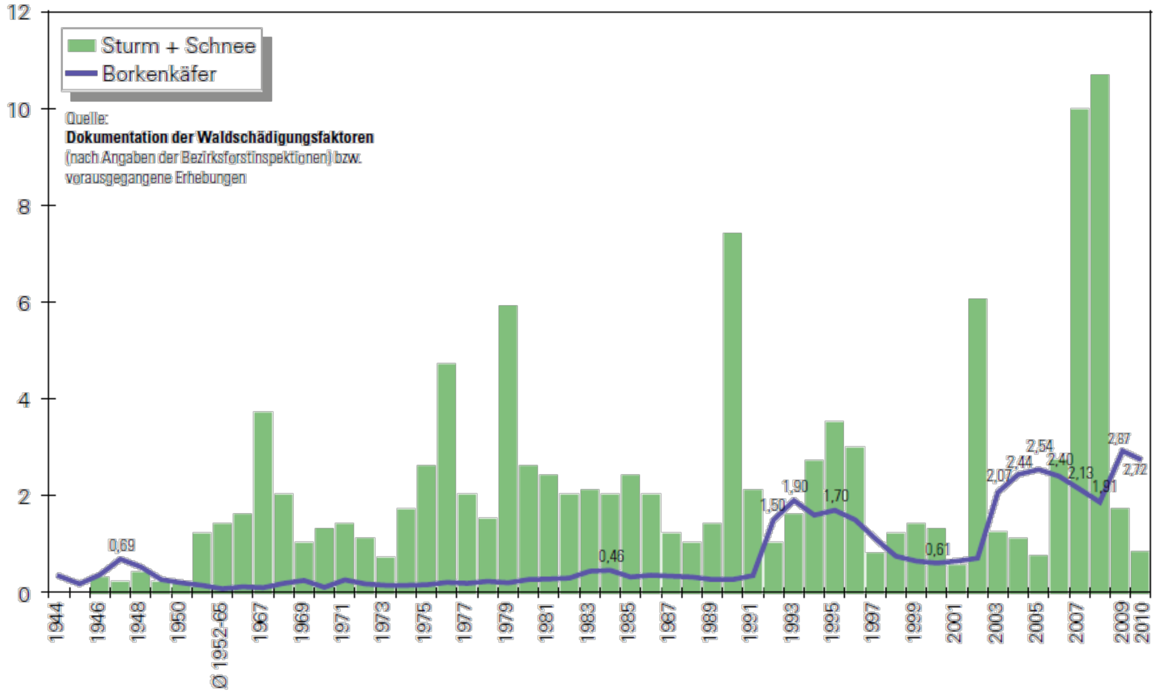


Fig. B-4: Trends in damage caused by major forest disturbance agents in Austria. Bars: wind and snow damage. Line: bark beetle damage. Source: Tomiczek et al. (2011).

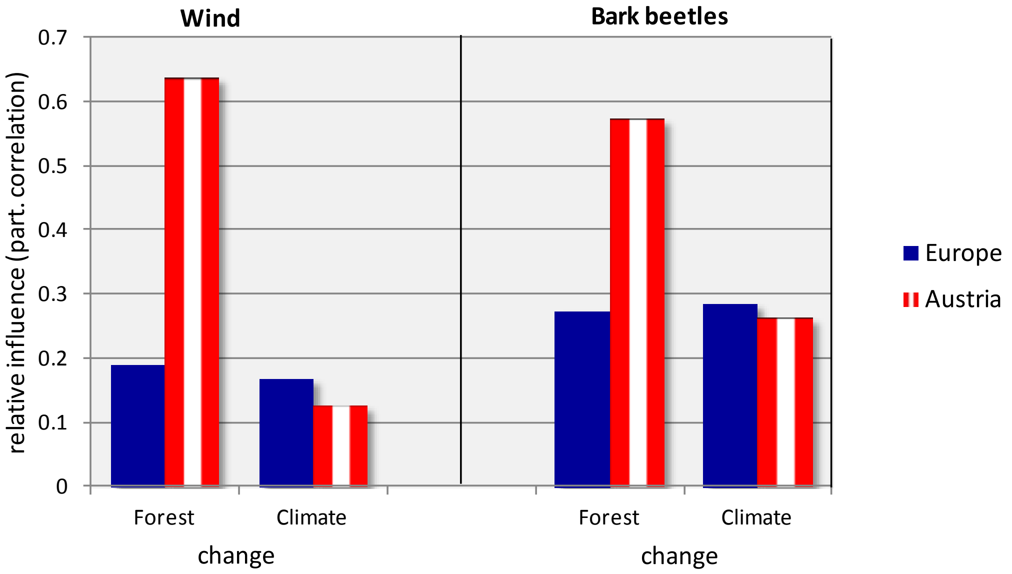


Fig. B-5: The relative influence of climate and forest change on the disturbance increase in Austria for the period 1958 to 2001. European-scale values from the analysis by Seidl et al. (2011b) are indicated for reference purposes.

B-4.2 Drivers of spatio-temporal variation in disturbance damage

B-4.2.1 Predisposing (slow) factors

Our findings document that vegetation-related variables play a key role in disturbance predisposition. For all three disturbance agents, an indicator of species composition was found to have the overall highest standardized influence on disturbance damage. The share of pure spruce stands (V_{SM}) was found to be the most important determinant of wind predisposition (Fig. B-6). Also the proportion of ÖBf-managed forests ($S_{ÖBf}$) and the average growing stock per district (V_{GS}) were positively related to average wind damage. Factors describing the long-term windiness of districts (C_W, C_{TTD}), on the other hand, were found to have a negative relationship with wind damage. Overall, the wind predisposition PCR explained 34.4% of the spatial variance in average annual wind damage.

