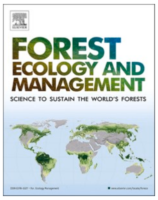
Forest Ecology and Management 509 (2022) 120071

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco



Natural disturbances risks in European Boreal and Temperate forests and their links to climate change – A review of modelling approaches

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ARTICLE INFO

Keywords:
Large-scale forest management
Risk assessment
Forest planning

ABSTRACT

It is expected that European Boreal and Temperate forests will be greatly affected by climate change, causing natural disturbances to increase in frequency and severity. To detangle how, through forest management, we can make forests less vulnerable to the impact of natural disturbances, we need to include the risks of such disturbances in our decision-making tools. The present review investigates: i) how the most important forestry-related natural disturbances are linked to climate change, and ii) different modelling approaches that assess the risks of natural disturbances and their applicability for large-scale forest management planning. Global warming will decrease frozen soil periods, which increases root rot, snow, ice and wind damage, cascading into an increment of bark beetle damage. Central Europe will experience a decrease in precipitation and increase in temperature, which lowers tree defenses against bark beetles and increases root rot infestations. Ice and wet snow damages are expected to increase in Northern Boreal forests, and to reduce in Temperate and Southern Boreal forests. However, lack of snow cover may increase cases of frost-damaged seedlings. The increased temperatures and drought periods, together with a fuel increment from other disturbances, likely enhance wildfire risk, especially for Temperate forests. For the review of European modelling approaches, thirty-nine disturbance models were assessed and categorized according to their required input variables and to the models' outputs. Probability models are usually common for all disturbance model approaches, however, models that predict disturbance effects seem to be scarce.

1. Introduction

Natural disturbances have complex effects on forest ecosystems. They might increase biodiversity indicators, such as species richness (Thom et al., 2017), but at the same time put ecosystems services at risk, causing the loss of millions of cubic meters of timber (Forzieri et al., 2020a; 2020b) and reducing forest's carbon storage (Thom & Seidl, 2016). In Europe's Temperate and Boreal forests, the major natural disturbances consist of windthrow, *Ips typographus* (L.) (bark beetle), wildfires, *Heterobasidium annosum* sensu lato (root rot), as well as snow and ice damages (Díaz-Yáñez et al., 2016; Seidl et al., 2017), all of which being potentially affected by climate change directly and indirectly (Seidl et al., 2017). The newly released IPCC report reiterates the global climate change concern, with the year of 2019 having had the highest atmospheric CO_2 concentrations in 2 million years (IPCC, 2021). Furthermore, global surface temperature rose by 1.09 °C [0.95 °C to 1.20 °C] from 2011 to 2020 when compared to pre-industrial periods (IPCC, 2021), with greater warming recorded in the Northern Extra-tropics (IPCC, 2019). Therefore, it is expected that European's Boreal and Temperate forests will be greatly affected by climate change, possibly causing natural disturbances to increase even further in occurrence and severity (Sutanto et al., 2020).

Forests cover 35% of Europe's total land area, representing 227 million hectares. Together, Boreal and Temperate forests cover approximately 158 million hectares of those areas, when not including Turkey and Russia (Forest Europe, 2020). Global warming affects forest production in many ways, sometimes in a positive manner. In Boreal forests, for instance, the higher temperature is responsible for an expansion in the length of the growing season (Jyske et al., 2014), as well as an increase in annual volume increment of 0.69 m^3 per hectare

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https://doi.org/10.1016/j.foreco.2022.120071
Received 6 October 2021; Received in revised form 19 December 2021; Accepted 25 January 2022

(Henttonen et al., 2017). However, forest vulnerability to natural disturbances has also been shown to increase, with around 58% of the European forests being at risk of biomass loss (Forzieri et al., 2021). During the thirty-year period between 1986 and 2016, 39 million hectares of forest area were disturbed (either by anthropogenic or natural causes), which accounts for 17% of Europe's forests (Senf and Seidl, 2021a). Moreover, over the period from 2018 to 2020, 4.74 million hectares of forest were disturbed in Europe, which shows that disturbance sizes and/or frequencies are increasing (Senf and Seidl, 2021b).

Apart from their ecological and social importance, forests are sources of income for forest owners that rely on a viable management to optimize their profits. Yet, when considering climate change, forests will have to be managed under high levels of uncertainty due to natural disturbances risks. Those can be reduced by the implementation of a more viable – adaptive - forest management, which is guided by the results of robust modelling. In order to build more resilient forests through adaptive forest management, two issues are important: 1) to identify the links between climate change and the natural disturbances that affect those forest ecosystems and 2) to internalize those natural disturbances risks into the forest management planning. There are many different natural disturbances models that have been developed at different scales and use different approaches, not necessarily meeting the needs of regular forest management. Those models, to be of practical use, should adopt input variables that are available in large spatial-scale inventories (e.g. national forest inventories – NFIs) or forest management plans, to be incorporated afterwards in forest simulators and decision support systems to cope with the natural disturbance risk elements in analyses.

Therefore, such a complex topic calls for an overview that synthesizes the most common risk elements involving natural disturbances and climate change. Additionally, to be relevant for forest managers as well as to facilitate future studies on natural disturbances risks in Boreal and Temperate European forests, there is a demand for an overview on natural disturbance modelling approaches. Thus, the aim of this work is to provide a review of modelling approaches of natural disturbances in European Boreal and Temperate forests. The specific objectives are to: 1) Identify common links between natural disturbances and climate change; 2) Describe common modelling approaches to tackle the aforementioned natural disturbances and assess their applicability for large scale forest management planning. It is important to emphasize that the present review does not aim at providing an exhaustive analysis of all links between natural disturbances and climate change, much less all natural disturbances modelling approaches that have been developed. We believe it is more relevant for forest managers to have an overview of the most common disturbance/climate change links and a critical overview of the most appropriate natural disturbances modelling approaches for large scale forest management planning, understanding also which ones can take climate change into account.

2. Literature review

In this review, 245 recent peer-reviewed papers and 16 relevant reports written in English were used. The literature was selected by using a combination of keywords for each disturbance agent: ("root rot" OR "heterobasidion" OR "windthrow" OR "wind damage" OR "bark beetle" OR "typographus" OR "snow damage" OR "ice damage" OR "fires") AND ("forest" OR "management") AND ("temperate" OR "boreal"). To focus on the first objective of the paper – the links between natural disturbances and climate change – one more key term was used: ("climate" OR "climate change"), while for the second objective of the paper – the evaluation of modelling approaches – the key term added was ("model"). Additional papers were identified throughout the reviewing process by referring to pertinent studies that were cited in the reviewed literature.

To create a common knowledge base of the issue, the next section of this review introduces an overview of major natural disturbances in European Boreal and Temperate forests. Section 4 deals with the links between climate change and natural disturbances, while Sections 5 and 6 presents and assesses, respectively, the modelling approaches.

3. Overview of natural disturbances in European Boreal and Temperate forests

3.1. Windthrow

Wind damage in Europe is caused by two phenomena: Extratropical cyclones and convective storms (Pettit et al., 2021). Extratropical cyclones develop in Europe during autumn and winter months and are defined by strong winds that increase their speed quickly into violent gusts (Martínez-Alvarado et al., 2014). Those windstorms happen where the atmospheric pressure is lower than surrounding areas, and in Europe such system – called low-pressure area – is usually found in the North Atlantic Ocean, progressing towards the north-east (Sharkey et al., 2020). Such events are capable of devastating huge areas and causing important socioeconomic impacts such as the three windstorms that hit Central Europe in 1999 in a period of less than a month: Anatol, Lothar and Martin, which were responsible for approximately 11.4 billion euro worth of damage (Roberts et al., 2014), with Lothar alone causing losses of 3.4 billion euro only for the forestry sector (Browning, 2004). The other driver of intense wind in Europe is convective storms, which are more common in the Southeastern part of the continent (Nagel et al., 2017). They usually occur during summer months and create speed winds that are higher than extratropical cyclones but affect smaller areas for shorter periods (Pettit et al., 2021).

