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Spatial configuration matters when removing windfelled trees to manage bark beetle disturbances in Central European forest landscapes

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Abstract

Windfelled Norway spruce (*Picea abies*) trees play a crucial role in triggering large-scale outbreaks of the European spruce bark beetle *Ips typographus.* Outbreak management therefore strives to remove windfelled trees to reduce the risk of outbreaks, a measure referred to as sanitation logging (SL). Although this practice has been traditionally applied, its efficiency in preventing outbreaks remains poorly understood. We used the landscape simulation model iLand to investigate the effects of different spatial configurations and intensities of SL of windfelled trees on the subsequent disturbance by bark beetles. We studied differences between SL applied evenly across the landscape, focused on the vicinity of roads (scenario of limited logging resources) and concentrated in a contiguous block (scenario of spatially diversified management objectives). We focused on a 16 050 ha forest landscape in Central Europe. The removal of >80% of all windfelled trees is required to substantially reduce bark beetle disturbances. Focusing SL on the vicinity of roads created a "fire break effect" on bark beetle spread, and was moderately efficient in reducing landscape-scale bark beetle disturbance. Block treatments substantially reduced outbreaks in treated areas. Leaving parts of the landscape untreated (e.g., conservation areas) had no significant amplifying effect on outbreaks in managed areas. Climate change increased bark beetle disturbances and reduced the effect of SL. Our results suggest that past outbreak management methods will not be sufficient to counteract climate-mediated increases in bark beetle disturbance.

Keywords

Wind-bark beetle interactions; Forest landscape; Process-based ecosystem modelling; Climate change; Sanitation logging

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1 Introduction

Disturbances from bark beetles have increased sevenfold in Europe's forests since the 1970s (Seidl et al., 2014a). Recent bark beetle outbreaks have reached supranational scales (Senf and Seidl, 2018), increasingly challenging the management responses traditionally applied to mitigate bark beetle outbreaks. Research indicates that future climate change will further fuel bark beetle outbreaks (Jönsson et al., 2009; Seidl et al., 2017), with potential adverse effects on the sustainable supply of ecosystem services to society (Morris et al., 2018). In particular, the number of generation cycles completed per year will increase for important bark beetle species (Baier et al., 2007; Berec et al., 2013; Fleischer et al., 2016), fanning population growth. Bark beetles can also expand into new territories because of relaxed thermal limitations (Jönsson et al., 2009). In addition, drought events, which are expected to become more frequent in the future (IPCC, 2014; King and Karoly, 2017), reduce the capacity of trees to defend themselves against bark beetle attacks (Matthews et al., 2018).

Taken together, bark beetle disturbances are expected to be among the most climate sensitive processes in forest ecosystems (Lindner et al., 2010). Managing bark beetle outbreaks is thus a key challenge for forest managers. Yet, there are indications that some traditionally applied bark beetle management measures may become inefficient under the conditions expected for the future (Dobor et al., 2019a; Hlásny et al., 2019), making a quantitative evaluation of bark beetle management measures a key priority for research (Morris et al., 2017).

Sanitation logging (SL) has been an important part of the management response to outbreaks of the European spruce bark beetle *Ipstypographus* (Coleoptera: Curculionidae, Scolytinae) in Europe (Hlásny and Turčáni, 2013; Stadelmann et al., 2013; Wermelinger, 2004). SL entails the removal of infested host trees and/or healthy trees in the vicinity of beetle spots with the aim to prevent and mitigate the spread of bark beetle outbreaks. SL is applied during outbreaks to eradicate infestation spots, from which beetles spread to surrounding stands. It is, however, also applied in endemic phases of bark beetle development (i. e. when populations are low and beetles selectively infest and kill only freshly dead and weakened trees) in order to keep beetle populations below the eruptive threshold (Raffa et al., 2008; Wermelinger, 2004). SL is also used to disrupt the connectedness of outbreak areas via the removal of potential host trees in the vicinity of outbreak spots with the aim to reduce beetle spread (Seidl et al., 2016b).

Outbreaks of the European spruce bark beetle are typically triggered by windthrows (Mezei et al., 2017; Økland et al., 2016; Schroeder and Lindelöw, 2002), which provide large amounts of breeding substrate in form of broken or uprooted trees. As these trees provide favourable breeding conditions but are only weakly protected by tree defences they are preferred by beetles over vigorous live trees (Komonen et al., 2011; Matthews et al., 2018). Large windthrows thus attract beetles from surrounding areas and initially act as a sink for the beetle population. When this resource is exhausted (typically in one to two years), a substantially enlarged beetle population leaves the windthrown area and colonizes surrounding live trees (Eriksson et al., 2007; Wichmann and Ravn, 2001). SL therefore aims to remove windfelled trees before the beetles are spreading to surrounding areas (Schroeder, 2007; Stadelmann et al., 2013; Wichmann and Ravn, 2001).

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Despite the long tradition in applying SL in forestry practice there is very little quantitative evidence on the effect of such management measures on bark beetle populations and the amount of trees killed by bark beetles (but see for example Mezei et al., 2017; Stadelmann et al., 2013). This is particularly true for conditions where outbreak areas are large and beetle pressure is high, as is expected for the coming decades. Studies on bark beetle management have instead focused on the assessment and optimization of different trapping devices (Galko et al., 2016; Holuša et al., 2017), have improved the detection of infested trees using remote sensing (Abdullah et al., 2019, 2018), and made recommendations on how to prioritize fellings based on forest structure, storm gap size and other factors (Schroeder, 2010). The broader implications of the removal of disturbed trees has come into focus recently, with assessments of its effects on biodiversity, ecosystem services, forest recovery, as well as carbon and nutrient cycles (Leverkus et al., 2018; Lindenmayer and Noss, 2006; Thorn et al., 2017). The efficiency of SL to reduce subsequent bark beetle damage – frequently given as the primary motivation to conduct SL by managers and thus a key element in the discussion on salvage and SL – remains understudied to date. As SL is time- and labour-intensive, particular questions of interest relate to the optimal rate and spatial pattern of SL, and whether SL will be able to mitigate bark beetle outbreaks under future climatic conditions.