The model of bark beetle predisposition generally had a higher number of significant variables, and in total explained 44.0% of the spatial variation in mean bark beetle damage. The most influential variable was found to be the proportion of coniferous trees (i.e., host trees, V_C). The most important climatic factor in the analysis was the variation in water supply (C_{WS}), an indicator related to the occurrence of drought. Further factors with considerable influence on average bark beetle damage were a higher share of Norway spruce than expected from the potential natural vegetation (V_{PNV-S}), the share of forests managed by the ÖBf ($S_{ÖBf}$), and the growing stock (V_{GS}) (Fig. B-7).

Compared to wind and bark beetles, the snow predisposition model had only limited explanatory power (R^2=0.211). The share of pure Norway spruce stands (V_{SM}) was found to have the highest positive influence on average snow damage, with stem damage (both from harvest operations and bark peeling, S_{BP} and S_{HD}) being also significant in the final PCR model (Fig. B-8).

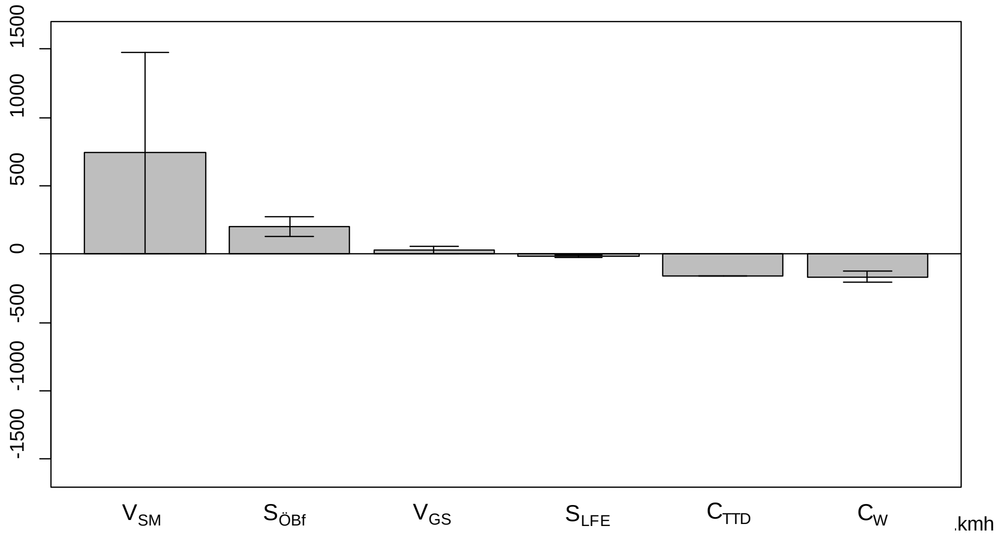
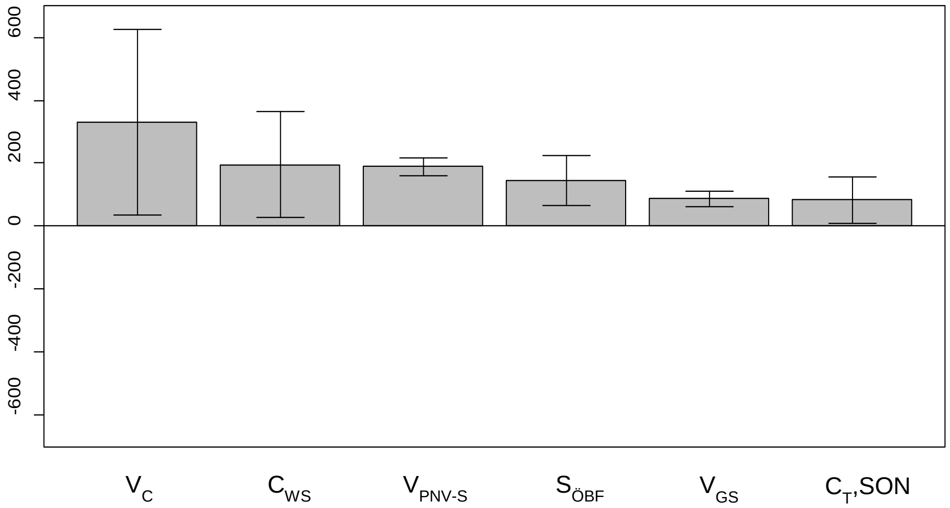


Fig. B-6: Marginal sensitivity of wind damage (m³ per 1,000 ha) to predisposing factors. The coefficients indicate how much average wind damage would change per 1,000 ha by a change of one standard deviation in the respective explanatory variable. Whiskers indicate 95% confidence intervals, and only variables significant in the PCR are displayed. For description of indicators see Tab. B-1.