When windstorms hit forest areas they can cause a variety of injuries to the trees, from light damage such as breaking their branches, to heavy damage such as stem breakage and uprooting, which ultimately leads to mortality. Such heavy wind-induced damages are called windthrow (Gardiner et al., 2008) and they occur mostly in forest edges (Schelhaas et al., 2007), but some windstorms are capable of damaging whole stands (Suvanto et al., 2019). Windthrow risks are usually closely related to specific tree species (Mayer et al., 2005; Panferov et al., 2009), such as the conifers Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco) (Schelhaas et al., 2007; Albrecht et al., 2013) and Norway spruce (*Picea abies* [L.] Karst) (Panferov et al., 2009; Schmidt et al., 2010), with deciduous trees being less susceptible to this type of damage (Klaus et al., 2011; Panayotov et al., 2011). Other variables that affect wind damage are trees' height and diameter (Schelhaas et al., 2007), and silvicultural interventions, such as thinning treatments (Albrecht et al., 2012).

Recent databases (Forzieri et al., 2020b) show that France had around 875 thousand hectares of damaged forests after Klaus and Xhyntia windstorms in 2009 and 2010, respectively, not including Lothar and Martin storms that damaged 176 million m^3 of timber (Gardiner et al., 2010). Considering the period from 2000 to 2018, the forests of Poland are the second most affected in Europe, with 46 thousand hectares of damaged forests after a windstorm in 2017 (Forzieri et al., 2020b). Italy follows next with 42 thousand hectares of damaged forest after Vaia storm taking place in 2018 (Chirici et al., 2019), while Germany lost 31 thousand hectares to the Kyrill storm in 2007 and Sweden lost 25 thousand hectares of forest in 2005 due to the Gudrun storm (Forzieri et al., 2020b).

3.2. Bark beetle

Bark beetles, mainly *Ips typographus* (L.), are amongst the most devastating biotic agents affecting forests globally (Anderegg et al., 2015). Their main host is Norway spruce, which is the dominant tree species in Southern Scandinavia and Central Europe (Schelhaas et al., 2018), covering around 25% of Europe's total forest stock (Hlásny et al., 2021a). Norway spruce tolerates soils with low fertility and grows well under different climatic conditions (Jandl, 2020), and even-aged Norway spruce monocultures commonly substitute natural forests in

Northern Temperate and Boreal forests (Holmström et al., 2016). However, being such a popular choice among forest owners and managers also means that all this area is exposed to a potential outbreak of bark beetles.

Historically, bark beetles' outbreaks are often associated with windthrow events, such as the case of the *I. typographus* outbreak that took place in western Finland in 1975 after a severe storm, and damaged at least 64% of the windthrown Norway spruce (Annila & Petäistö, 1978), and the windstorm Kyrill in 2007 in the Bohemian Forest, that triggered an outbreak that doomed more than one million spruce trees (Berec et al., 2013). Some outbreak events, however, do not seem to have a connection with a previous damage by wind. For instance, the recent (2018-present) large-scale outbreak in Central Europe shows that, apart from windthrow, drought and high temperatures are also drivers of bark beetles' outbreaks (Marini et al., 2017; Fernandez-Carrillo et al., 2020; Hlásny et al., 2021b).

It is estimated that around 2005, bark beetles average annual damage overtook forest fire's importance in Europe (Seidl et al., 2014b). From 1950 to 2000, bark beetles damaged per year around 2.9 million m^3 of wood in the continent (Schelhaas et al., 2003), and with the increase in damage occurrences to 14.5 million m^3 per year from 2000 to 2010, (Seidl et al., 2014b) predicted that from 2021 to 2030, bark beetle damage would reach 17.9 million m^3 per year. However, recent events in Central Europe show that bark beetle damage has already surpassed that prediction. In 2019, 20.7 million m^3 of the harvested spruce timber in Czech Republic were infested by bark beetle (Fernandez-Carrillo et al., 2020). Simultaneously, Germany recorded 31.7 million m^3 of timber damaged by insects, with bark beetles being the main concern. In 2020 that number escalated to 43.3 million m^3, only in Germany (Statistisches Bundesamt, 2021).

In Europe, *I. typographus* is present in most countries, except for Ireland, Portugal and Spain where the insect is confirmed absent by surveys (Jeger et al., 2017). Apart from them, in the United Kingdom in November 2018, several beetles were caught in traps in a forest in South-eastern England, but eradication measures have been taken, therefore the current status of *I. typographus* in the United Kingdom is "under eradication" (EPPO, 2021).

3.3. *Wildfire*

Fire is the most studied natural disturbance in Temperate and Boreal forests (Seidl et al., 2017) even if wildfires are mostly localized in the Mediterranean region (Forest Europe, 2020). Apart from Turkey, the temperate regions of Central-East and South-East Europe mostly seem to have occurrences of low intensity fires (Adámek et al., 2018), such as the case of Bulgaria, where only 4% of the study area has been affected by fires of low intensity in the last 200 years (Panayotov et al., 2011). Overall, up until 2000 fire occurrences in Europe were considered as negligible when compared to the rest of the world (Mouillot & Field, 2005).

However, large wildfires in recent years have affected regions where fires were not of relevance in the past. For instance, in Sweden two wildfire events demonstrated the disturbance's importance for boreal forests (Pinto et al., 2020). In 2014 a fire in Central Sweden burned around 14 thousand hectares, having started due to forestry operations but easily spreading due to the combination of a drought period and high winds. In 2018 several fires events burned together approximately 21 thousand hectares in Sweden. In general, the southernmost vegetation zones in Sweden (nemoral and boreo-nemoral) have a higher fire risk when compared to the other boreal regions in the country (Pinto et al., 2020).

3.4. *Root rot*

In Europe, one of the most damaging diseases is the root rot caused by the *Heterobasidion* genus. The economic losses have been estimated to be around 800 million euros per year (Woodward et al., 1998). However, this estimation is based on more than twenty years old data, and recent economic evaluations of *Heterobasidion spp* damages are lacking. In Europe, the *Heterobasidion* genus is mainly occurring in three intersterile species that have preference for different hosts: the main host for *Heterobasidion annosum* (Fr.) Bref sensu stricto is *Pinus* and *Juniperus*, while for *Heterobasidion parviporum* Niemelä & Korhonen it is *Picea* (spruces) and for *Heterobasidion abietinum* Niemelä & Korhonen it is *Abies* (firs) (Asiegbu et al., 2005). Those three species compose the species complex *Heterobasidion annosum* sensu lato (*H. annosum* s.l.), which is widespread throughout Europe.