Our overall objective was to evaluate the effect of a wide range of SL intensities and spatial configurations on future bark beetle disturbances. Specifically, we assessed how different spatial configurations of SL on the landscape affect its efficiency for reducing bark beetle disturbances. This question was motivated by the fact that timely SL operations are frequently restricted, either by limited accessibility of disturbed stands (Lamers et al., 2014) or by the nature conservation status of certain tracts of a forest landscape (Müller et al., 2018). Furthermore, we asked if and how climate change modulates the effects of SL treatments on bark beetle dynamics. Based on previous findings and current process understanding we hypothesized that spatially concentrated applications of SL with high treatment intensity are most efficient (Dobor et al., 2019a; 2019b), but that a climate-mediated increase in bark beetle population levels will strongly reduce the efficiency of SL. In order to capture the complex interplay between (future) climate, bark beetle populations, and host trees we employed process-based simulations using the model iLand (Seidl et al., 2012a). Simulation modelling allowed us to overcome common difficulties in the analysis of forest disturbances, such as the quantification of reference conditions (here: a landscape not treated with SL but otherwise similar to the treated landscape).

2 Materials and methods

2.1 Study landscape

The study landscape is located in Slovakia in the Low Tatras Mountains (Central Europe). The landscape covers an area of 16 050 ha, of which 70% are covered with forests. The elevation range is 620–1550 m a.s.l. Air temperature during the growing season (April–September) ranges from 12 to 15 °C, and growing-season precipitation ranges from 380 to 510 mm. Norway spruce (*Picea abies* (L.) Karst.) makes up 70% of the tree species composition, with Silver fir (*Abies alba* Mill.) and European beech (*Fagus sylvatica* L.) as other canopy-dominant tree species. Forests in the region are intensively managed for timber production. The dominant silvicultural approach to regenerate mixed stands containing a fir and/or beech component is a uniform shelterwood cut (a progressive cutting that leads to the establishment of a new cohort of trees under the canopy of the retained mature trees). In spruce monocultures, a small-scale clear-cutting system is applied. The forests in the study landscape have experienced severe wind and bark beetle disturbances since 2007, affecting 39% of the forest area until 2010 (Dobor et al., 2018). Management responses to disturbance include extensive salvage and SL, beetle trapping, a decrease in regular harvests as well as efforts to establish stands with a more diverse tree species composition in order to decrease future disturbance risk. The disturbance patterns and management responses in our study landscape are characteristic for the recent disturbance history in many Central European forest landscapes (Senf et al., 2017).

2.2 Definitions

There is considerable terminological confusion in the literature regarding management measures applied to mitigate bark beetle outbreaks. The term sanitation logging is often used interchangeably with the term salvage logging (e.g. Fettig et al., 2007). In other instances, the two terms are used to denote different aspects of bark beetle management (e.g. removal of windblown trees to prevent their infestation vs. removal of standing infested trees to prevent beetle spread; Stadelmann et al., 2013; Wermelinger, 2004). We here define sanitation logging as any tree removal activity which aims to prevent the risk of bark beetle attack to adjacent trees and/or mitigate bark beetle spread. In contrast, we use term salvage logging for tree removal activities which are conducted with the primary aim to recoup economic losses from disturbances or reduce disturbance-induced hazards to infrastructure and human safety (Molinas-Gonzáles et al., 2017).

2.3 Simulation model

The model iLand (Seidl et al., 2012a) is a process-based ecosystem model that simulates forest landscape dynamics in a hierarchical multi-scale framework (e.g., Mäkelä, 2003), i.e. treating different processes at different spatial and temporal scales. The main entity in the model is a tree, for which the demographic processes of growth, mortality, and regeneration are simulated. Processes at the stand and landscape scale constrain the dynamics of individual trees and thus allow for a robust scaling of tree-scale processes to large areas (Seidl et al., 2012a). The model was extensively tested and evaluated across a range of ecosystems in Europe and North America in previous studies (Braziunas et al., 2018; Seidl et al., 2012b; Silva Pedro et al., 2015; Thom et al., 2017a). Furthermore, the model was successfully tested for the study landscape investigated here by Dobor et al. (2018), focusing on productivity, natural mortality (i.e. mortality caused by stress and competition for resources) and regeneration patterns in a pattern-oriented modelling approach.

iLand simulates disturbances in a spatially explicit manner and contains process-based modules for several disturbance agents. Wind disturbance is simulated in the model based on input regarding wind (i. e., speed, direction, duration, day of year of occurrence), which can be derived from meteorological observations of specific wind events, statistical descriptions of historical wind regimes, or simulations generated by climate models (Seidl et al., 2014a).

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The model initiates wind disturbances in locations, where canopy rugosity changes abruptly, i.e., where vertical differences between the top heights of neighbouring grid cells exceed 10 m (e.g. Blennow and Sallnäs, 2004). The impact of a wind event is simulated iteratively, with forest structure – including the appearance of new edges – being updated over the course of the duration of the wind event. In each iteration the model calculates critical wind speeds for uprooting and breakage of affected trees (Seidl et al., 2014a) if the wind speed in the current iteration exceeds these critical wind speeds, the tree is either broken or uprooted. The simulated wind disturbance patterns are thus an emergent property of the wind forcing in combination with the prevailing forest structure.

The iLand bark beetle disturbance module simulates phenology and development of the European spruce bark beetle, spatially explicit dispersal of beetles, colonization and tree defence, as well as temperature-related overwintering success of beetles (Seidl and Rammer, 2017). Outbreak are either triggered by wind disturbance, or happen independently based on climate-sensitive background infestation probability. Bark beetle development is simulated based on temperature-sensitive beetle phenology (Baier et al., 2007), allowing for the development of multiple beetle generations per year under favourable climatic conditions. For reasons of computational efficiency the model does not track individual beetles but beetle cohorts, which are defined as the minimum number of beetles needed to colonize a tree. Every brood tree disperses a number of beetle cohorts determined by the effective reproductive rate of the beetles, which was here set to 20 (see Wermelinger and Seifert, 1998). Sister broods are assumed to have a 50% reduced reproductive rate (Anderbrant, 2006). The emerging beetles disperse in two stages: First, their general dispersal distance and direction is determined based on a symmetrical dispersal kernel parameterized from field data. Subsequently, beetles actively search for host trees within their perceptive range. A beetle cohort attacking a tree has to first overcome the trees' defence system. iLand dynamically simulates tree stress based on the carbon balance of a tree. The thus derived stress index is used as an indicator of tree defence against bark beetles. Freshly wind-disturbed trees are assumed to be defenceless against bark beetle attacks, and are thus also preferred by beetles in their host search. Consequently, the timely removal of windfelled trees (i.e., before beetle development is completed) affects the subsequent bark beetle outbreak dynamics. Simulated natural bark beetle mortality accounts for both overwintering mortality and density-dependent effects of antagonists.

