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Scientific response to intensifying bark beetle outbreaks in Europe and North America

T. Hlásny [a,*], S. Zimová [a], B. Bentz [b]

[a] Czech University of Life Sciences Prague, Faculty of Forestry and Wood Sciences, Kamýcká 129, 165 21 Prague 6, Czech Republic
[b] United States Department of Agriculture Forest Service, Rocky Mountain Research Station, 860 North 1200 East, Logan, Utah 84321, United States

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ABSTRACT

Tree-killing bark beetles are globally the most destructive forest pests and their impacts have increased in recent decades. Such an increase has been consistently reported from Europe and North America, and it is, with high confidence, driven by climate change. We investigated how the scientific community in both continents responded to this situation by conducting a comprehensive search of the Scopus database from 1970 to 2020. Studies that investigated interactions between climate change and two prominent bark beetles in Europe and North America, the European spruce bark beetle *Ips typographus* (ESBB) and the mountain pine beetle *Dendroctonus ponderosae* (MPB), were identified. We used several hierarchical search criteria, starting from general aspects of pest – climate change interactions, to studies with clear implications for management and policies.

We found that authors investigating the two bark beetle species mentioned climate change in publications beginning in 1998, and have constituted 8.9 and 13.8 % of all studies on ESBB (N = 987) and MPB (N = 1479) recorded in Scopus. However, only part of these studies addressed climate change as a fundamental or integral part of their research design (59.1 % in ESBB and 38.7 % in MPB). We identified 30 studies on ESBB and 50 studies on MPB which informed efforts towards improving bark beetle management strategies to address climate change-affected ecosystem dynamics. Publications on both insects consistently highlighted the importance of vegetation management aiming to reduce the risk and severity of outbreaks and prevent large-scale population expansion. Only a minor portion of studies placed their findings into the context of relevant policies and legislation, and this connection was particularly lacking in studies on MPB.

We conclude that research on bark beetle management under climate change has received inadequate attention and it lags behind observed and foreseen global-scale impacts. We suggest that focused and applied research with clear management implications is needed to develop new climate-adapted and evidence-based management strategies.

1. Introduction

Forests of the Northern Hemisphere have experienced increased tree mortality that exceeds historical observations and has doubled over the most recent four decades (Allen et al., 2015; Carnicer et al., 2011; Senf et al., 2018). This intensification has emerged from the interplay of chronic abiotic drivers such as rising temperatures and human-caused land-use transformations, and episodic disturbances such as wildfire, drought, windthrow and insect infestations (McDowell et al., 2020; Seidl et al., 2014; Thom et al., 2013). For example, historical forest management in Europe has largely transformed species composition resulting in homogenized forest stands and landscapes that are increasingly vulnerable to an array of natural disturbances (Seidl et al., 2011; Schelhaas et al., 2003; Stritih et al., 2021). The interaction of European forests with climate extremes repeatedly triggered large-scale tree mortality, for example, in 2003, 2015 and 2018 (Hlásny et al., 2021b; Rouault et al., 2006; Senf et al., 2020).

In Europe and North America, forest managers and natural resource policy makers have been increasingly confronted with outbreaks of multiple insect species that thrive in warmer and drier climates (Anderegg et al., 2015; Kautz et al., 2017; Kolb et al., 2016). There is evidence that this trend will continue in the future in some landscapes as climate continues to warm (Bentz et al., 2019b, 2010; Seidl et al., 2017). Climate change may, for example, accelerate insect generation time,

* Corresponding author.
E-mail address: hlasny@fld.czu.cz (T. Hlásny).

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reduce overwintering mortality, modify inter-and intra-specific interactions with host trees and community associates, and facilitate species range expansions which may result in invasions of native and non-native species into new regions (Forrest, 2016; Garnas, 2018; Marini et al., 2017; Seidl et al., 2017; Weed et al., 2013). One group of insects which has received particular attention in recent decades is bark beetles (Coleoptera: Curculionidae, Scolytinae). While the majority of species in this group breed in dead and dying trees, a few conifer-feeding species can exhibit intermittent eruptive outbreaks resulting in landscape-scale tree mortality (Audley et al., 2020; Biedermann et al., 2019; Raffa et al., 2008).