Furthermore, the common management practice of thinning trees is a well-known spreading route for *H. annosum* s.l., since it opens up fresh wood surfaces for spores to establish (Garbelotto & Gonthier, 2013). In Finland, 15% to 20% of spruce trees have some level of infection caused by *H. annosum* s.l. (Venäläinen et al., 2020), while in Norway it affects 9.5% of Norway spruce trees at breast height (Hylen & Granhus, 2018). In Latvia, recent assessments show that locally, 30% to 39% of Norway spruces are infected by root rot (Klavina et al., 2021) and in the Italian Alps this number can get as high as 71% (Gonthier et al., 2012). Usually, Norway spruces older than 30 years old infected by *H. annosum* s.l. grow 10% slower than healthy trees (Hellgren & Stenlid, 1995). Yield loss, however, varies depending on different variables such as number of infected trees, time period since the start of infection, stand age and productivity (Arhipova et al., 2011).

3.5. *Snow and ice*

Ice storm damages are notably more studied in North America than in Europe, despite the relatively common occurrence - two or three events per year - of freezing rain in Central and Eastern Europe between November and February (Klopčič et al., 2020). Ice storms differ from regular windstorms by the accumulation at least 6.3 mm of ice (Irland, 2000). In 1996, an ice storm destroyed 35 thousand m^3 of timber in Northern Hungary (Aszalós et al., 2012) and in 2014 an extreme ice storm caused damage to more than 500 thousand hectares of forests across Slovenia and Northern Croatia. In terms of extent and total wood volume loss, this event was the most catastrophic ever recorded in the region, with more than half of the trees being severely damaged or dead (Nagel et al., 2016). Following this disturbance event, the summer of 2015 was the second warmest on record in Slovenia and the consequence was the most severe bark beetle attack in history, affecting more than 1.2 million m^3 of timber (Nagel et al., 2016; de Groot et al., 2018).

In Norway, the most common disturbance for spruce and birch forests is snow damage, happening specially in the Southern and Northern region, in clusters in mountainous areas (Díaz-Yáñez et al., 2016). However, it is difficult to differentiate snow damage from wind damage because both often occur simultaneously (Hlásny et al., 2011).

4. Links between climate change and natural disturbances

Climate change projections involve how different paths of socio-economic development and climate policy efforts will affect greenhouse gases emissions. To illustrate the potential climate change projections, different climate scenarios have been created, the most common ones being the Special Report on Emissions Scenarios (SRES) (Nakicenovic et al., 2000) and the Representative Concentration Pathway (RCP) (IPCC, 2014). The SRES was developed to describe four different storylines (Al, A2, Bl, and B2) that assume distinct directions for future developments by 2100 according to economic development, demographic and technological change. Under those four storylines, six scenarios were created, where, by the end of 2100, A1F1 and A2 present greater emissions of CO_2, A1B and B2 intermediate emissions, and A1T and B1 lesser emissions. For a more detailed description of each scenario refer to Nakicenovic et al. (2000). As an improvement of SRES, the RCP was created adding climate policy to its four scenarios: the RCP8.5 is comparable to the SRES A1FI and A2 scenarios, with global mean temperature projected to rise 2.6 °C to 4.8 °C. The RCP6.0 is similar to B2 scenario and global mean temperature would likely rise 1.4 °C to 3.1 °C. The RCP4.5 is similar to B1, and global mean temperature should rise 1.1 °C to 2.6 °C. Finally, the RCP2.6 does not have an equivalent in SRES, but it is the scenario where, with the lowest emissions, global mean temperature would increase 0.3 °C to 1.7 °C (IPCC, 2014).

4.1. Temperature

North and Central Europe will likely experience a temperature increase of 1 to 3 °C (depending on the latitude) during winter in the next 30 years (Fig. 1) (IPCC, 2013).

The warmer temperature will have direct, indirect and cascading effects on natural disturbances in Boreal and Temperate forests (Fig. 2). *Heterobasidion* activity starts close to −4°C and declines around 33 °C, with optimum temperatures for development between 20 °C and 30 °C (Müller et al., 2014). For Norway spruce, damages from *H. annosum* s.l. are greater when the temperature sum is either below 800 or when it exceeds 1100 day degrees (Thor et al., 2005). Therefore, Temperate and Boreal forests experiencing warmer temperatures can be expected to endure more sporulation and infection frequency of the fungi (La Porta et al., 2008). Likewise, with winter time temperature elevated by up to 4 °C, it is expected that the duration of unfrozen soil will increase from its original 7–8 months to 9–10 months per year (Peltola et al., 1999a; 1999b; Gregow et al., 2011). In response to that, basidiospore production of *H. annosum s.l.* will likely rise.

H. annosum s.l. is also responsible for increasing trees susceptibility to uprooting due to wind (Mattila & Nuutinen, 2007) and ice and snow load. Such circumstances associated with the reduced root anchorage due to unfrozen soil will likely increase even more the uprooting occurrences (Saad et al., 2017; Gregow et al., 2011). For instance, in Southern boreal forests, in a scenario 4 °C warmer, 80% of all high winds will occur during unfrozen soil periods (Peltola et al., 1999a; 1999b).

Cascading effects will also take place, some of which receive little attention on the literature, and some are still unknown. For instance, on