2.4 Landscape initialization and experimental design

Data from Forest Management Plans (FMP; Source: National Forest Centre, Slovakia) were used to initialize the current state of the forest vegetation in the simulations. The data were collected in the field at a 10-year inventory cycle, and contain statistical descriptions of forest stands within compartments with variable size (ca 3–15 ha). The FMP attributes used to initialize the landscape in iLand were number of trees per hectare, stand age, and diameter at breast height (DBH). Individual tree diameters were randomly drawn from diameter distributions centred on the mean DBH of each stand, with the variance derived from forest plots in the region. Tree heights of all individuals were calculated based on species-specific diameter-height curves. Saplings (trees below 4 m height) were initialized as height cohort with tree height data derived from FMPs. iLand furthermore requires information on soil

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type and depth and uses plant-available nitrogen (N) as a proxy for nutrient availability. This information was derived from the national forest soil database of Slovakia (Source: National Forest Centre, Slovakia).

We evaluated forest development under different intensities and spatial patterns of SL for the period from 1996 (i.e., the year of the initialization of the study landscape based on FMP data) to 2050. We used this time horizon because of its relevance for current management decision making. Moreover, climate conditions after 2050 start to critically constrain spruce persistence in our study landscape. Reference climate data (i.e. representing a continuation of past climatic conditions) were developed based on the observed climate for 1996–2016 by random sampling of years with replacement. To assess the effects of climate change, we studied six climate change scenarios, derived from three regional climate model (RCM) runs conducted within the framework of the CORDEX project (Coordinated Regional Climate Down-scaling Experiment; Giorgi et al., 2009). Each RCM was driven by two Representative Concentration *Pathway scenarios,* i.e., RCP 4.5 and RCP 8.5 (Supplementary material).

We prescribed wind events to occur in the years 2000, 2010 and 2030 in all scenarios. Each wind event was simulated with five different wind speeds, which were randomly drawn from a distribution of maximum hourly wind speeds observed at the nearby meteorological station Poprad–Gánovce (Source: Slovak Hydrometeorological Institute) between 1996 and 2018. The simulated wind events were 90 min long, and wind directions were set based on the prevailing wind directions in the region (east-northeast in 2000, west-southwest in 2010 and 2030). The average amount of windfelled trees simulated with these settings corresponded well with observed wind disturbance data for Slovakia between 1990 and 2015 (Konôpka et al., 2016).

Bark beetle dynamics was simulated based on the model structure and parameterization introduced by Seidl and Rammer (2017) (see also Supplementary material). Simulated bark beetle disturbances matched observed bark beetle dynamics well, with the proportion of bark beetle disturbed timber volume being in the range of 70–120% of windfelled timber (based on national forest damage statistics, Source: National Forest Centre, Slovakia) and with bark beetle infestations occurring primarily in the vicinity of windthrows with only minor infestation spots occurring independently of windthrows (based on the inspection of satellite imagery from the region; Dobor et al., 2018; Potterf et al., 2019).

To assess the effect of the spatial configuration of SL we simulated three different spatial patterns: uniform SL over the entire study landscape (U), SL only in the vicinity of forest roads (R), and SL in a contiguous subset of the landscape (block design, B) (Fig. 1). Scenario R represents a situation in which limited logging resources are available, restricting sanitation efforts to stands that are easily accessible. In contrast, scenario B illustrates the development if different management objectives need to be met on the landscape, with SL being restricted to certain areas, while other areas are exempt from treatments (e.g., due to considerations of nature conservation). Two treatment levels were simulated for scenarios R and B, treating 40% and 60% of the total forest area in the landscape. These two SL intensities correspond to buffer widths of 60 and 100 m (in each direction from the road),

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respectively, in the scenario R. For each spatial configuration scenario different levels of SL intensity were simulated, representing different percentages of windfelled trees detected and removed by management. In scenarios R and B, SL intensities of 60% and 95% (I60, I95) were simulated, resulting in a total of eight SL scenarios: R40-I60, R40-I95, R60-I60, R60-I95 and B40–I60, B40–I95, B60–I60, B60–I95. In the uniform scenario U, a total of seven different SL intensity levels forming an intensity gradient were simulated (i.e., 0, 20, 40, 60, 80, and 95% of windfelled trees removed).

The effect of SL was evaluated with regard to three different response variables: (i) the landscape-scale reduction of bark beetle disturbance relative to values reached in the absence of SL, (ii) the disturbance reduction in the treated areas, and (iii) the disturbance reduction in untreated areas. To consistently compare the effects of different spatial configurations and intensities of SL we derived a standardized sanitation intensity (SSI, %), which was calculated as the sanitation intensity (SI, %) multiplied by the portion of treated forest area (Area, %) (Eq. (1)):

$$SSI = \frac{SI \times Area}{100} \quad [1]$$

In scenario U the SSI equals SI. To further elucidate SSI values, we also investigated the relationship between SSI, the amount of disturbed spruce volume extracted, and the amount of remaining disturbed spruce volume (Appendix A).

3 Results

3.1 Wind and bark beetle impacts in the absence of sanitation logging

The amount of spruce trees disturbed by wind ranged from 25 to 40 m^3 ha^{-1} during the wind event in the year 2000 (range is based on simulation outputs driven by 5 different wind settings), with 11–23 m^3 ha^{-1} and 39–60 m^3 ha^{-1} being disturbed in the years 2010 and 2030, respectively (Fig. 2). This represents 8–14, 3–7 and 12–21% of the Norway spruce growing stock in the landscape. Each wind event triggered outbreak of bark beetles, with 20–26, 51–77 and 30–45 m^3 ha^{-1} killed volume in the absence of SL. The average bark beetle disturbance during the full simulation period was 2.0–2.5 m^3 ha^{-1} $year^{-1}$ ($Dist_{vol}$), representing an annual loss rate of 0.6–0.8% of live spruce volume on the landscape (Dist%) (Appendix B).

Climate change affected the windfelled volume only marginally in the first wind event, while the remaining two windthrows were more sensitive to climate change (Fig. 2). The timber volume affected by bark beetles increased by 1–17, 11–40, and 220–300% in the three outbreak waves under climate change compared to reference climate. $Dist_{vol}$ was in the range of 4.2-4.3 m^3 $ha^{-1}year^{-1}$, resulting in a cumulative timber volume disturbed of 226–234 m^3 ha^{-1} over the 54-year simulation period; the cumulative amount reached under reference climate was 111–136 m^3 ha^{-1}, Fig. 2). Climate change resulted in larger and more severe bark beetle epidemics, while the endemic phases between outbreaks remained similar to reference conditions also under climate change.