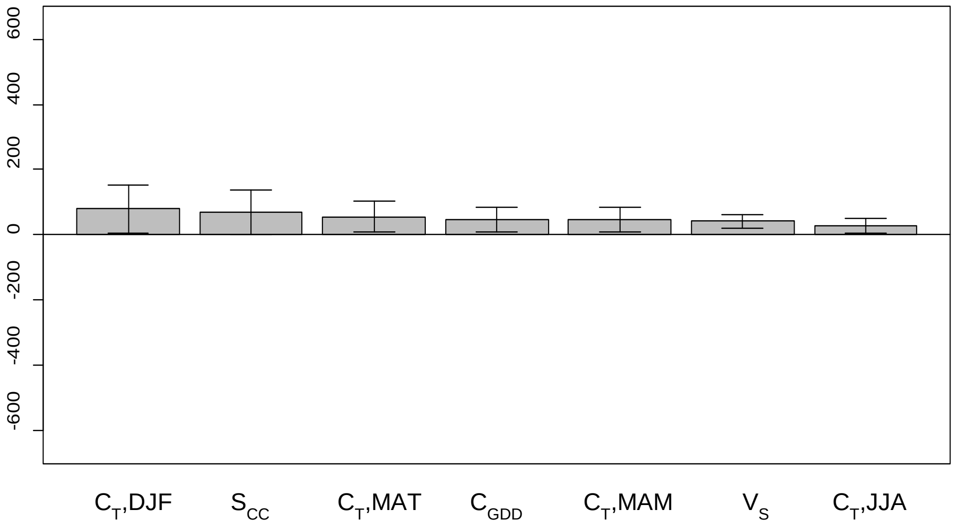


Fig. B-7: Marginal sensitivity of bark beetle damage (m³ per 1,000 ha) to predisposing factors. The coefficients indicate how much average bark beetle damage would change per 1,000 ha by a change of one standard deviation in the respective explanatory variable. Whiskers indicate 95% confidence intervals, and only variables significant in the PCR are displayed. For description of indicators see Tab. B-1.

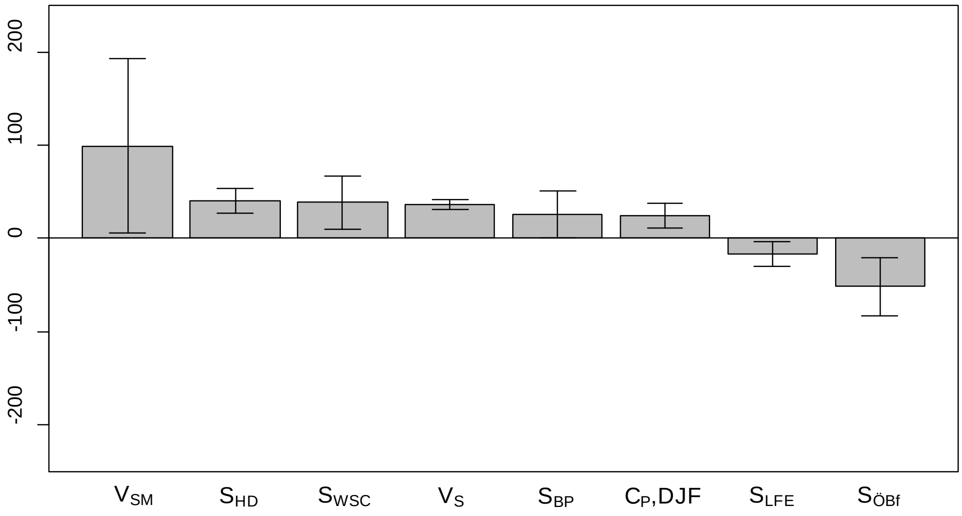


Fig. B-8: Marginal sensitivity of snow damage (m^3 per 1,000 ha) to predisposing factors. The coefficients indicate how much average snow damage would change per 1,000 ha by a change of one standard deviation in the respective explanatory variable. Whiskers indicate 95% confidence intervals, and only variables significant in the PCR are displayed. For description of indicators see Tab. B-1.

B-4.2.2 Inciting (fast) factors

The inciting factor of paramount importance for wind damage is without question the occurrence of high wind speeds (Gardiner et al. 2010). However, no high quality wind data with the spatio-temporal coverage required for this study were available. We thus used a wind event dummy as proxy (W_{WD}), which, despite its limited information content, was retained as significant in the final MLR model of wind occurrence. Of comparable explanatory power was mean daily maximum temperature in winter ($W_{MTMAX-DJF}$), underlining that frozen soils considerably increase the critical wind speed of forests to winter storms (see also Usbeck et al. 2010). As third indicator maximum daily precipitation in summer months ($W_{RMAX-JJA}$) entered the final model, which is a proxy for the frequency and intensity of summer thunderstorm occurrence, which are frequently associated with high wind speeds. Overall, the MLR of inciting factors for wind explained only 17.0% of the residual variance in disturbance damage (Tab. B-5).

As with predisposition, the occurrence model for bark beetles achieved a higher explanatory power as the corresponding MLR for wind, explaining 41.3% of the temporal residuals of the first analysis step. The by far dominating factor group was disturbance interactions, with temporal autocorrelation with bark beetle damage of the previous year (T_{DIB-1}) accounting for the overwhelming share of the variation explained in this second analysis step (Tab. B-6). Interactions with wind damage (T_{DIW}), which are widely hypothesized to be strongly related to the occurrence of bark beetle damage (Økland and Bjørnstad 2006), were significant in the model, but only of subordinate explanatory power compared to variables of spatial and temporal autocorrelation.

Due to the low explanatory power of the first analysis step the second analysis step for snow damage was suspended.

Tab. B-5: Results of a multiple linear regression and analysis of variance of inciting factors of annual wind damage residuals.