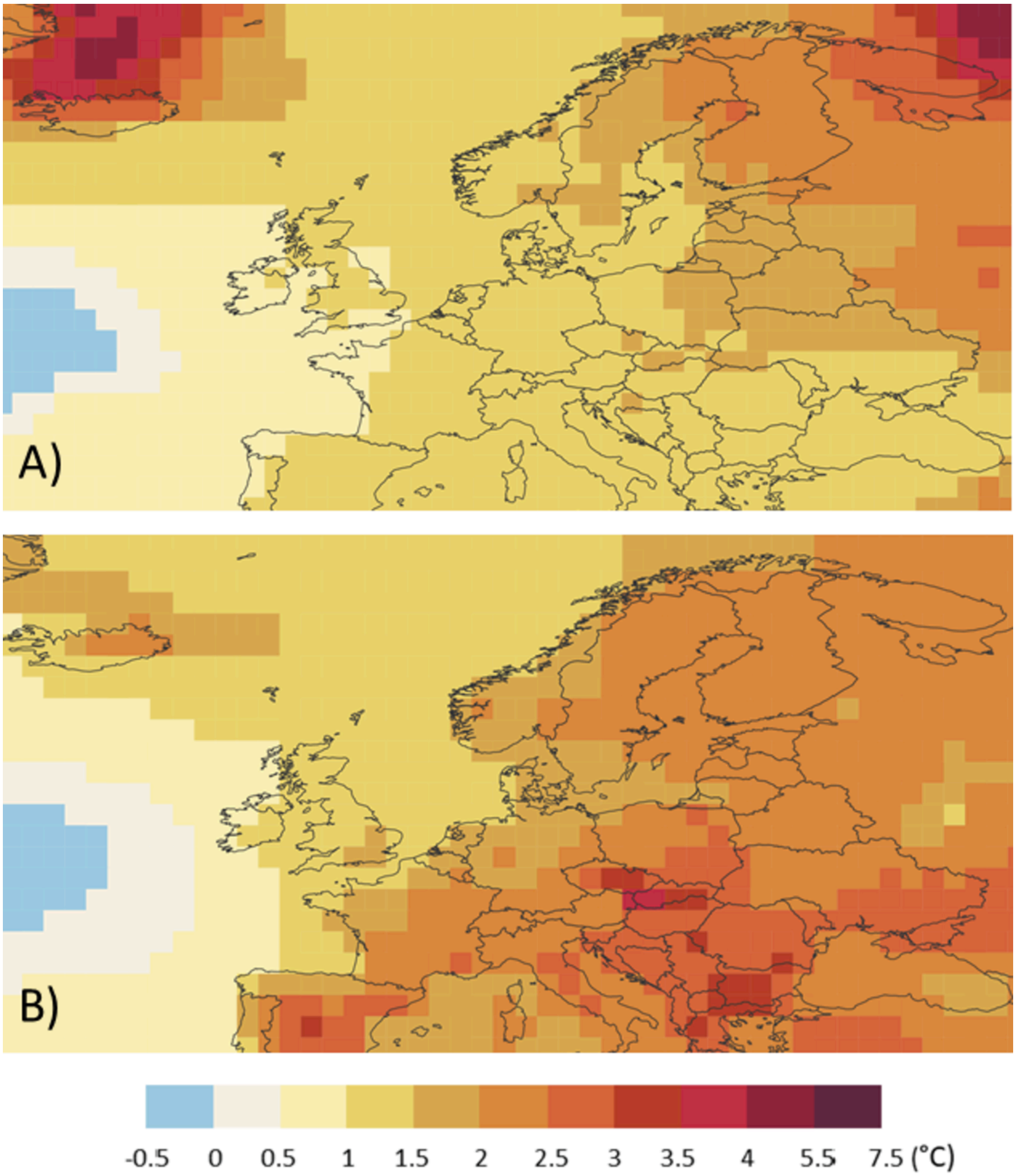

Fig. 1. Map of temperature change for 2050–2070 with respect to 1980–2000 in the RCP4.5 scenario, for winter (A) and summer (B), representing the ensemble average of the NCAR Community Climate System Model (CCSM) projections retrieved from NCAR (2004).

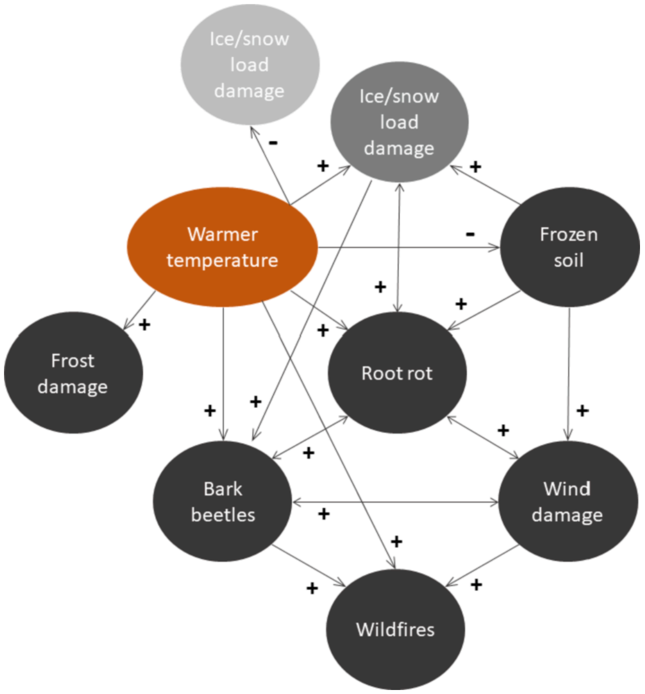

Fig. 2. Summary of direct, indirect and cascading natural disturbances effects of warmer temperatures in Boreal and Temperate forests. For ice and snow load damage, light and dark grey colors indicate the different situations for Southern Boreal/Temperate forests and Northern Boreal forests, respectively.

our literature review we did not find any article regarding the effects that windthrow events have on *H. annosum* s.l. infections, but one can anticipate that a wind-disturbed area, with broken and uprooted trees, have increased chances of root rot infection, since there would be an increase in freshly exposed wood surfaces for spores to colonize.

The increase in uprooted and broken trees due to wind, snow and ice load, together with the increase of *H. annosum* s.l. occurrences, will likely boost the *I. typographus* outbreaks frequencies (Temperli et al., 2013; Seidl & Rammer, 2017), since bark beetles initially attack weakened or dying trees (Lausch et al., 2013). Apart from this indirect effect, the increasing temperature will also affect *I. typographus* directly, by influencing their metabolic rate, reducing their development time, increasing performance and fitness (Jönsson et al., 2009) and/or affecting their number of generations (Baier et al., 2007). For instance, in South Sweden, where nowadays the weather supports only one bark beetle generation per year, estimations show that during the next 50 years, bark beetles will be able to develop a second generation in 30–49% of the years (Jönsson et al., 2009). When bark beetle populations are high enough they may also attack healthy trees (Honkaniemi et al., 2018), which will have a severe effect on the forest production.

Another cascading effect missing in the literature was the bark beetle effect on wind damage. Even though it is clear and well-studied that wind-felled trees are more susceptible to bark beetle attacks, the link between previous *I. typographus* outbreaks and windthrow-susceptibility was not mentioned in the literature. It makes sense, however, that such link exists, since the bark beetle damage weakens the trees by destroying the inner bark and cutting off their nutrient flow, making them more susceptible to breakage due to wind.

Snow and ice damages are said to be one of the natural disturbances that will not increase due to climate change (Seidl et al., 2017). However, such conclusion seems to be only true at global scale. If the focus shifts to Europe alone, the scenario might change. Snow is a thermal insulator for soils, and the loss of snow cover, due to global warming, can increase soil freezing which may be harmful for fine roots of seedlings (Groffman et al., 2001). Consequently, Central and Eastern Europe and coastal areas of Nordic countries will likely experience an increase of frost damage (Buma et al., 2017). In Finland, the effect of such disturbance is also being perceived in the growth reduction of Norway spruce, which has been related to the occurrences of freezing temperatures periods with no insulating snow cover (Suvanto et al., 2017). For ice storms, estimations for the European region are still lacking, but in Northern regions of the United States they are predicted to increase in frequency due to warmer temperature (Klima & Morgan, 2015).

The debris and fine fuel left after windstorms, snow damages, ice storms, and bark beetle attacks can add to the fuel loading in forests, intensifying wildfires even in forest types where live forests are not typically flammable (Mitchell, 2013). Therefore, the occurrences of wildfires will most likely increase in Europe, which is not only directly linked to the increase in temperature associated with climate change (Sutanto et al., 2020), but also to the interaction with other natural disturbances. After a wildfire starts, Sweden, Finland and Western Russia are the most vulnerable regions in European Temperate and Boreal forests, as they would be the ones losing more biomass in such event (Forzieri et al., 2021).

4.2. Precipitation

In Northern Europe, from fall to winter, it is predicted that precipitation will increase around 10% for the RCP4.5 scenario in the next 30 years, while for Central Europe this increment will be slightly less expressive (Fig. 3). During spring and summer, however, Central Europe will likely experience a decrease of precipitation, growing concerns about drought issues in the region (IPCC, 2013).

Fig. 4 shows a summary of direct, indirect and cascading effects of reduced precipitation that will likely happen in Central Europe (A) and the effects of increased precipitation in Northern Europe (B).

Uprooting from windthrow often happens when high winds coincide with saturated forest soil, and therefore lacks root anchorage (Mitchell, 2013). Consequently, besides temperature, precipitation is also an important variable for windthrow risk. Apart from that it is predicted that the strongest wind events will be more frequent around the 60° latitudes (Gastineau & Soden, 2009), where Boreal and Northern Temperate forests are situated. Therefore, windthrow risks can increase up to 90% under A1B scenario towards 2100 (Panferov et al., 2009).

The probability of *H. annosum* s.l. infection decreases with the increasing soil moisture (Thor et al., 2005). However, some studies state that an increasing precipitation is expected to favor basidiospore production (Redfern & Stenlid, 1998 as cited in Müller et al., 2014). For Central Europe during summer, where precipitation is expected to decrease, young Norway spruce may suffer greater damages from the fungi (Terhonen et al., 2019), but sporulation of *H. annosum* s.l. may also be reduced due to drought periods (Müller et al., 2014). Therefore, climate change may affect the seasonal patterns of the different fungi's infection stages (Müller et al., 2014).