3.2 Effect of sanitation logging on bark beetle disturbance

3.2.1 Logging equally across the landscape—The live spruce volume annually affected by bark beetles (Dist%) decreased nonlinearly with increasing SI when the treatment was applied throughout the entire landscape (Fig. 3). A strong decrease in Dist% occurred at SIs above 60%, corresponding to the retention of less than 1.5 m^3 $year^{-1}$ ha^{-1} of disturbed spruce timber on the landscape (see Appendix A for the relationship between SI and the spruce timber volume retained and extracted). An SI of 80% decreased Dist% by 34% relative to simulations without SL, and an SI of 95% by 67%.

Climate change decreased the efficiency of SL regardless of sanitation intensity. While Dist% increased at least threefold as a result of climate change (Fig. 3), the dampening effect of SL decreased from 67% under reference climate to 47% under climate change for an SI of 95%. For an SI of 80%, the suppressing effect decreased from 34% under reference climate to 17% under climate change.

Spatial pattern of bark beetle disturbance in the absence of SL and with a high intensity sanitation removal can be seen in the maps in Fig. 4.

3.2.2 The effect of different spatial patterns of sanitation logging—We used standardized sanitation intensity (SSI; Eq. (1)) to compare different spatial patterns of SL to the previously described effect of applying sanitation throughout the entire landscape (Fig. 3, Supplementary material). SL of blocks and road buffers on 40 and 60% (R40, B40 and R60, B60) of the landscape with an intensity of 95% (i.e. resulting in a SSI of 38 and 57%, respectively) reduced Dist% more efficiently than applying the same SSI throughout the landscape. This indicates a greater sanitation success if the treatment was conducted with high intensity over a small area compared to removing approximately the same amount of infested trees distributed across the entire landscape. The difference between spatial patterns of SL was, however, not significant for small SSI values. SL was more efficient when applied in blocks than in road buffers. Climate change reduced the efficiency of sanitation regardless of spatial pattern.

3.2.3 Sanitation effects on treated and untreated areas—SL of 60 and 95% intensity applied only within road buffers covering 60% of the total area of landscape decreased the amount of trees killed by bark beetles from 2.23 (variant without SL) to 2.03 and 1.27 m^3 ha^{-1} $year^{-1}$ inside the treated area (i.e. by 9 and 43%, Fig. 5). In case of 95% SI inside the road buffer the damage (1.27 m^3 ha^{-1} $year^{-1}$) was higher compared to the case when SL was applied over the whole landscape (0.85 m^3 ha^{-1} $year^{-1}$). For 60% SI the difference is smaller. Specifically, bark beetle disturbances in untreated areas were reduced from 2.24 to 2.17 and 1.91 m^3 ha^{-1} $year^{-1}$ (i.e. by 3 and 15%) through treating road buffers. Hence, SL in road buffers dampened disturbances outside of the treated areas via inhibiting the spread of bark beetles.

Blocked SL (95% intensity) reduced the disturbance rate within the treated areas by 63% (from 2.62 to 0.96 m^3 ha^{-1} $year^{-1}$), and damage rates did not differ significantly from values reached under the SL applied in the whole landscape (1.00 m^3 ha^{-1} $year^{-1}$) (Fig. 5). SI of 60% resulted in the reduction of bark beetle disturbance by 11%. Bark beetle disturbances in untreated areas were not affected by blocked SL, with disturbance levels outside treated areas equalling those in simulations without SL. In contrast to SL along roads, the interaction between treated and untreated areas was negligible in the block design.

Climate change reduced the overall efficiency of SL; disturbance reduction with SI of 95% within road buffers was only 21% (compared to 43% under reference climate) and effect on untreated areas was negligible. In case of blocked SL, disturbance reduction was 34% only, compared to 63% under reference climate. Effect of SL with intensity of 60% was negligible in either spatial design (Fig. 5).

Similar effects as were previously described were observed also when only 40% of the landscape was treated (not shown here), though the effect of SL was less distinct.

4 Discussion

4.1 Methodological considerations and limitation

We used a process-based model allowing us to dynamically quantify disturbance impacts, their interactions and feedbacks on vegetation, as well as the effects of climate change and management in a consistent simulation framework. Our approach not only accounted for the amplifying direct effects of climate change on bark beetle development and tree defence capacity but also considered negative vegetation feedbacks such as a modified forest structure and consequently disturbance susceptibility after outbreaks (Thom et al., 2017b), and thus realistically mimics the complexity of the interactions between vegetation dynamics, climate and disturbances.

Despite the high level of process detail of our simulation framework, reproducing complex disturbance regimes in models remains challenging (Seidl et al., 2011). Processes not considered in the model applied here include, for example, the effect of altered microclimate at forest edges that emerge after harvests or windthows on the development of bark beetles (Kausrud et al., 2011; Kautz et al., 2013). It is thus important to test the applied model – being a simplification of reality – with regard to its ability to reproduce patterns observed in reality (Grimm et al., 2005). In this regard we previously conducted in depth analyses on the plausibility of simulated vegetation – disturbance interactions, including regeneration after disturbance and post-disturbance productivity patterns (Dobor et al., 2018; Thom et al., 2017a). The plausibility of simulated wind impacts and bark beetle dynamics was successfully evaluated against independent data (Seidl and Rammer, 2017). Moreover, the used model settings generated a good match of here simulated bark beetle dynamics with observed infestation patterns in terms of the proportion between wind and bark beetle damage and the close adjacency of bark beetle infestations to the windfelled stands (e.g. Potterf et al., 2019). An important deviation from expected patterns was observed with regard to the spatial pattern of simulated wind impact, which was relatively scattered throughout the landscape (i.e. occurring at wind-exposed forest edges, based on the model logic). In the Carpathian Mountains, however, wind disturbances are often triggered by strong katabatic winds (also called bora), which frequently result in large high-severity patches of wind disturbance (Fleischer, 2008). Differences in wind disturbance patterns may in turn result in different bark beetle dynamics in the simulations. For example, Potterf and

Bone (2017) found that the scattered windthrow is more conducive to bark beetle outbreaks than large, concentrated wind disturbance patches. This underlines that the spatial variation in windthrow patterns and their effect on bark beetle dynamics warrants attention in future research.