Two prominent bark beetle species in the Northern Hemisphere are the European spruce bark beetle *Ips typographus* L. (ESBB), and the mountain pine beetle *Dendroctonus ponderosae* Hopkins (MPB). Recent ESBB outbreaks in Europe fuelled by extreme weather have reached supranational scales (Seidl et al., 2016a; Senf and Seidl, 2018), and in western North America, MPB outbreaks impacted millions of pine hectares in a single decade (i.e., 2000 to 2010) (Cooke and Carroll, 2017; Meddens et al., 2012).

The ESBB is native to Norway spruce (*Picea abies* L Karst) forests in Eurasia and is found across the entire distribution of its host (Christiansen and Bakke, 1988). ESBB population outbreaks mainly occur in mature spruce stands with low species diversity, which are often created by intense production-oriented forest management (Hlásny and Turčáni, 2013; Wermelinger, 2004). ESBB outbreaks are typically triggered by windthrow, though drought, air pollution and other stressors affecting tree vigour are also important predisposing and inciting factors (Grodzki et al., 2004; Hlásny et al., 2021b; Marini et al., 2017; Mezei et al., 2017). Recent ESBB outbreaks were found to exhibit a biome-wide synchronisation driven by climate extremes (Senf and Seidl, 2018).

MPB is native to pine (*Pinus*) forests of western North America, although the current distribution is not as extensive as its pine hosts which are found further north and east in Canada and further south into mainland Mexico than the current MPB distribution (Cooke and Carroll, 2017; Dowle et al., 2017). Recent warming has resulted in rapid northward expansion in northern British Columbia and western Alberta, Canada (Janes et al., 2014), but new infestations have not been observed south of the current distribution in the southwest United States (USA) (Soderberg et al., 2021). Similar to ESBB, mature stands with low species diversity are associated with MPB outbreaks (Fettig et al., 2014a, 2014b), in addition to weather that supports appropriate seasonal timing, reduced overwintering mortality and synchronous adult emergence (Bentz et al., 2019b; Logan and Bentz, 1999; Régnière and Bentz, 2007).

Because outbreaks of bark beetles compromise ecosystem services, including timber production, recreation and carbon sequestration, and can negatively affect human communities (Grégoire et al., 2015; Morris et al., 2017; Thom and Seidl, 2016), various strategies for outbreak control have been formulated and they are often anchored in forestry legislation (Fettig et al., 2014a, 2014b; Hlásny et al., 2019; Wermelinger, 2004).

Direct control involves short-term tactics to address a current infestation and includes search and removal or incineration of infested trees (i.e., sanitation), reduction of breeding substrates (e.g., salvaging of windfelled trees in the case of ESBB), application of insecticides, and population manipulation with semiochemicals (Bentz et al., 2019a; Seybold et al., 2018). Post-outbreak salvage logging of beetle-killed trees is a common strategy used to recover value from dead trees, and is often combined with sanitation logging wherein infested trees are also removed (Leverkus et al., 2020; Stadelmann et al., 2013). Salvage and sanitary operations, and beetle population manipulation using trapping, are being frequently used in attempts to mitigate and control ESBB outbreaks in Europe (Stadelmann et al., 2013; Wermelinger, 2004). In North America, post MPB outbreak salvage logging is often targeted at facilitating regeneration, reducing fuel loads, and altering fire behaviour (Collins et al., 2012; Gillette et al., 2014; Hood et al., 2017), rather than controlling future MPB-caused disturbances.

Indirect control measures, which are intended to be preventative and are applied prior to an outbreak, are aimed at manipulation of stand and landscape conditions to reduce the risk of outbreaks by improving tree vigour and reducing host tree density, age, and connectedness (Dobor et al., 2020a; Fettig et al., 2014a; Wermelinger, 2004; Zimová et al., 2020); we refer to these measures here collectively as vegetation management. For example, pre-outbreak thinning aimed at changing stand conditions can reduce susceptibility to MPB-caused tree mortality when applied in advance (Fettig et al., 2014b). However, recent observations in Europe suggest that prior management interventions may increase the forests‘ susceptibility to disturbances such as wind and bark beetles due to the locally reduced sheltering effect (Stritih et al., 2021).