For snow load damages, snow is expected to decrease in Central Europe (Kilpeläinen et al., 2010; Lehtonen et al., 2016), as a consequence of the higher temperature. However, in Northern boreal forests, a more humid climate will increase wet and frozen snow damages (Lehtonen et al., 2016).

Norway spruce trees typically have a shallow root system (Caudullo et al., 2016) and therefore show low tolerance to drought stress (Vitali et al., 2017; Krejza et al., 2021). The intensified and prolonged summer droughts in Central Europe (IPCC, 2013) will exert a drought stress and lower defenses of spruce trees (Rouault et al., 2006; Kausrud et al., 2012 Netherer et al., 2015), increasing predisposition to *I. typographus attacks*. For this reason, warm temperatures together with dry summers are the main abiotic reason for high severity outbreaks of *I. typographus* (Marini et al., 2012).

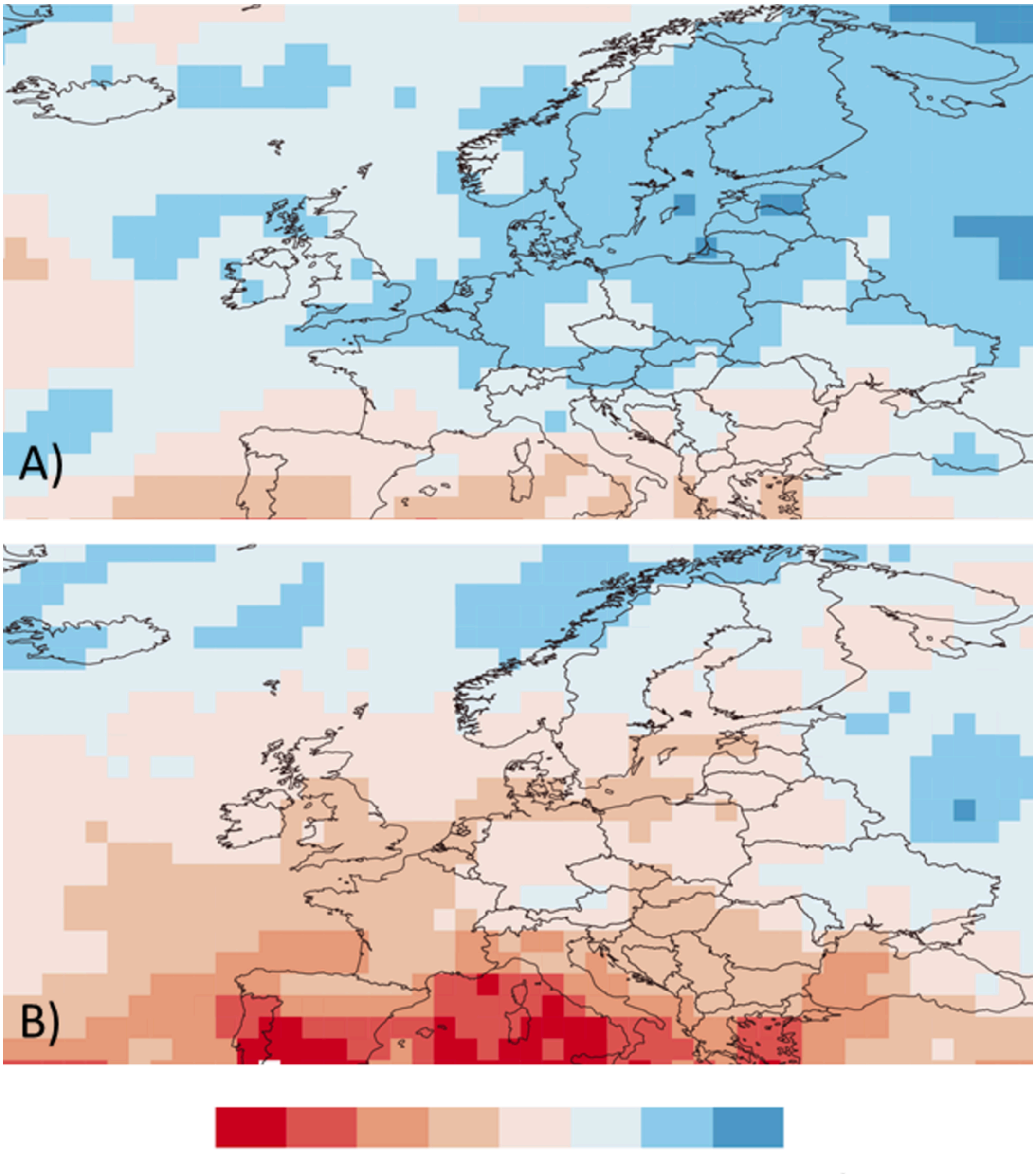

Fig. 3. Map of precipitation change for 2050–2070 with respect to 1980–2000 in the RCP4.5 scenario, for the periods of October - March (A) and April - September (B), representing the ensemble average of the NCAR Community Climate System Model (CCSM) projections retrieved from NCAR (2004).

5. Modelling natural disturbances

Thirty-nine different modelling approaches for natural disturbances in Temperate and Boreal European forests are summarized in Table 1. The analysis of the models is focused on two aspects: 1) the required input variables, which indicates the applicability of large-scale forest management planning and if such models can address climate change impacts, and 2) the model outputs, which demonstrate their capacity to assess natural disturbances risks.

In order to tackle the first aspect of the models analysis, the variables used as inputs are separated in groups of Climatic, Forest, Soil, Topographic, Wind speed, Snow load, Windthrow, Lightning, Anthropogenic and Previous Damage variables. The “Climatic” variables are related to variables that can be used to predict direct effects of climate change, such as temperature and precipitation. The “Forest” variables are the ones that include tree/stand characteristics and management treatments, such as diameter at breast height (DBH), tree height, basal area per unit area, species composition, tree and stand age, thinning and pruning, among others. “Soil” variables are soil type and texture variables. “Topographic” variables indicate that the models use, for instance, slope, aspect or elevation. “Wind speed” indicates that the model requires either wind zone maps or a reference wind speed, while “Snow load” indicates the use of variables representing the snow weight that trees support. “Lightning” variables mean the model uses lightning frequency in the area of interest. “Anthropogenic” variables represent the use of population density or land use information, and “Previous Damage” variables express that the models need information from past infestations or damages.