Explanatory variable	Unit	Coefficient	P-value	Variance explained
$W_{MTMAX-DJF}$	°C	416.7	<0.001	10.1%
W_{WD}	dummy	1826.5	<0.001	6.4%
$W_{RMAX-JJA}$	ratio	1299.9	0.135	0.4%

Tab. B-6: Results of a multiple linear regression and analysis of variance of inciting factors of annual bark beetle damage residuals.

Explanatory variable	Unit	Coefficient	P-value	Variance explained
T_{DIB-1}	m³ per 1000 ha	0.563	<0.001	34.3%
S_{DIA}	m³ per 1000 ha	0.129	<0.001	4.2%
T_{DIW-2}	m³ per 1000 ha	0.025	0.003	1.3%
T_{DIW-1}	m³ per 1000 ha	0.021	0.027	0.7%
W_{N1-JJA}	ratio	-723.7	0.067	0.5%
$W_{RMAX-JJA}$	ratio	-454.6	0.107	0.4%

B-4.2.3 Spatio-temporal drivers of disturbance regimes

In total, our analysis explained between 21.1% (snow) and 67.1% (bark beetles) of the spatio-temporal variation in the Austrian disturbance regime (Fig. B-9). The slow factor complex (predisposition), addressing spatial variation, had a higher explanatory power for all agents compared to the fast factor complex (occurrence), addressing temporal variation. This finding, together with the considerable variance explained overall for wind and bark beetles, suggests that disturbance damage at moderate to large scales, such as the forest district scale of this analysis, are less erratic than when studied at the stand or plot scale (cf. Urban et al. 1987 for the role of scale on inferential potential in ecology). The analysis presented in Fig. B-9 also shows that factors which can be actively influenced by forest management, i.e. in particular the composition and structure of the forest vegetation, have a considerably influence on disturbance. Silvicultural measures thus have considerable potential to shape disturbance regimes. Also factors related to stewardship, summarizing societal indicators as well as indicators broadly characterizing the prevailing management system were found to have a considerable influence on disturbance damage, highlighting the importance of addressing forest ecosystems from a coupled human and natural systems perspective (Liu et al. 2007). Finally, our two-step analysis also showed that spatio-temporal interactions within the disturbance regime are of considerable importance in the context of bark beetle damage.

Fig. B-9: Relative contribution of slow (predisposition) and fast (occurrence) drivers to the spatio-temporal variation in the Austria's disturbance regime. For every disturbance agent, the overall amount of variance explained in the two-step analysis is indicated in the bottom box, with the respective contributions to this explanatory power indicated for the respective variable groups. Top panel: wind, central panel: bark beetles, lower panel: snow.

B-4.3 Lessons learned for forest management and climate change adaptation

B-4.3.1 Hotspots of forest disturbance in Austria

An important aspect of successful adaptation is to allocate the (usually scarce) resources for such management changes to areas where they have the largest impact. In order to aid adaptation to changing disturbance regimes in Austria in this regard, we analyzed the hotspots of disturbance predisposition, mapping the predicted average disturbance level expected from the PCR in analysis step 1. Wind predisposition varied considerably over Austria, generally decreasing in eastern districts as well as the very south and west of the country (Fig. B-10). Clusters of elevated predisposition could be identified for Upper Austria and western parts of Lower Austria, as well as the upper Salzach and Mur valleys. In contrast, the distribution of relative predisposition to bark beetles more strongly reflected the large geomorphological conditions in Austria, with large parts of the inner Alps currently less susceptible compared to districts in pre-alpine areas. Predisposition is also low in north-eastern Austria, which is largely dominated by broadleaved trees and thus has low host availability for the bark beetle species investigated in this study. A clear hotspot of bark beetle predisposition was found in Upper Austria south of the river Danube, where relatively mild climate and high host availability coincide (Fig. B-10). Snow predisposition was found to be highest in the Mühlviertel region of northern Austria, and also elevated in districts along the eastern rim of the Alps. It was found to be comparatively low in eastern Austria, as well as in districts of the inner Alps (Fig. B-10). Considering that we found evidence for the support of the hypothesis of amplifying effects of interactions between wind and bark beetle disturbances in our data (see Tab. B-6), areas particularly susceptible to disturbance damage are those with elevated predisposition against both wind *and* bark beetles. Based on our findings, southern and central Upper Austria as well as Lower Austria roughly west of the river Traisen appear to be particularly prone to suffer from positive feedbacks between wind and bark beetles, and thus have to be seen as particularly susceptible disturbance hotspots in Austria (Fig. B-11).

B-4.3.2 Early warning indicators of disturbance damage

The spatial hotspots identified in the previous section relate to the effect of slowly changing factors on the average damage level, and are thus important determinants framing forest management in different areas in Austria. However, it would be also desirable to obtain indicators that can inform managers of an impending disturbance risk in order to allow monitoring to be intensified and countermeasures to be prepared. With regard to wind disturbance we, however, could not find such indicators in this study. Our data rather confirms the widely maintained notion that wind events are stochastic, and that the only preparation possible in management is one focusing on preparedness and long-term remedies (e.g., insurance, wet storage facilities, see e.g., Gardiner et al. 2010). With regard to bark beetle damage, on the other hand, our study clearly showed that a high amount of damage can be explained by the damage of the previous year. This is illustrated by the coefficients of the MLR in analysis step 2 (Tab. B-6), which indicate that for every m^3 of bark beetle damage in the current year, 0.56 m^3 of damage from bark beetles can be expected in the following year. This strong temporal autocorrelation inherent in the disturbance regime can be utilized in management to direct attention and resources particularly to those areas that have been suffering from outbreaks in the previous year, in order to mitigate the effect of bark beetle disturbance in the near-term future. This, in fact, is recommended already to practitioners and implemented in many forest enterprises in Austria. However, considering a further amplification under climate change, this information could be further developed into a potent risk management tool by integrating efforts of real-time bark beetle monitoring (e.g., BFW 2012) with information on previous damage (e.g., assimilated from a new near-term damage reporting system based on mobile devices) and long-term predisposition assessments (e.g., Fig. B-10).