Recent changes in climate are having direct and positive influences on beetle population dynamics, in addition to compromised resistance of host trees (Raffa et al., 2008). Aggravating social impacts of bark beetle outbreaks, conflicts with local management objectives such as forest productivity and biodiversity conservation are becoming increasingly recognized with Europe's traditional forest management systems (Leverkus et al., 2021; Müller et al., 2008; Thorn et al., 2017a, 2017b). In North America, monitoring and adaptive management, using prescribed fire and mechanical thinning, to reduce stand densities and increase drought resilience prior to outbreak initiation are proposed, although often difficult to apply as humans increasingly move into the wildland urban interface (Fettig et al., 2019). In some cases, recent bark beetle outbreaks have no precedent and an appropriate management response is therefore difficult to formulate based on previous events (Bentz et al., 2005). It is clear that management strategies based on the historical experience may no longer accommodate new demands associated with changing disturbance regimes (Leverkus et al., 2021). These and other facts highlight that a shift in management paradigm towards more comprehensive, anticipatory, climate-adapted and evidence-based strategies is needed (Abrams et al., 2018; Cooke and Carroll, 2017; Dhar et al., 2016; Lieffers et al., 2020).

It remains unclear if scientists have responded to these challenges and whether a critical body of knowledge exists to inform forest management- and policy-making in response to rapidly changing conditions in consistent and comprehensive manners. We ask in this study how the scientific community in Europe and North America responded to the emergent risks and what research attention bark beetle outbreaks amplified by climate change have received. We conducted a comprehensive literature search to evaluate how relevant scientific evidence has accumulated over time and whether the research provides adequate and timely alert to forestry policies and management planning. We evaluate temporal, geographic and thematic patterns of publications on bark beetles and management under climate change, identify differences in the scientific response between the two continents, and formulate recommendations for future research. We hypothesized that research on bark beetles has significantly advanced during the recent twenty years on both continents in response to the increasing recognition of risk related to changing disturbance regimes. We further hypothesized that research devoted to active management of bark beetle outbreaks has been more abundant in Europe than in North America, due to the generally greater management intensity of European forests and differences in attack behaviour and active management options for ESBB relative to MPB. Finally, we expected that research linking bark beetle outbreaks and forest management and policy would be lacking, which is a phenomenon recognized across scientific disciplines.

2. Methods

2.1. Literature review

On November 6, 2020 we performed a literature search using the Scopus database (SciVerse Scopus, 2020) and set the cut-off year for the inclusion of the records to 1970; i.e. before an intensive research on ecosystem dynamics affected by climate change had commenced. We searched Abstract, Title and Keywords (both author and index keywords) for specific combinations of search terms. We note that the Scopus database, and therefore our search criteria, excluded publications that were not associated with scientific journals.

We used a three-level hierarchical search design (Table 1). Level A addressed a broad area of bark beetle dynamics, impacts and management. The search criteria used were different variants of English and Latin names of the two bark beetle species covered in our study, the ESBB and MPB. At this level, no manual assessment of the filtered records was conducted.

Search B refined the previous search A, and combined it with terms „climate change“, „climate warming“, „global change“ and „global warming“ (Table 1). Next, we created a subset of the search B, and conducted a manual assessment of the identified records (search B-MR). We discarded studies where formulations related to climate change were used in general terms only, for example, to introduce the addressed topic and increase its attractiveness and applicability; however, climate change was not an integral or fundamental part of research, i.e., the publications did not address the changing ecosystem dynamics and/or management constraints related to climate change. The search B-MR thus provides a realistic approximation of publication patterns on bark beetle dynamics affected by climate change, including impacts, methodological advances and management responses.

Table 1
A design of the literature search using the Scopus database, with the search criteria and number of identified records indicated. Column *MR* indicates number of records retained after the manual refinement of records identified in the primary search. + denotes publications, which were not identified based on the search criteria in Scopus but were added from other sources.