An important dataset available for forest managers in most European countries are National Forest Inventories (NFIs), which provide extensive empirical forest data and are commonly used for estimation of forest goods and services (Atkinson et al., 2020). Those data are gathered at regular intervals across European countries and NFIs usually collect variables such as species composition, stand age, DBH and basal area per

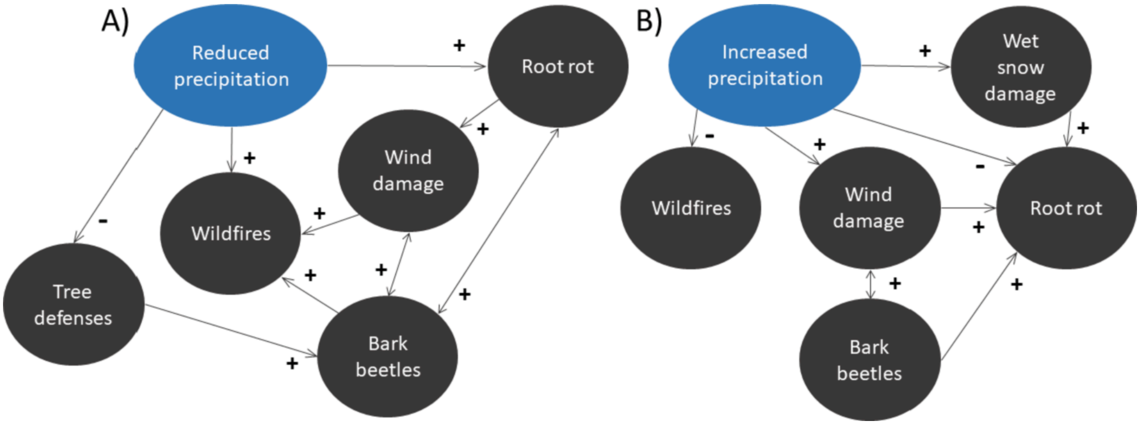

Fig. 4. Summary of direct, indirect and interaction effects of reduced precipitation in Central Europe's Temperate forests (A) and effects of increased precipitation in Northern Europe (B).

area unit, here referred as "Forest" variables, but less frequently do they have information on detailed damages, such as frequency of stump infection of *Heterobasidion* spp. or bark beetle damage percentage, referred here as "Previous Damage" variables. If a model needs such variables' inputs, it indicates a limitation for the model's applicability in large-scale planning.

For the second aspect of the model analysis, the outputs of the models are divided into Probability (Prob.), Effect, Management (Mgmt), and Other. "Prob." means the model has output on disturbance probability, "Effect" means it has some outputs on disturbance effects on forest (such as damage intensity or tree mortality), "Mgmt" means the outputs are linked to forest management by means of input variables describing forest structure (such as the case of models using DBH, tree height, basal area per unit area, species composition, tree and stand age, etc.) and "Other" means the outputs are not related to "Prob.", "Effect" and "Mgmt", but rather to outputs on disturbance dynamics, phenology, and dispersal.

The concept of each model is divided into "Empirical", covering statistical models – e.g. regression, classification, and regression trees, and "Mechanistic", which covers the process-based approaches. Empirical models, also called statistical models, rely on observed data to predict a certain phenomenon, while mechanistic models rely on fundamental and natural principles or defined processes to make their predictions. Although these two model types are distinguished in this review, no models are completely empirical or mechanistic, and they often comprise a mix of both concepts. The "Location" of the models indicates where the models were calibrated/parameterized, and "Special features" either explains what "Other" outputs the models provide (e.g. disturbance dynamics, phenology, or dispersal) or which model – if any - the model in analysis uses.

6. Assessment of modelling approaches

6.1. Wind damage

For wind damage, some models estimate the 'critical wind speed' required to break or uproot trees within a forest, and the probability of such wind speed to occur at a specific forest location (Gardiner et al., 2008). In the present study, four critical wind speed models are addressed, namely, HWIND (Peltola et al., 1999a), GALES (Gardiner et al., 2000), FOREOLE by (Ancelin et al., 2004) and ForGEM-W (Schelhaas et al., 2007), all of which use in general forest and wind speed variables to determine tree's resistance to breaking and uprooting.

All wind damage models use forest variables, therefore all of them have management relevance. Most of them use wind speed and topographic variables as well, however, some empirical models require previous windthrow information (Ni Dhubhain et al., 2001; Schmidt et al., 2010, Albrecht et al., 2012, Hanewinkel et al., 2014), which limits the applicability of such models in large-scale planning. The models from Seidl et al. (2014a), Suvanto et al. (2019), and Forzieri et al. (2020b) also use climatic variables (temperature and precipitation) and are therefore able to address climate change impacts on wind damage.

The models that predict effects of wind damage usually refer to two effects, stem breakage and uprooting, which by definition refers to windthrow, and thus only consider that the trees will either die or survive unharmed (Seidl et al., 2011). Therefore, in the present review, the models considered to estimate effects of wind damage did so by separating windthrow damage by DBH, tree height or tree species. Those models were GALES by Gardiner et al. (2000), HWIND by Peltola et al. (1999a), Ancelin et al. (2004), ForGEM-W by Schelhaas et al. (2007), Schmidt et al. (2010), Albrecht et al. (2012), Hanewinkel et al. (2014), Seidl et al. (2014a); Díaz-Yáñez et al. (2019) and Forzieri et al. (2020b), while the rest of the model approaches used in this review (e.g. Ni Dhubhain et al., 2001, Schindler et al., 2009, Saarinen et al., 2016, Suvanto et al., 2019) estimate solely the probability of windthrow occurrence, with no distinction between which trees would be affected. Five models, however, deal with probability and effects of windthrow jointly: HWIND by Peltola et al. (1999a), GALES by Albrecht et al., 2012, Gardiner et al., 2000, Schmidt et al., 2010, and Díaz-Yáñez et al. (2019) and consequently may be used for risk assessment.

The models GALES by Gardiner et al. (2000) and HWIND by Peltola et al. (1999a) are the most used models to calculate critical wind speed within a forest in the literature. They are, however, limited to predict critical wind speeds for homogeneous stands, where a representative tree is extrapolated as a whole stand. Taking this into account, the models FOREOLE by Ancelin et al. (2004) and ForGEM-W by Schelhaas et al. (2007) changed the critical wind speed approach, being able to make predictions for heterogeneous forest stands based on individual trees. Practical application of those two approaches, however, depends on the availability of stand growth models and/or individual tree growth models. The models from Schmidt et al. (2010) and Albrecht et al. (2012), are able to predict probability, effects and also have management outputs, but both require previous information from a windthrow event to be separated by tree species. The model from Díaz-Yáñez et al. (2019), on the other hand, uses variables easily retrieved from NFIs and is able to estimate probability and effects of wind and snow damage.

Apart from that, damaged trees that fall within a stand can break or uproot adjacent trees (Mitchell, 2013), but the risks considered in most existing models usually take into account a constant forest stand condition (Seidl et al., 2011), and do not consider the wind impact as a dynamic process. In this regard, two models take a different approach when compared to the others. The model from (Seidl et al., 2014a) simulates the creation of new gaps and new edges in the forest as a result of the wind damage, which therefore become susceptible to more wind

Table 1
Examples of models to analyze natural disturbances in European Temperate and Boreal forests and their reference to the original paper.