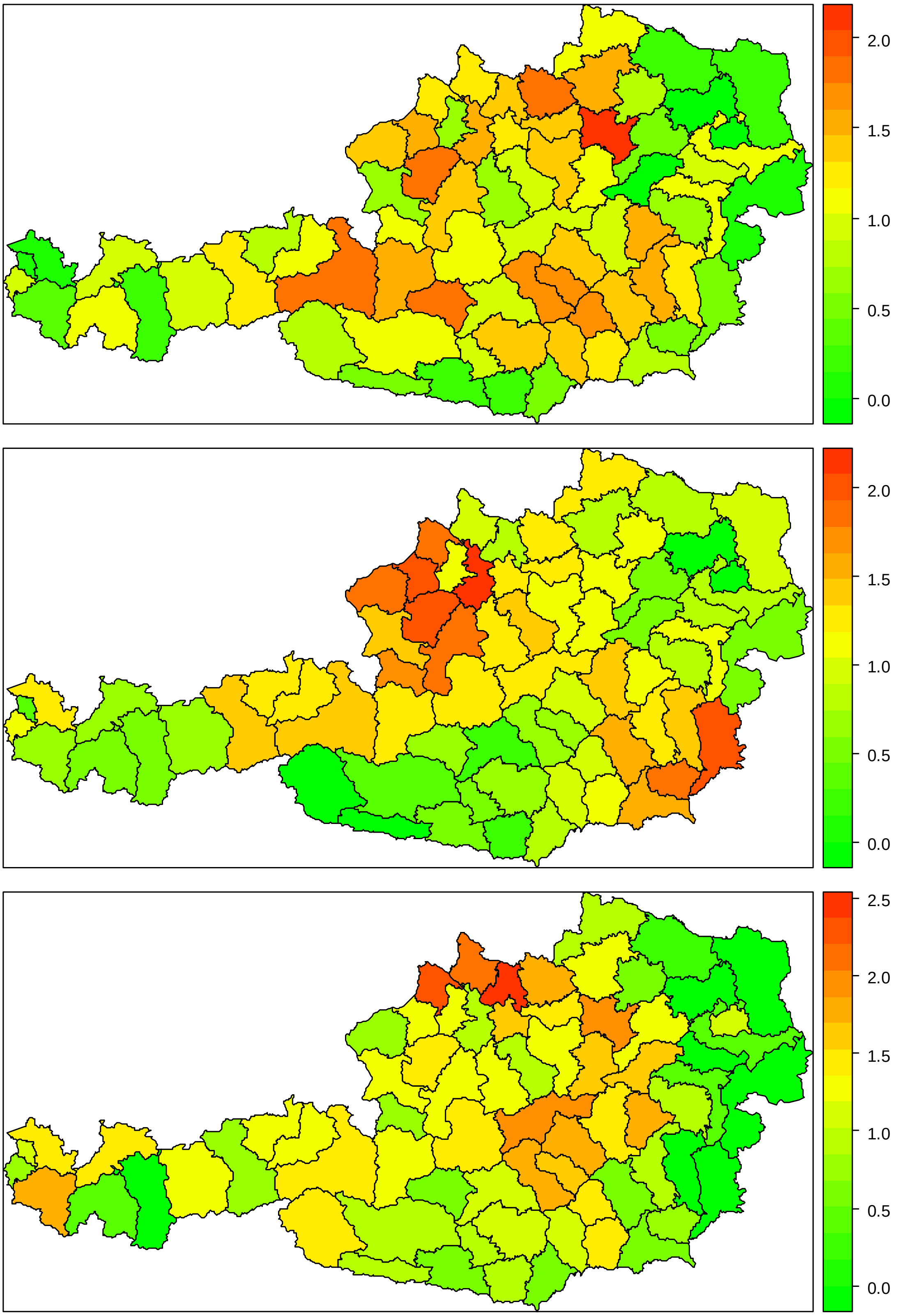


Fig. B-10: Hotspots of relative predisposition to wind (upper panel), bark beetle (central panel), and snow (lower panel) damage in Austria. Values indicate disturbance damage per unit area relative to the country average.