Search code	Information obtained	Search criteria	No. of records	No. of records (MR)
A	Bark beetle research in a broad sense			—
A1	European situation, *I. typographus*	(“spruce bark beetle” OR “typographus”)	987	—
A2	N. American situation, *D. ponderosae*	(“mountain pine beetle” OR “Dendroctonus ponderosae” OR “D. ponderosae”)	1479	—
B	Research on interactions of bark beetles and climate change	—		
B1	European situation, *I. typographus*	(“spruce bark beetle” OR “typographus”) AND (“climate change” OR “climatic change” OR “climate warming” OR “global change” OR “global warming”)	88	49 + 3
B2	N. American situation, *D. ponderosae*	(“mountain pine beetle” OR “Dendroctonus ponderosae” OR “D. ponderosae”) AND (“climate change” OR “climatic change” OR “climate warming” OR “global change” OR “global warming”)	204	69 + 10
C	Implications for management, decision- and policy-making	—	—	
C1	European situation, *I. typographus*	Manually refined search B1	—	27 + 3
C2	N. American situation, *D. ponderosae*	Manually refined search B2	—	44 + 6

The most narrowly focused search C contained manually refined records from the search B-MR. Only those records were retained which explicitly pointed out the risks from bark beetles or formulated recommendations on the management of bark beetle outbreaks amplified by climate change. The search C thus addresses studies which translated the knowledge of bark beetle ecology and population dynamics into information supporting management decisions and policy-making.

Because some studies on the addressed topic may have not been identified using our search criteria (e.g. terms on climate change, management and policy were not used in title and abstract but they were in the main text), we conducted a complementary search combining different formulations of ESBB and MPB (Table 1) with words “climate” and “policy”. Thus identified papers were evaluated and a few of them were added into the previously described categories. In this way, 3 papers on ESBB and 10 papers on MPB were added. The PRISMA flow diagrams for both reviews (i.e. ESBB and MPB) are in Supplementary material A.

For the identified European studies, geographical patterns were analyzed by country. Studies conducted in Canada and the USA could not be easily categorized by province or state, and patterns were therefore analyzed separately by country. Temporal patterns were included based on the year of journal publication. After reviewing all study abstracts, we identified five major thematic areas that each study was placed within. We also reviewed all papers identified in search C for references to policy and legislation, which could have either contributed to the initiation of a given study (typically mentioned in Introduction), or a study had policy implications (typically mentioned in Discussion). Finally, we collected different statistics about forest conditions in the addressed European countries, such as total forest area and the proportion of Norway spruce (FAO, 2020, different national sources; Supplementary Material B), and used them to identify factors that underly the publication performance.

We note that if any single study addressed more than one country, thematic area, or policy instrument, it was counted multiple times. Therefore, total number of cases in these evaluations differs from the total number of publications evaluated.

3. Results

3.1. Temporal frequency

The literature search showed a substantially greater number of studies dedicated to MPB than ESBB (searches A1 and A2; 1479 vs. 987 studies) (Supplementary material C). The publication frequency increased more or less monotonously for ESBB, while studies on MPB sharply increased after 2004 and peaked in 2014. After 2004, the number of studies on MPB exceeded ESBB by 49.9 % (Fig. 1).

The pattern of publication frequency changed when the previous search criteria were combined with terms containing different formulations of phrases related to climate change (B1 and B2; Table 1). These studies started to appear after ca 1998 and increased sharply after 2004. The increase was more pronounced for MPB, reaching, on average, 12 papers published annually over the recent 15 years (199 papers in total; 17.5% of A2 in 2005 – 2020). In the case of ESBB, the average publication rate over this recent period was only 5.3 studies per year (84 papers in total; 14.8 % of A1 in 2005 – 2020) (Supplementary material C).

A closer look at the content of publications identified in search B showed that only a fraction of these studies addressed climate change as an integral part of the research design or provided specific inferences towards a climate change – bark beetle interaction. Specifically, search B-MR identified 52 studies for ESBB (59.1 % of search B1) and 79 studies for MPB (38.7 % of search B2).