Another aspect that needs to be considered in the interpretation of our results is the specific implementation of SL simulated here. Although forest management typically strives to remove the windfelled trees as soon as possible in order to prevent wood degradation and colonization by beetles (Wermelinger, 2004), a swift treatment is often hampered by logistical challenges and considerations of forestry operation. We here exclusively simulated SL removals in the year of disturbance, i.e. before colonizing beetles can spread to surrounding areas. In reality, however, colonization of and dispersal from windfelled trees can happen simultaneously over a period of several years. Studies show, for instance, that the colonization rate of windfelled spruce trees can be higher in the second year than in the first year after the storm (Schroeder, 2010). Some evidence even suggests that windfelled trees are suitable breeding material for bark beetles for more than three summers (Wermelinger et al., 2013), particularly when cold and wet conditions keep the phloem of windfelled trees moist (Holuša et al., 2017). A further management measure in the context of responding to bark beetle outbreaks in Central Europe is the search for and removal of standing infested trees in the surrounding of the windfelled areas or previous infestation spots (Wermelinger et al., 2012). We did not simulate this measure here in order to being able to isolate the effect of removing windfelled trees on bark beetle dynamics. Further works should include this element of SL, as its efficiency remains incompletely understood (e.g. Stadelmann et al., 2013), particularly where outbreak areas are large.

4.2 Implications for outbreak management

Our findings indicate that even relatively small amounts of windfelled Norway spruce trees remaining after high intensity SL are sufficient to trigger a transition from endemic to epidemic conditions in the population dynamics of the European spruce bark beetle. This critical transition was further facilitated by climate change, which amplified the simulated bark beetle disturbance even under very high intensity SL. This finding is supported by the analyses of Marini et al. (2017), who found that bark beetle population eruptions can be driven by climate when the amount of windfelled trees is small. In contrast, a large surplus of windfelled trees can boost population dynamics above the threshold for a successful colonization of healthy trees irrespective of climate conditions. This indicates that outbreaks can be prevented by high intensity SL only under a specific set of factors, i.e. if windblown areas are limited, windfelled trees can be efficiently removed and climate conditions are not particularly favourable for bark beetle development. Due to the climatic changes expected for the coming decades, such constellations will become less likely in the future, and outbreaks will be increasingly triggered even in the absence of windfelled trees (Marini et al., 2017; Netherer et al., 2015; Seidl et al., 2016a). This makes the “hotter droughts” (Millar and Stephenson, 2015) expected for the future a particular concern in the context of forest disturbances (Sommerfeld et al., 2018).

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Consistently with previous research (e.g. Jönsson et al., 2009; Seidl et al., 2009), climate change had a strong impact on the simulated future bark beetle disturbance in our analyses, and caused a doubling of the timber volume disturbed by bark beetles. Climate change also reduced the efficiency of SL, with the effect being more pronounced at low intensities of SL. Given that achieving high SL intensities could be increasingly challenged by more frequent and severe disturbances in the future (Seidl et al., 2017), climate change could render SL to become largely inefficient. It is also noteworthy that we here only focused on the first half of the 21st century, in which climate change is still relatively moderate compared to the later parts of the century. Consequently, the efficiency of SL can be expected to decrease even more strongly than reported here in the second half of the 21st century. However, over longer periods of time also dampening feedbacks on bark beetle outbreaks can be expected via changes in forest structure and composition (Temperli et al., 2013; Thom et al., 2017c).

We here tested the effect of different spatial patterns of SL, with important implications for the management of Norway spruce forests in Europe. We first focused on treatments along the existing road network, as accessibility is often a key factor limiting the timely implementation of management measures. Although limited levels of road infrastructure are typical for, for example, Canada or Siberia (Lamers et al., 2014), many European regions also suffer from an insufficiently developed forest road network. This can, for example, lead to overharvesting of accessible locations, limited options for small-scale silvicultural interventions or inefficient disturbance management, including salvage and sanitation operations (Kolström et al., 2011). We found that conducting SL exclusively along roads – even when applied at high intensity – was not effective in reducing bark beetle disturbances, with the landscape-scale rate of disturbance being close to the untreated simulations. This finding is likely related to the width of the road buffers treated here (120 and 200 m, respectively), which was chosen to reflect considerations of forest engineering rather than those of bark beetle ecology. As the effective dispersal range of the European spruce bark beetle is around 500 m (e.g. Kautz et al., 2011; Potterf et al., 2019), considerably wider buffers would be needed to shelter areas from dispersing beetles. Treating road buffers did, however, also dampen bark beetle outbreaks in adjacent untreated areas, as the road network in our study landscape is well developed and treatments along roads create breaks for the spread of the disturbance (similar to fire breaks on the landscape, Russo et al., 2016). Efficiency of SL within road buffers was, however, largely reduced by climate change.

The second spatial pattern of SL analysed here addresses the concerns about bark beetles spreading from non-intervention areas to neighbouring production forests (Grodzki et al., 2006; Montano et al., 2016; Potterf et al., 2019; Potterf and Bone, 2017). In this regard we could show that applying SL in a blocked design (i.e., only in the parts of the landscape designated as intensively managed) substantially reduced the impact of bark beetles on the areas treated and, equalled the efficiency of SL treatments applied across the whole landscape. This indicates that retaining the deadwood created by wind disturbances in some portions of the landscape (e.g., in order to increase biodiversity) does not harm production forestry in other parts of the landscape as long as SL is applied intensively in the latter areas. In contrast to applying SL along road buffers, blocked SL did not dampen outbreaks in adjacent untreated areas. This finding can be partly attributed to the relatively even distribution of wind disturbances in our landscape, which triggered bark beetle outbreaks throughout the simulation area. If wind disturbance risk would be high in treated and low in untreated areas (e.g., due to an elevated structural and compositional diversity of the latter), a stronger influence of treatments on untreated areas could be expected.

5 Conclusions

While the evidence for an ongoing intensification of forest disturbances in Europe is growing (Seidl et al., 2014b; Senf et al., 2018), our current understanding of the efficiency of approaches to dampen disturbances through management remains incomplete. This particularly applies for the management of bark beetles, which are strongly responding to climate change, while their management remains largely based on past heuristics. Here we show that the magnitude of bark beetle disturbances will increase further in the coming decades, while the efficiency of SL of windfelled trees in dampening bark beetle outbreaks declines. We specifically show that due to a climate-mediated proliferation of bark beetle development also a very limited amount of windfelled trees is sufficient for triggering the critical transition from endemic to epidemic population dynamics. Our study further highlights that applying SL at low to medium intensities is not efficient and should thus be avoided. In contrast, early and concentrated removal of windfelled trees can substantially reduce the impact of bark beetles.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgements

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Data availability statement

Results are archived in the Zenodo open-access repository, http://doi.org/10.5281/zenodo.3484679 (Dobor et al., 2019b). Additional information on the used ecosystem model, including the source code can be found at http://iland.boku.ac.at.