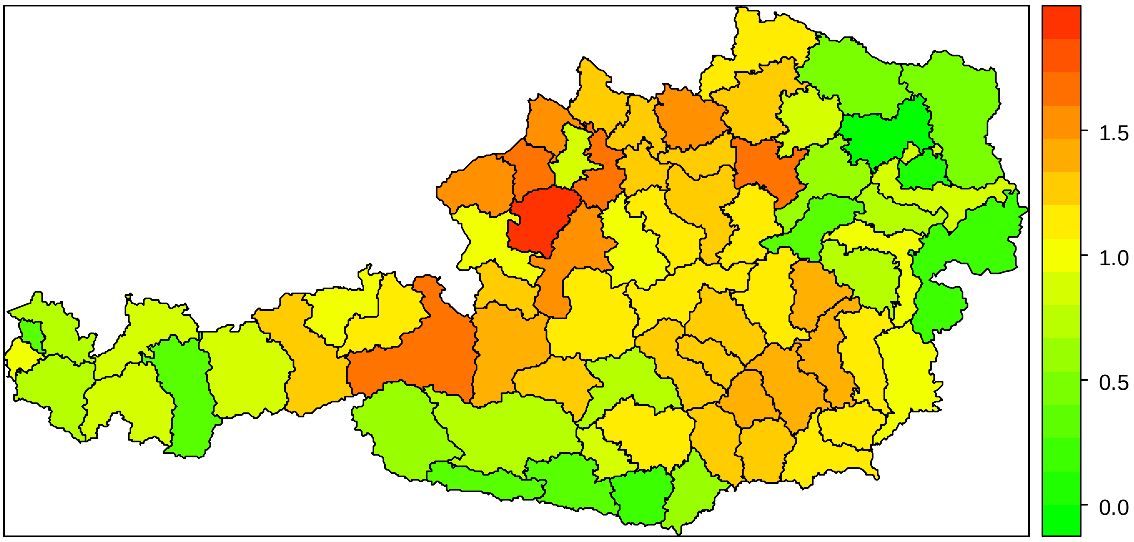


Fig. B-11: Aggregated relative predisposition (weighted by damaged volume) to wind, bark beetle, and snow damage in Austria. Values indicate total disturbance damage per unit area relative to the country average.

B-5 Discussion

B-5.1 Issues of data and methodology

All statistical analyses ultimately depend on data and data quality. In this regard it has to be noted that the disturbance data used in this analysis are among the best of their kind in Europe, and present a unique opportunity to better understand Austria’s disturbance regime. Uncertainties nonetheless remain, for one thing because reporting is done by a large number of individual forestry professionals in a bottom-up approach, which induces a certain level of subjectiveness into the reporting process. However, since we focus on Austria's main damage agents here, which do not require a high level of expertise for their identification (unlike, e.g., many pathogens or invasive pests), we assess the data to be fairly reliable. In addition, the data used here were homogenized and quality-checked by experts of the BFW, adding to the robustness of the data material.

Also a large majority of the driver data used in this analysis come from highly robust sources and are collected using standardized methodology, such as, e.g., the data of the AFI (2012) or the weather and climate data of ZAMG (2012b,c). However, a crucial weather indicator with regard to wind damage, peak gust wind speed, was not available from these sources, which is a major limiting factor in the analysis of inciting factors of wind disturbance. To alleviate this issue we used qualitative information on storm history based on the ZAMG extreme events report (ZAMG 2012d) to create a dummy variable for the occurrence of strong winds. Since this includes subjective assessments both with regard to the classification of a significant storm event as well as with regard to its exact spatial location and extent, uncertainty with regard to the main weather-related trigger of wind damage remains.

More generally, a further limiting factor of the study was the relatively short time series of disturbance data available for detailed analysis, consisting of only 9 years of observations. Notwithstanding the fact that the analysis of a longer time series would be desirable, potential negative effects were to some degree compensated by the fact that the study did investigate relatively large spatial aggregates of data (districts, rather than e.g., individual inventory plots or stands), which already integrate a considerable amount of the stand- to landscape scale variation of the disturbance regime. Overall, the detailed analyses presented in sections B-4.2 and B-4.3 utilized data from 9 years for 72 districts, amounting to 648 observations. Statistical power in general and the ability to identify significant driver variables would increase with a higher number of observations. It might thus be of interest to conduct similar analyses in the future, when more data become available.

Using principle component regression was found to be an appropriate method for solving the problem of multicollinearity in this study. The considered alternative, applying multiple linear regression with prior reduction of correlated predictors, would have reduced the overall explanatory power of the analysis in step 1 considerably (Morzuch, Ruark 1991), with potential adverse effects on the analysis in step 2. The PCR helped to overcome this problem by orthogonalization of the predictors. However, the elimination of principle components from the PCR is an intricate task, for which several different approaches have been proposed in the literature, ultimately resulting in different final PCR models. In this study, we aimed at finding a middle ground between significance in predictors (via eliminating PCs with little information content) and a loss in R^2 due to this reduction (Jolliffe 2002). A different mechanism of variable selection in the PCR, however, is likely to have resulted in differences in the final models, e.g. with regard to the significant driver variables of disturbance damage. Despite using a strongly data-driven statistical analysis in this study, a subjective component to the analysis thus remains.

As the focus of the second analysis step was in particular on identifying the most important inciting factors (rather than on maximizing the explanatory power of the analysis), a stepwise linear regression model with prior elimination of correlated predictors was used. However, again, the approach to eliminate variables in order to avoid multicollinearity is to some degree subjective. In this study, a threshold correlation of r=0.4 between predictors was set in order to exclude strongly correlated variables from the model. Other methods for dealing with multicollinearity could have been applied, such as the use of variance-inflation factors or the condition index (Hedderich and Sachs 2011).