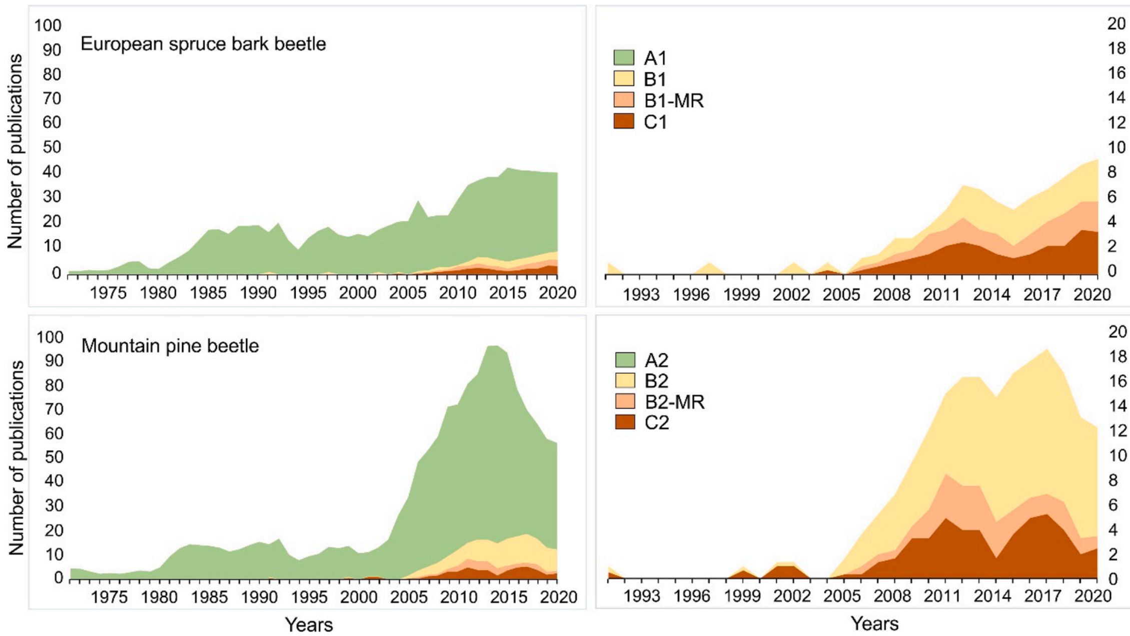

Fig. 1. Annual number of studies related to the European spruce bark beetle (ESSB) (top row) and mountain pine beetle (MPB) (bottom row) (A1, A2), ESBB and MPB dynamics and climate change (B1, B2 and B1-MR, B2-MR), and management and policy implications (C1, C2) included in the Scopus database. Descriptions of the search criteria used is indicated in Table 1. A moving window smoothing (k = 3) was applied on all time series for visualisation purposes.

The most narrowly formulated search C, which retained only studies formulating clear recommendations for bark beetle management under climate change or containing warnings about climate-change mediated amplification of bark beetle disturbance identified 30 studies for ESBB and 50 studies for MPB. This represents 34.1 and 24.5 % of studies from search B, respectively. These publications are listed in Supplementary material D.

Because a temporal increase in identified publications (base searches A1 and A2) can be confounded by the general increase in the Scopus coverage over time, we compared the annual relative increase in number of identified publications with the relative increase in the number of journals included in Scopus (Supplementary material E). This analysis indicated that annual number of identified ESBB and MPB publications increased at a higher rate than the general increase in Scopus coverage. This difference was more distinct in MPB than in ESBB.

3.2. Geographic pattern

We identified a distinct difference in the geographical pattern of publications on ESBB and MPB. While most of the studies on MPB addressed the entire range of the insect in either the USA or Canada (i.e., not individual states or provinces), studies on ESBB predominantly addressed individual countries in Europe.