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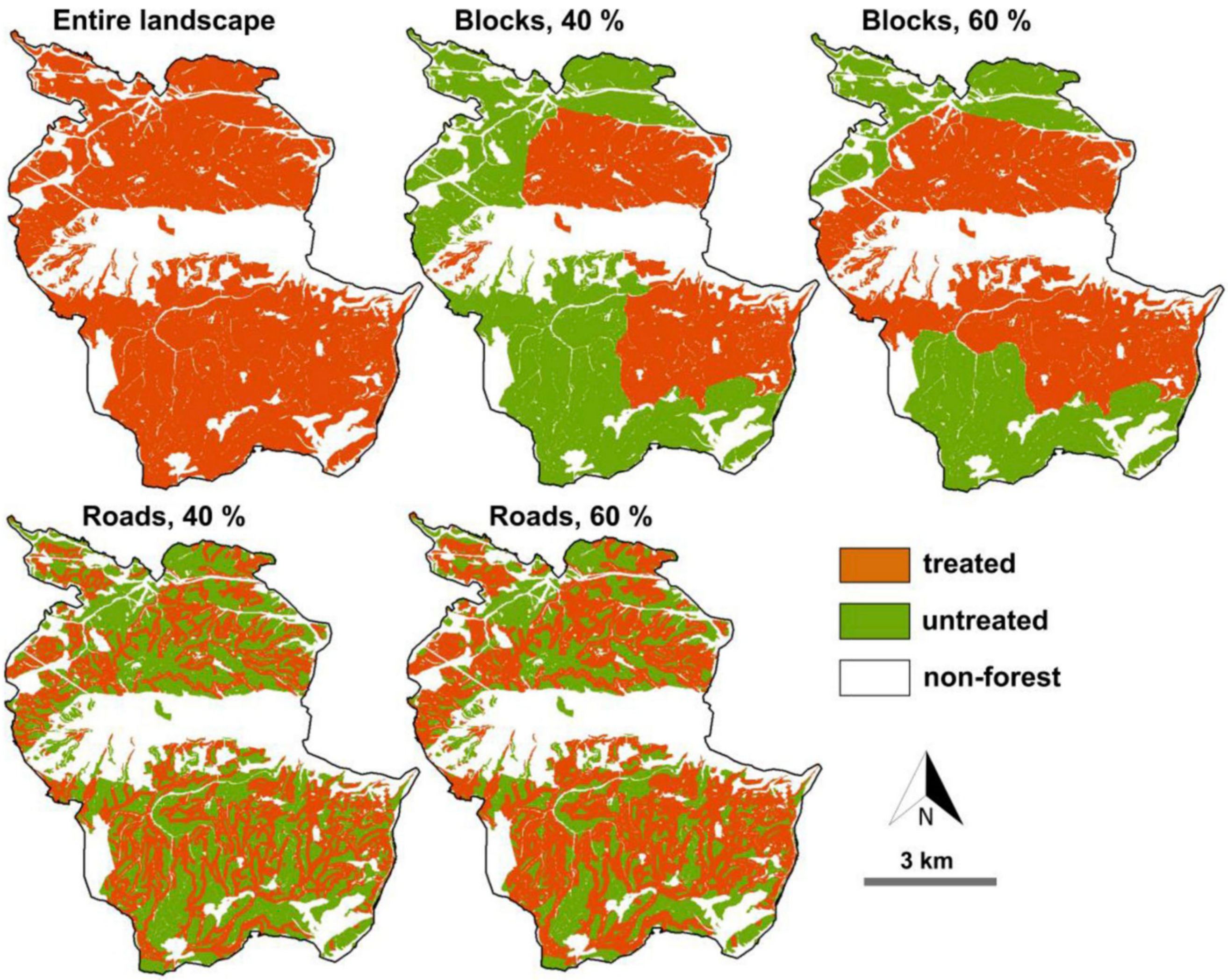

Fig. 1.

The five spatial configurations of sanitation logging studied on the landscape. Percent values in the figure indicate the proportion of the total forest area that is treated.

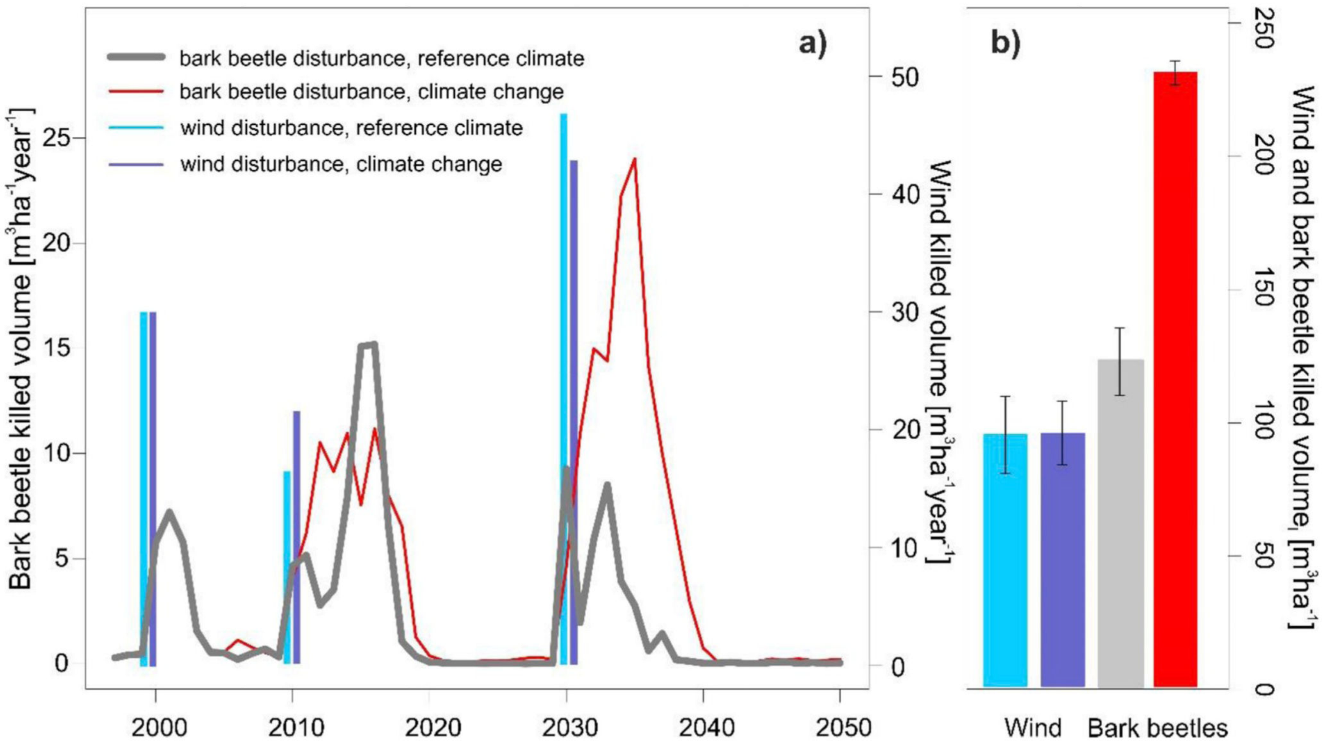

Fig. 2.