Disturbances	Location	Analysis models	Inputs	Outputs				Special features	Citation
				Prob.	Effect	Mgmt	Other		
Wind damage	Finland	Mechanistic	Forest	X	X	X	X	Critical wind speed model	GALES by Gardiner et al., 2000
	Ireland	Empirical	Forest, Soil, Wind speed, Previous Damage	X		X			Ni Dhubhain et al., 2001
	France	Mechanistic	Forest, Wind speed		X	X	X	Critical wind speed model	FOREOLE by Ancelin et al., 2004
	Netherlands	Mechanistic	Forest, Wind speed		X	X	X	Critical wind speed model	ForGEM-W by Schelhaas et al., 2007
	Germany	Empirical	Forest, Soil, Topographic	X		X			Schindler et al., 2009
	Germany	Empirical	Forest, Topographic, Previous Damage	X	X	X			Schmidt et al., 2010
	Germany	Empirical	Forest, Soil, Topographic, Wind speed, Previous Damage	X	X	X			Albrecht et al., 2012
	Switzerland	Empirical	Forest, Topographic, Previous Damage		X	X			Hanewinkel et al., 2014
	Sweden	Mechanistic	Climatic, Forest, Soil, Topographic, Wind speed		X	X			Seidl et al., 2014a
	Finland	Empirical	Forest, Topographic	X		X			Saarinen et al., 2016
	Finland	Empirical	Climatic, Forest, Soil, Wind speed	X		X			Suvanto et al., 2019
	Europe	Empirical	Climatic, Forest, Topographic, Wind speed		X	X			Forzieri et al., 2020b
Bark beetles	Austria	Mechanistic	Climatic, Topographic, Previous Damage				X	Phenology model	PHENIPS by Baier et al., 2007
	Sweden and Denmark	Mechanistic	Climatic				X	Phenology model	Jönsson et al., 2007
	Austria	Mechanistic	Climatic, Forest, Soil, Previous Damage	X	X	X		Uses PHENIPS	Seidl et al., 2007
	Austria	Meta-model	Climatic, Forest	X	X	X			Seidl et al., 2009
	Germany and Switzerland	Empirical	Climatic, Forest, Soil, Previous Damage	X	X	X	X	Uses PHENIPS	Temperli et al., 2013
	-	Mechanistic	Forest			X		Dispersal model	IPS by Kautz et al., 2014
	Austria	Mechanistic	Climatic, Forest, Previous Damage	X		X	X	Uses PHENIPS	Seidl & Rammer, 2017
	Finland	Mechanistic	Forest, Previous Damage		X	X		Uses WINDROT	BBDYN by Honkaniemi et al., 2018
Wildfire	Canada	Mechanistic	Climatic, Wind speed				X	Fire danger prediction	FWI by Van Wagner, 1987
	Worldwide	Mechanistic	Climatic, Forest, Soil, Lightning	X	X	X			Arora & Boer, 2005
	Worldwide	Mechanistic	Climatic, Forest, Soil, Lightning, Anthropogenic	X	X	X			Kloster et al., 2010
	Europe	Mechanistic	Climatic, Forest, Soil, Lightning, Anthropogenic	X	X	X			CLM-AB MOD Migliavacca et al., 2013
	Europe	Mechanistic	Climatic, Forest	X	X	X		Uses FWI	Khabarov et al., 2016
	Italian Alps	Empirical	Climatic, Topographic, Anthropogenic	X					Vacchiano et al., 2018
	Europe	Empirical	Climatic, Forest, Anthropogenic		X	X		Uses FWI	Forzieri et al., 2020b
	Sweden	Empirical	Climatic, Wind speed, Forest, Anthropogenic	X	X	X		Uses FWI	Pinto et al., 2020
	Serbia	Empirical	Climatic, Forest, Topographic, Anthropogenic	X		X			Milanović et al., 2021
Root rot	Sweden and Finland	Mechanistic	Climatic, Forest, Previous Damage	X	X	X			Rotstand by Pukkala et al., 2005
	Sweden	Empirical	Climatic, Forest, Topographic	X		X			Thor et al., 2005
	Italian Alps	Empirical	Forest, Topographic		X	X			Gonthier et al., 2012
	Finland	Mechanistic	Climatic, Forest, Previous Damage	X	X	X			Hmodel by Honkaniemi et al., 2014
	Norway	Empirical	Climatic, Forest, Topographic, Previous Damage	X		X			Hylen & Granhus, 2018
Snow damage	Czech Republic	Empirical	Climatic, Forest, Topographic		X	X			Hlásny et al., 2011
Ice damage	Hungary	Empirical	Forest, Topographic	X		X			Aszalós et al., 2012
	Central and Northern Europe	Empirical	Climatic				X	Freezing rain prediction	

(*continued on next page*)

Table 1 (*continued*)

Disturbances	Location	Analysis models	Inputs	Outputs				Special features	Citation
				Prob.	Effect	Mgmt	Other		
									FMI$_{CLIM}$ by Kämäräinen et al., 2017
Wind damage and Snow damage	Finland	Mechanistic	Forest, Snow load	X	X	X	X	Critical wind speed/ snow loading model	HWIND by Peltola et al., 1999a
Wind damage and Snow damage	Norway	Empirical	Forest, Soil, Topographic	X	X	X		Uses machine learning	Díaz-Yáñez et al., 2019

damage; and the model ForGEM-W that adds the interaction between tree crowns and roots, which can either cause a better support by neighbouring trees or a greater damage by falling trees hitting other trees (Schelhaas et al., 2007).

Considering the above mentioned, the mechanistic model ForGEM-W by Schelhaas et al. (2007) stands out for the incorporation of trees' competition and support by other trees, as well as the ability to consider stands with more variation, such as uneven-aged stands, however, it requires inputs that cannot be derived from NFI data, which limites the usage of this model to a smaller scale. On the other hand, GALES by Gardiner et al. (2000), HWIND by Peltola et al. (1999a), and the model from Díaz-Yáñez et al. (2019), which are able to make windthrow risk assessments for even-aged homogeneous stands, require inputs that can be retrieved effortlessly from NFIs (DBH, tree height and spacing), making them easy to use on large-scale forest planning.

6.2. *Bark beetles*

A phenology model predicts the life cycle events of insects, such as time of initiation of swarming, timing of development of generations, onset of infestation, etc. For bark beetles, two common examples of phenology models are the one from Jönsson et al. (2007) and the PHENIPS model (Baier et al., 2007), the latter being one of the most used phenology model for bark beetles. Furthermore, dispersal models (e.g. IPS by Kautz et al., 2014) predict bark beetles' spatial dispersal, aggregation and colonization of trees. Phenology models and dispersal models are not used directly for forest management purposes, since they are focused mainly on the insects' characteristics, and not on the forest characteristics. They are, however, included in most bark beetle risk assessment studies, and therefore their inclusion in the present study is justifiable.

Apart from the model from Seidl et al. (2009), all other model approaches included in this review use either the PHENIPS model to account for beettles' development (Seidl et al., 2007, Temperli et al., 2013, Seidl & Rammer, 2017) or the WINDROT model to account for windthrow and root rot affected trees (BBDYN by Honkaniemi et al., 2018). When using the PHENIPS model, there is a need of information on bark beetle infestation, such as number of beetles catched on traps, to be able to model the swarming and onset of infestation. Furthermore, the use of WINDROT model is also restricted since root rot infestation variables are needed. With this in mind, the model from (Seidl et al., 2009) stands out as being the only one that, instead of a phenology model, uses a proxy for beetle development, which is converted into a stand level hazard score. This change in approach allowed the analysis to be done at country level, since bark beetle infestation variables were not necessary.

Most of the model approaches (Baier et al., 2007, Jönsson et al., 2007, Seidl et al., 2007, Seidl et al., 2009, Temperli et al., 2013, Seidl & Rammer, 2017) except for IPS by Kautz et al. (2014) and BBDYN by Honkaniemi et al. (2018), use climatic variables such as temperature and precipitation and can therefore adress climate change impacts on bark beetle damage.

To conduct a risk analysis, the probability of occurrence and the effects of natural disturbances are needed. Most bark beetle models, however, focus only on one or the other. For instance, the model from Seidl & Rammer (2017) estimates only the probability of outbreak and colonization, while the BBDYN model (Honkaniemi et al., 2018) estimates only the effects of bark beetles, i.e. the number of trees killed by bark beetles. In the literature reviewed, three bark beetle models are able to estimate both probability and effects of damage jointly (Seidl et al. 2007, Seidl et al., 2009, Temperli et al. 2013). Therefore, when considering the models presented in this review, the model from Seidl et al., (2009) is the most suitable option for forest management planning at country level, regarding the inputs required, the ability to estimate probability and effects of damage, and the possibility to adress climate change.