In the case of ESBB, the greatest number of publications identified by the search B1-MR (Table 1) addressed Central Europe (59 %), followed by Northern Europe (31 %) (Fig. 2) (Supplementary material F). At a country scale, the greatest number of studies was reported from Sweden and Germany. In contrast, Southern Europe represented by Italy, Eastern Europe represented by Russia, and Western Europe represented by Belgium and France, received only minor attention. The geographical pattern of studies identified using the searches B1-MR and C1 was similar to the total area of Norway spruce in the countries (R-square 0.37

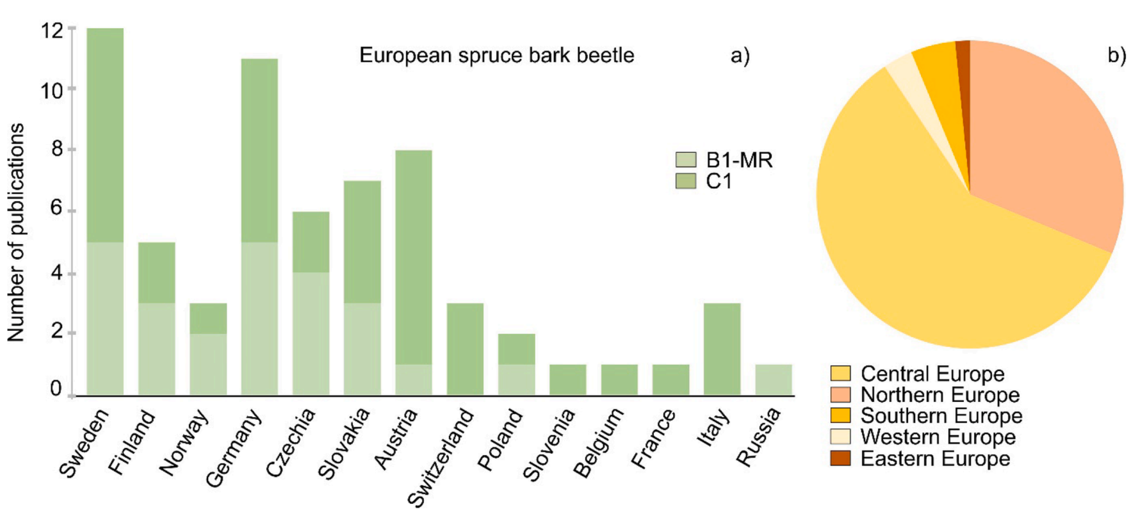

Fig. 2. Geographical distribution of studies on various interactions of ESBB and climate change in Europe identified in the Scopus database using search criteria from Table 1. We note that C1 is displayed as a subset of B1-MR.

for B1-MR and 0.21 for C1, Supplementary material B). The association with other predictors, including total forest area or proportion of spruce in the forest, was less strongly correlated.

In North America, a slightly greater number of publications addressed USA (47%) compared to Canada (41%). Fewer publications in the B2-MR search (12%) addressed the entire MPB range across both countries in North America.

3.3. Thematic areas

We identified five broad categories of findings in C1 and C2 studies (Fig. 3). First, a large portion of publications informed, in quantifiable terms, forecasted impacts due to both ESBB and MPB. These studies included increased levels of disturbed growing stock (e.g. Boucher et al., 2018; Dobor et al., 2020a, 2020b; Fettig et al., 2019; Logan et al., 2010), reduced forest carbon, at least in the short term (e.g. Arora et al., 2016; Seidl et al., 2014) or impacts on public health (Embrey et al., 2012). All evaluated studies consistently reported an increase in future impacts, yet the magnitude of the impact varied depending on factors such as the future time period considered, level of climate forcing, and geographic location.

Observed range expansion and forecasted insect distribution were predominantly reported from North America where pines extend further north in western Canada than the historical MPB range (e.g. Bentz et al., 2019b; Cooke and Carroll, 2017; Janes et al., 2014; Zhou et al., 2019). While past range expansion for ESSB was not reported from Europe, a few publications forecasted possible northward (Økland et al., 2015) and upward (Jakoby et al., 2019) expansion under climate change (category Forecasting distribution, Fig. 3).