(a) Temporal development of wind and bark beetle disturbance in Norway spruce stands simulated by iLand in the absence of sanitation logging. Shown is the average over five wind scenarios and an ensemble of climate change scenarios. Columns indicating the wind impact under reference climate and climate change are displayed in different years for presentation purposes. (b) Cumulative timber volume disturbed over the 54-year simulation period under different climate conditions is shown.

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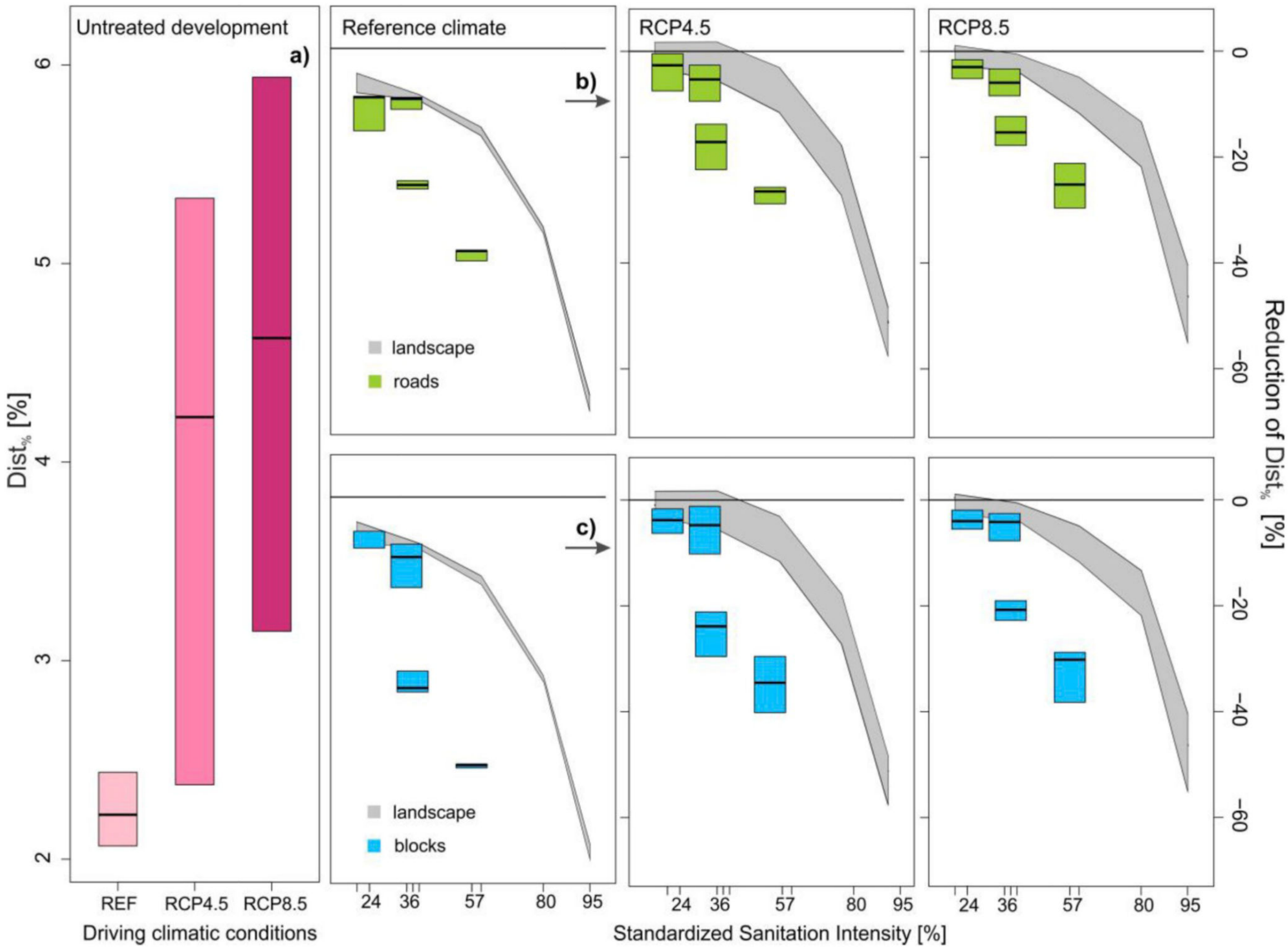

Fig. 3.

Response of the per cent of living spruce killed by bark beetles (Dist%) to different intensities of sanitation logging conducted equally over the whole landscape, within road buffers and within contiguous blocks under three different climate conditions. Figure a) shows values of Dist% in the whole landscape without sanitation logging, which is the reference value for figures b) and c). Figures b) and c) show relative differences from values reached under the variant with no sanitation logging. REF - Reference climate, RCP - Representative Concentration Pathway scenario.