6.3. *Wildfires*

The Fire Weather Index (FWI) System, developed by the Canadian Forest Service but applied worldwide (Van Wagner, 1987), is one of the largest-used wildfire danger rating systems. The FWI System empirically reflects the combination of the different fuel moisture codes and fire behavior indices, using only climatic variables to rate the potential fire intensity (Van Wagner, 1987; Dupuy et al., 2020). Fire risk in Europe can be affected by natural conditions related to topographic, soil and forest variables (Alexander et al., 2006; Dillon et al., 2011; Harris & Taylor, 2017; Adámek et al., 2018), but many models also include variables that represent lightning frequency in the area, and anthropogenic variables that represent population density, landuse information, distance to roads from ignition points, among others (e.g. Arora & Boer, 2005; Kloster et al., 2010; Migliavacca et al., 2013; Vacchiano et al., 2018; Pinto et al., 2020; Milanović et al., 2021). In addition, fire history of the area (Coppoletta et al., 2015) might be an important variable for wildfire risk prediction.

All wildfire models use climatic variables, therefore all of them can adress climate change. Most of them also need forest, soil, lightning and anthropogenic variables, however, the model from Khabarov et al. (2016) only uses climatic and forest variables, while also using parts of the FWI System by Van Wagner, (1987). Furthermore, most of the models estimate both probability of occurrence and effects of wildfires (e.g. Arora & Boer, 2005; Kloster et al., 2010; CLM-AB MOD by Migliavacca et al., 2013; SFM by Khabarov et al., 2016, and Pinto et al., 2020) while two of them only estimate probability (Vacchiano et al., 2018; Milanović et al., 2021) and one of them estimate only effects of wildfire (Forzieri et al., 2020b).Therefore, the most relevant and complete model approach, presented in this review, that can be used for Temperate and Boreal regions, is SFM developed by Khabarov et al., (2016).

6.4. *Root rot*

The probability of root rot occurrence is related to climatic, forest and topographic variables (Hylen & Granhus, 2018), and all root rot models included in this review can adress climate change - with the exception of the model from Gonthier et al. (2012). The proportion of *P. abies* in the stand is another important variable affecting root rot probability (Thor et al., 2005), as well as the diameter of the host tree, the length of the growing season and tree age. Larger and older trees have an increased exposure to spore infection, and thus a higher probability of root rot occurrence, while a shorter growing season decreases the exposure and the probability of root rot occurrence.

Modelling root rot development calls for the inclusion of diseases stages, such as spore infection, fungal growth in roots, stump, and stem, and development of decay (Asiegbu et al., 2005). The models Rotstand by Pukkala et al. (2005) and Hmodel by Honkaniemi et al. (2014), that simulate *H. annosum* s.l. dynamics at stand level, are the only ones that estimate both probability and effects of disease. The models are also able to analyse different management alternatives affecting disease development. However, none of the models is practical in terms of required input data, since some of the data are not promptly available from NFIs or other free sources. An example of such input is the "proportion of *H. parviporum* infections related to the total *H. annosum* s.l. infections" needed for Hmodel by Honkaniemi et al. (2014), which would require a prior field survey.

As an alternative, other models only require data available from NFIs, such as the model developed by Thor et al. (2005), which shares many similarities with the model from Hylen & Granhus (2018), as both of them estimate probability of root rot occurrence at tree's breast height, but do not account for effects of root rot (e.g. fungal growth up the stem). Another example of model that uses only inputs readily available in forest inventories is from Gonthier et al. (2012), which differently from the other two ones, predicts the economic impacts (losses in yield and value of timber) of *H. annosum* s.l., instead of estimating probability of occurrence.

6.5. Snow and ice damage

The snow damage risk usually depends on climatic variables such as temperature, wind and precipitation, as well as on forest and topographic factors (Päätalo, 2000). When dealing with Northern conditions, however, it is difficult to distinguish the nature between wind and snow damages (Díaz-Yáñez et al., 2019). Therefore some models deal with both disturbances at the same time (e.g. HWIND by Peltola et al., 1999a and Díaz-Yáñez et al., 2019). The model from HWIND by Peltola et al. (1999a) uses forest and snow load variables to be able to predict the critical turning moment and wind speed at which trees break or get uprooted. In the model, the snow load is estimated by the snowfall distributed into the tree's crown area. As discussed on section 6.1, the HWIND model deals jointly with probability and effects of wind and snow, therefore it may be used for risk assessment. However, it is limited to predict the critical turning moment for even-aged homogeneous stands. The model from Díaz-Yáñez et al. (2019) also integrates wind and snow damage, being able to estimate both their probability and effects. Furthermore, the model uses variables easily retrieved from NFIs, such as DBH, density of trees, altitude and slope of terrain.

For this review, one model by Hlásny et al. (2011) was found to tackle snow damage alone, without dealing with other disturbances mutually. The regression model uses climatic, forest and topographic variables to estimate the effects of snow damage in spruce forests, therefore it is able to be used in a large-scale forest management planning, as well as to address climate change.

For ice damage, the model FMI_{CLIM} by Kämäräinen et al., (2017) makes a freezing rain prediction, but it does not account for probability and effects of ice damage. Whereas, the model from Aszalós et al. (2012) generates probability maps of ice disturbance with explanatory variables that are available in national inventories, such as height, diameter and age, and variables that could be relatively easily derived from digital elevation models (DEM) based on variables such as elevation, aspect and slope.

7. Conclusion

The present review has identified important links between the natural disturbances present in European Temperate and Boreal forests and climate change, and even though those areas might have different climate change impacts related to precipitation, some forest disturbances are expected to increase in both Temperate and Boreal forests. Attention should be given to Temperate forests that will experience a rise in temperature and drop in precipitation, which will likely increase bark beetle and root rot occurrences, both together expected to increase risks of windthrow in the case of high-speed winds, and finally rising wildfire risks due to the increment of fuel in the forest surface. Apart from that, Boreal forests will likely experience warmer temperature and a rise in precipitation, which can increase windthrow occurrences, as well as wet and frozen snow damage. As a consequence, bark beetle attacks and root rot infestations may increase, adding further to wildfire risk.

For the assessment of modelling approaches, the main issues regarding large-scale risk analyses of disturbances under climate change are relevant and easily-retrieving-input variables such as forest and climate ones, and relevant outputs for risk assessment, such as probability, effects, and management. This review shows that the ability to estimate probability of occurrences is fairly common for all disturbance models, and that they contribute with management outputs, since most of them use forest variables as input. However, an important limitation here seems to be the scarcity of models that predict effects of disturbances and that do not need previous damage variables as inputs. Of course, no model is a perfect model, and researchers need to be flexible when performing risk analysis. For the cases where no model predicts effects of disturbances and previous damage information is not available, some simpler solutions such as experts' judgments or mean values from literature, combined with sensitivity analysis, might be useful.

Due to past damages, some regions and countries have a long history of developing disturbance models. However, climate change will increase size and occurrences of disturbances, calling for risk assessments to be performed all over Europe. The present review presents models that can assist on that matter, and with relevant examination of models' validity, some of them are able to be validated outside the region where they were initialy fitted. After including those risks in decision-making tools, an adaptive forest management can make forests less vulnerable to the risks of natural disturbances and climate change.

Funding: Funding for this study was provided by the Norwegian Research Council through - the *Climate Smart Forestry Norway* project [NFR 302701]

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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