We identified a group of studies on the management of bark beetles under climate change aimed at direct control of insect populations, and a group of studies aimed at bark beetle control via vegetation management. While vegetation management studies received attention in both insect species, measures aimed at direct management of beetle populations dominated in Europe for ESSB. Of the papers focused on vegetation management, the authors consistently highlighted the importance of management fostering structural and tree species diversity at the scale of forest stands and landscapes to enhance resilience (Dhar et al., 2016; Dobor et al., 2020b; Dymond et al., 2014; Fettig et al., 2014b; Halofsky and Peterson, 2016; Honkaniemi et al., 2020) and reducing forest rotation length (Björkman et al., 2015; Zimová et al., 2020). Studies aimed at improving spatial forest configuration to mitigate long-distance dispersal of beetles were less frequent, highlighting, for example, the importance of spatially targeted harvesting (Sims et al., 2014).

Publications aimed at direct control of ESBB focused on sanitary removal of windfelled trees to prevent beetle colonization and population build-up, in addition to early removal of infested trees. Yet, while some authors promoted this practice (e.g. Ogris and Jurc, 2010), the efficacy of this practice under warmer climate was questioned (Dobor et al., 2020b). Studies aimed at direct manipulation of MPB populations, specifically in response to a changing climate, were focused on the use of semiochemicals and insecticides for protection of high value trees and stands (Keane et al., 2017; Seybold et al., 2018).

3.4. Policy implications

We found that a large part of studies on ESBB identified in the search B-MR (n = 52) did not refer to any policy or legislation document (70.2 %), nor did they explicitly specify the targeted instruments even though the information relevant for policy- and decision-making was provided (14.9 %). National legislation was referred to by 21.3 % of the studies, and global and EU instruments by 19.1 and 6.4 %, respectively. Among the global and EU instruments addressed, the Intergovernmental Panel on Climate Change (IPCC) reports were referred to most frequently (31.9 % of all B1-MR studies). However, the studies referred exclusively to the information about projected climate change rather than on chapters addressing risks to forests from climate change and pests (e.g. Nabuurs et al., 2007; Settele et al., 2015).

In the case of MPB, association of research and policy was even weaker than in ESBB. Of the studies identified in the B2-MR search, only 13% included discussions of societal and policy impacts in the USA and Canada following the recent 2000–2010 MPB outbreaks (e.g. Abrams et al., 2018; Cohen et al., 2016; Cottrell et al., 2020; McDaniels et al., 2012; Nelson, 2007). IPCC was mentioned as a reference for trends in climate change rather than effects on bark beetle outbreaks and policy. Other global policy instruments including Kyoto and the Paris Agreement were not specifically related to MPB outbreaks.

4. Discussion

Recent outbreaks of ESBB in Europe and MPB in North America have exceeded historical ranges and highlighted a lack of preparedness by policy-makers and managers to face the intensifying forest disturbances. This was in part due to an insufficient understanding regarding the potential for such large scale, climate-driven impacts. The responses were typically reactive and short-term aimed at protecting high value trees, reducing public hazards, recouping economic losses by salvaging, and reducing the risk of outbreak expansion. On the other hand, anticipatory strategies that consider shifting disturbance regimes and are consistent with climate change adaptation and mitigation agendas were lacking (Di Gregorio et al., 2017; Leverkus et al., 2021). A transformation of this type requires strong scientific support. We investigated how research dedicated to bark beetles developed over recent decades,