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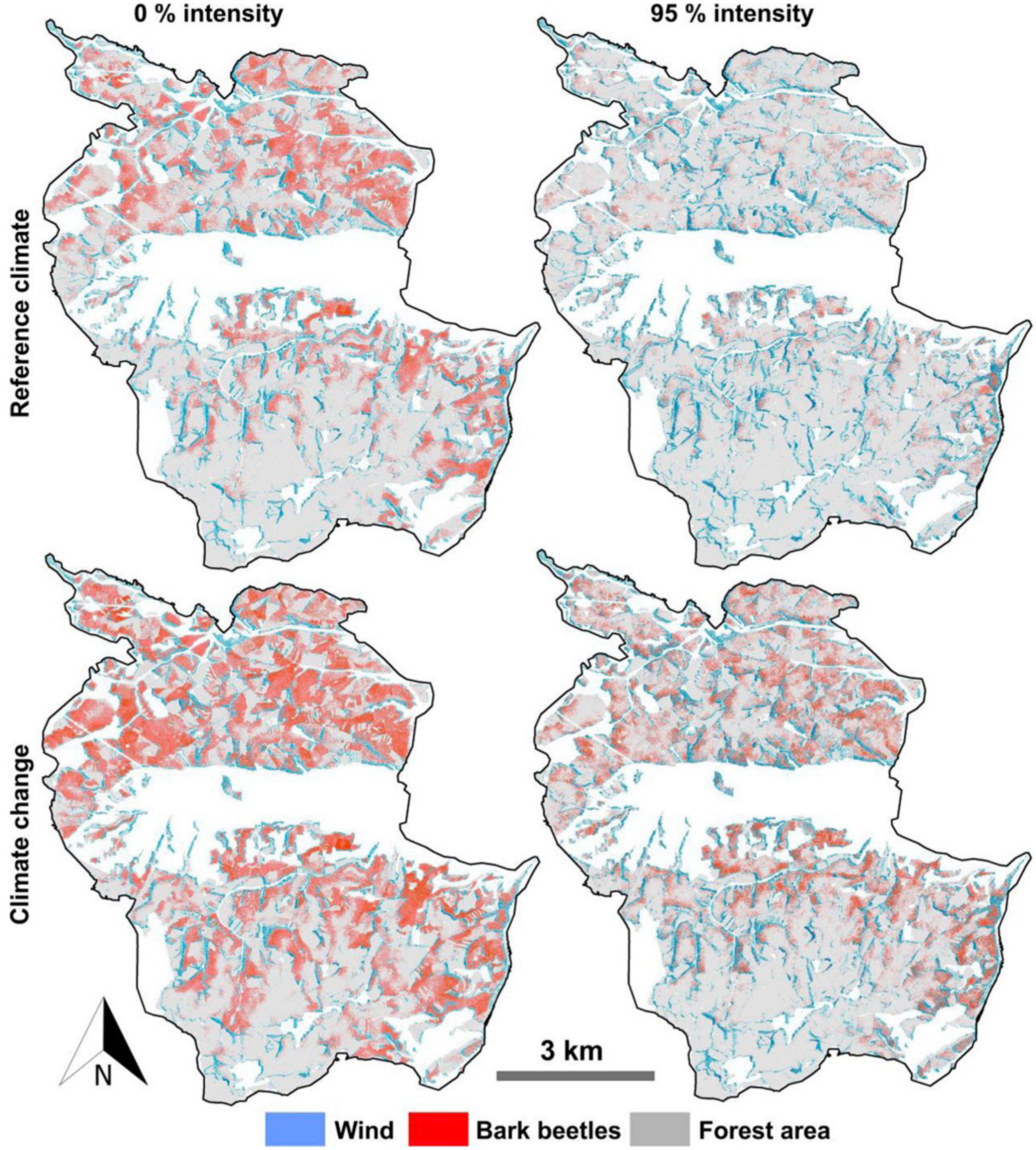

Fig. 4.

Spatial distribution of disturbances by wind and bark beetles between 1996 and 2050. Forest stands where total amount of disturbed trees during the 54-year period was above 0.03 m^3 ha^{-1} are highlighted. Variants with and without the effect of sanitation logging of windfelled trees are shown. Each variant was simulated under reference climate and climate change. The maps showing the effect of climate change result from averaged simulation outputs driven by three climate models nested within two greenhouse gas concentration scenarios RCP4.5 and RCP8.5 (i.e. six climate trajectories), and by 5 wind event time series.

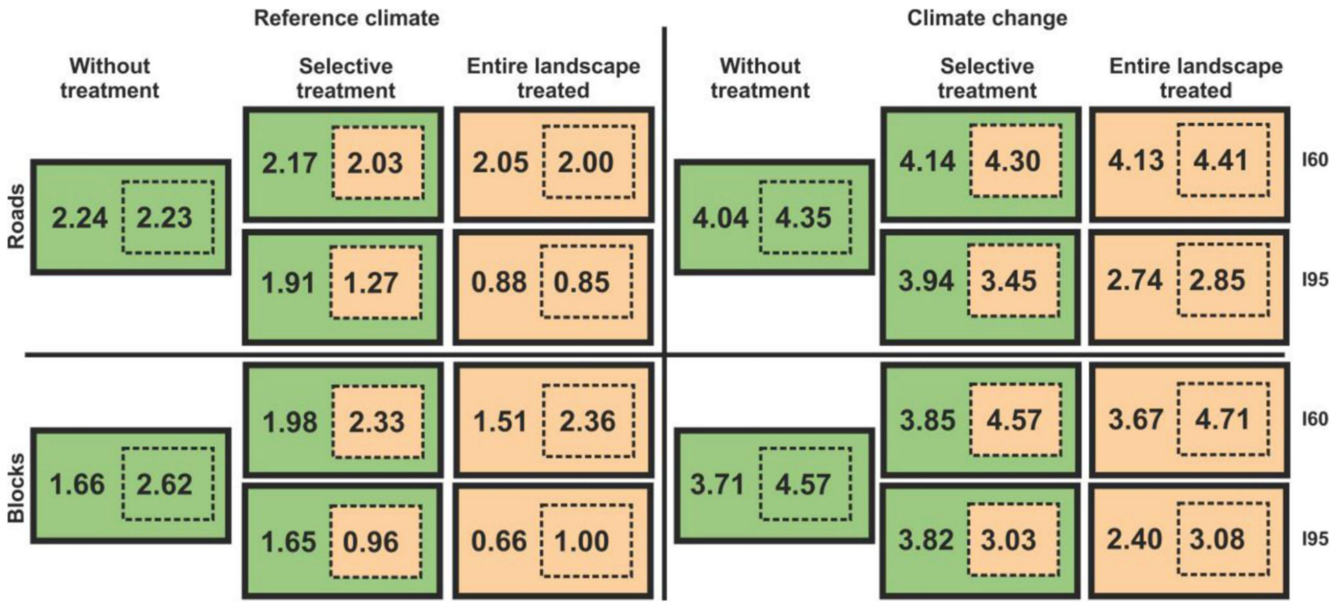

Fig. 5.

Effect of different spatial configurations of sanitation logging on bark beetle disturbance. Large rectangles represent the entire landscape, and the embedded rectangles represent areas of blocks and road buffers (green – area without treatment, orange – treated area). The left column (Without treatment) indicates the average volumes of trees killed by bark beetles (m^3 ha^{-1} $year^{-1}$) in the absence of sanitation logging (highest disturbance). The middle column (Selective treatment) shows situation, when only the areas within road buffer or blocks were treated (intermediate disturbance level). The right column (Entire landscape treated) indicates the same values reached with sanitation logging applied equally over the landscape (lowest disturbance). Two intensities of sanitation logging are presented – 60 and 95% (rows). The figure present variant where the treated area covers 60% of the entire landscape (see Methods for details). Simulation outputs for reference climate and average of six climate change scenarios are shown. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)