B-5.2 Disturbance drivers

The findings of our large-scale statistical analysis are widely congruent with previous analyses based on expert systems, process modeling, and site-specific empirical analyses. In particular, the importance of species composition in general and the share of Norway spruce in particular has been highlighted by many authors previously (e.g., Führer and Nopp 2001, Netherer and Nopp-Mayer 2005, Albrecht et al. 2012). The spatial patterning of disturbance predisposition found in this study (Fig. B-10, B-11), however, differs considerably from a recent expert assessment by Tomiczek and Schweiger (2012). Yet, these authors assessed a general and much broader defined forest risk compared to the agent-specific assessment of this study, which limits comparability. Furthermore, Tomiczek and Schweiger (2012) did not include variables describing the current composition and structure of forest vegetation in their analysis, which further contributes to divergence in assessments, since these variables were found to be of high relevance in this study (Fig. B-9).

With regard to the importance of spatial autocorrelation in the context of bark beetle damage found in this study it is interesting to note that empirical studies found a strong decline in *I. typographus* population density at a distance of merely 300 m from infested plots (Angst et al. 2012). Similar results were reported by Kautz et al. (2011), who found 95% of the infestations to occur within a radius of 500 m from previously attacked sites. The effect of spatial interactions might thus be even stronger at the stand scale than at the district scale investigated here. However, individual pioneer beetles can disperse over considerably distances (> 8,000 m, Botterweg 1982), and might be increasingly forced to such behavior under high population pressure. Considering that the spatial resolution of this analysis was coarse, it is thus particularly noteworthy that spatial autocorrelation was retained as a significant variable in the analysis.

Another interesting finding of the study was the positive relationship of wind and bark beetle damage with ÖBf AG ownership. This signifies that districts with a large share of ÖBf-managed forest were experiencing higher levels of disturbance damage during the study period. It is, however, not conclusively possible to connect ÖBf AG management to higher predisposition, as correlation does not equal causation. A possible explanation for this finding lies in a very high share of protective forests managed by the ÖBf (37.3%). These forests are usually more difficult to access and situated in complex terrain, complicating disturbance management. Furthermore and connected to this fact, the average productivity of ÖBf forests is lower than that of large commercial forest enterprises and the average Austrian forest area (AFI 2012). More productive sites support a trees' vitality, and strengthen their defenses against pests and diseases (Christiansen et al. 1987). Deeper and richer soils usually also support the anchorage of trees and thus the stability against wind. The positive effect of ÖBf-managed forest area on damage predisposition found in this study could thus also partly be related to a site/ productivity effect.

Based on theoretical considerations (Manion 1981, Seidl et al. 2011c) we here distinguished "fast" and "slow" driving variables of the disturbance regime explicitly. The importance of the role of scale is illustrated by the different indicators of windiness used in this study. While the dummy for extreme wind events (W_{WD}, short timescale) was significantly positively related to wind damage, factors related to the average long-term windiness of a site (describing the topographic exposure, C_{TTD}, as well as the wind climate, C_W) showed a negative relationship. The latter indicates a significant acclimation effect of forests to wind loading (Danjon et al. 2005), and underlines the importance of scale in analyzing ecological data (Urban et al. 1987, Wiens 1989). Based on these findings, strong wind events in areas that are generally less wind-exposed (i.e., where trees are less adapted to wind) can be expected to result in the greatest damage to forest ecosystems.

B-5.3 Implications in the context of climate change

Climate is expected to change considerably in the future (IPCC 2007). According to our analysis, the expected temperature increase in the future will likely further increase the predisposition of forest ecosystems in Austria to bark beetle damage (Fig B-7). Future changes in precipitation are still associated with high uncertainty. If, however, the variability in precipitation increases, and regional wet snow events become more frequent, a further amplification of bark beetle and snow damage is suggested from our analysis. It is important to note that a changing climate will not only affect the long-term average properties of the climate system but will also affect the frequency and occurrence of extreme weather events. A warming climate can, for instance, decrease the number of days with winter soil frost in many areas, which will increase the propensity towards damage from winter storms (Tab B-5, Usbeck et al. 2010). Furthermore, an increase in drought periods in summer will likely further facilitate bark beetle attacks via a drought-related weakening of host tree defense systems (Tab B-6, Lexer 1995). Overall, bark beetle disturbance was found to be the disturbance agent with the highest number of significant climate- and weather-related indicators in the final model. Bark beetles in particular also displayed a strong dependency on (intra- and inter-agent) interactions within the disturbance regime, which could further fan disturbance damage in an intensifying disturbance regime. Overall, for none of the climate- and weather-related factors which were found to be significant drivers of Austria’s disturbance regime a decreasing trend can be expected under future climate change (IPCC 2007, 2012). In other words, with unchanged or further increasing drivers it is likely that disturbance regimes will further intensify in the future. This underlines the importance of timely adaptation measures in silviculture, in order ensure the sustainable provisioning of ecosystem services also under changing disturbance regimes.

B-6 Conclusion

Forest disturbance regimes are intensifying at continental scale, and the frequency and severity of damage from agents such as wind and bark beetles are expected to increase further in the future. We here analyzed the spatio-temporal variation in Austria’s disturbance regime, finding evidence for a considerable climate sensitivity of disturbances. However, our analysis also showed that factors related to the structure and composition of forest ecosystems, together with indicators of their stewardship, had an overall larger influence on disturbance regimes than climate and weather. This highlights the fact that there is considerable potential to counteract the expected climate-driven intensification in the disturbance regime by means of forest management. We found that of particular importance in this regard are aspects of species composition. The promotion of mixed, less conifer-dominated stands emerged as the most promising single measure to simultaneously reduce the susceptibility to wind, bark beetles and snow in climate change adaptation efforts. In order to support this process of adaptation in forest management, we have identified spatial hotspots of disturbance predisposition in Austria, finding that large parts of Upper and Lower Austria west of the river Traisen are particularly prone to both wind and bark beetle disturbance. Adaptation measures in these areas would thus be particularly needed. In turn, adaptation measures in these areas can be expected to yield especially high “returns on investment” with regard to the reduction of disturbance risk. Our findings also corroborate the importance of spatio-temporal interactions particularly in the context of bark beetle damage, underlining the potential of bark beetle monitoring as an early warning indicator of disturbance damage in the near-term future. Overall, the study thus contributes to a better and more quantitative understanding of Austria’s disturbance regime, and provides insights of relevance to the implementation of the Austrian climate change adaptation strategy, which, among other things, explicitly includes a measure on improved disturbance management. However, it has to be noted that in order to be able to implement concrete adaptation measures the local landscape scale context needs to be considered. An important next step would thus be to develop strategies for improved disturbance management in selected forest landscapes across Austria, and further test and improve the findings of the current study in the context of studies that focus more strongly on the scale of forest management decision making (i.e., tree, stand, landscape).

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Tables

Appendix

Tab. B-A1: Correlation of individual predictors of predisposition to wind damage

predictor	correlation coefficient	p-value
V_{SM}	0.426	0.000
V_{S}	0.381	0.001
V_{C}	0.298	0.011
S_{HD}	0.276	0.019
S_{BP}	0.209	0.078
V_{GS}	0.205	0.084
S_{CC}	0.186	0.118
V_{PNV-C}	0.165	0.167
$S_{\text{ÖBf}}$	0.146	0.220
V_{SSA}	0.043	0.723
C_{TTD} (3000 m)	0.039	0.747
C_{SF}	0.021	0.862
V_{PNV-S}	0.004	0.971
C_{TTD} (2000 m)	-0.054	0.650
C_{TTD} (1000 m)	-0.141	0.237
C_{W}	-0.167	0.160
C_{TTD} (500 m)	-0.214	0.071
S_{LFE}	-0.236	0.046

Tab. B-A2: Correlation of individual predictors of predisposition to bark beetle damage

predictor	correlation coefficient	p-value
V_{PNV-C}	0.366	0.002
V_{PNV-S}	0.307	0.009
V_{GS}	0.264	0.025
C_{T-DJF}	0.245	0.038
C_{T-SON}	0.223	0.059
C_{WS}	0.223	0.060
$S_{\text{ÖBf}}$	0.216	0.068
C_{T}	0.216	0.069
C_{T-MAM}	0.215	0.069
C_{GDD}	0.200	0.093
C_{T-JJA}	0.188	0.115
V_{S}	0.157	0.187
V_{SM}	0.106	0.376
V_{C}	0.096	0.421
S_{CC}	0.093	0.435
S_{RD}	0.067	0.587
S_{FSS}	-0.007	0.950
V_{SSA}	-0.036	0.767
S_{LFE}	-0.294	0.012

Tab. B-A3: Correlation of individual predictors of predisposition to snow damage

predictor	correlation coefficient	p-value
V_{SM}	0.314	0.007
V_{S}	0.283	0.016
S_{HD}	0.278	0.018
V_{GS}	0.224	0.059
V_{C}	0.202	0.089
V_{PNV-C}	0.173	0.147
C_{WSC}	0.112	0.348
C_{P-DJF}	0.099	0.406
S_{BP}	0.087	0.469
C_{T-DJF}	0.027	0.825
V_{MA}	0.001	0.992
V_{PNV-S}	-0.030	0.802
S_{LFE}	-0.030	0.793
V_{SSA}	-0.124	0.300
$S_{ÖBf}$	-0.141	0.238

Tab. B-A4: Correlation of individual predictors of occurrence to wind damage

predictor	correlation coefficient	p-value
W_{MTMAX}	0.340	0.000
W_{t-DJF}	0.332	0.000
$W_{MTMIN-DJF}$	0.311	0.000
$W_{RMAX-SON}$	0.210	0.000
$W_{RMAX-JJA}$	0.029	0.460
$W_{RMAX-MAM}$	0.029	0.466
$W_{RMAX-DJF}$	-0.053	0.177

Tab. B-A5: Correlation of individual predictors of occurrence to bark beetle damage

predictor	correlation coefficient	p-value
T_{DIB-1}	0.543	0.000
S_{DIA}	0.352	0.000
T_{DIB-2}	0.260	0.000
T_{DIW-2}	0.189	0.000
S_{DIA-1}	0.145	0.000
T_{DIW-1}	0.118	0.005
$W_{RMAX-SON}$	0.037	0.352
W_{N1-MAM}	0.013	0.749
W_{t-SON}	0.003	0.943
$W_{MTMAX-SON}$	0.003	0.945
$W_{MTMIN-DJF}$	-0.002	0.958
W_{t-JJA}	-0.007	0.862
$W_{MTMAX-JJA}$	-0.008	0.840
W_{t-MAM}	-0.011	0.777
W_{N1-JJA}	-0.012	0.753
$W_{MTMAX-MAM}$	-0.014	0.724
W_{t-DJF}	-0.024	0.535
$W_{RSUM-MAM}$	-0.050	0.204
$W_{RMAX-MAM}$	-0.060	0.127
$W_{RSUM-SON}$	-0.061	0.121
$W_{RSUM-JJA}$	-0.114	0.004
$W_{RMAX-JJA}$	-0.132	0.001