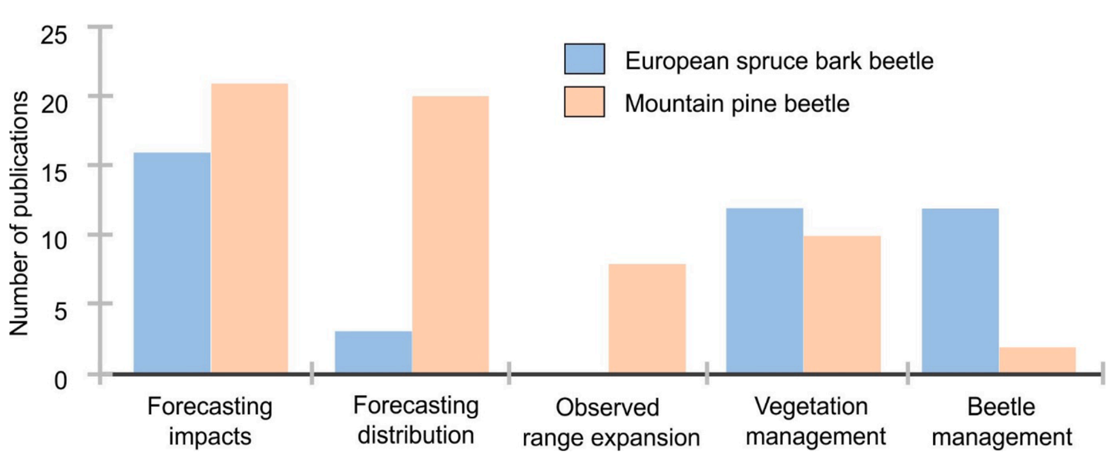

Fig. 3. Number of studies identified using the search C in the Scopus database in five thematic categories.

with an aim to understand the evolution of scientific interest in the interactions among bark beetles, management, and climate change. We also compared European and North American perspectives, which differ in climate policies, attitudes towards the control of natural disturbances, and current management strategies and tactics.

4.1. Temporal evolution and geographical patterns

We found that research on ESBB (search A) resulted in 20–25 publications annually during the period 1980–2010 (only considering publications included in Scopus) and accelerated after 2010, though this increase was not large. In North America, research on MPB resulted in 10–15 publications annually in the period 1980–2002, and then increased dramatically, culminating in 90 publications during the peak years 2010–2012. Although the annual number of publications is likely underestimated due to considering only a single database (Bramer et al., 2017), the overall temporal pattern suggests that research communities in both continents have steadily increased the number of studies on ESBB and MPB. Our study does not allow us to attribute such an increase unambiguously, yet factors such as recent outbreak intensification and increasing recognition of the risk to vital ecosystem goods and services (Dhar et al., 2016; Morris et al., 2018) can be assumed to play an important role. Factors such as increasing Scopus coverage during the investigated period (Supplementary material E) and increasing pressure on academics for publications (Grimes et al., 2018), however, need to also be considered.

The role of climate change (or climate in general) in the dynamics of ESBB and MPB has long been recognized, and guidelines for management of these notable species are part of the classic forestry literature (e.g. Cole and Amman, 1980; Christiansen and Bakke, 1988; Økland et al., 2015; Safranyik and Carroll, 2006). However, publications addressing bark beetle management under climate change only started to appear after ~ 2005 in both continents, and represent a small fraction of total bark beetle publications. Interestingly, research on adaptive capacity to climate change (in a broad sense) was found to accelerate globally after 2004 (Siders, 2019).

Bark beetle publications containing any mention of climate change were more abundant in North America (slightly dominated by publications from the USA) than in Europe, both in absolute and relative terms. Climate change policies, however, are likely to be more consistent and supportive to climate change research in the EU than the USA (McCright et al., 2016; Rayner and Jordan, 2016). Indeed, when subject matter was considered, publications on bark beetle management, climate, and policy dominated in Europe, but represented only 30% of publications on MPB. This difference very likely reflects the contrast in management intensity in European and North American forests, in addition to distinct differences between ESBB and MPB ecology and different options for active management of ESBB and MPB. A majority of ESBB outbreaks in Europe occur in spruce forests managed for timber production and control of ESBB is a high management priority. Moreover, the propensity of ESBB to attack recently downed trees motivates the sanitary removal of windfelled trees to prevent beetle colonization and population buildup (Mezei et al., 2017; Stadelmann et al., 2013). In contrast, MPB is largely restricted to attacking standing live trees, and a majority of MPB outbreaks occur in unmanaged forests and wilderness areas, where suppression of native insects is often not the intent or objective of management (Fettig et al., 2014b). In managed forests of North America, however, responses including targeted harvesting and prescribed fire are being used to increase stand resilience to multiple disturbances including MPB (Knapp et al., 2021; "Mountain pine beetle in Alberta – Strategy," 2021).

4.2. Management implications

We found that a majority of publications were focused on the investigation of ecological patterns and processes of bark beetle outbreak dynamics in a changing climate rather than on future management planning. As indicated previously, such a tendency was more obvious in MPB than in ESBB. Even though we identified a subset of publications formulating management recommendations, they were often exploratory, lacked experimental studies testing various strategies or were generated as by-products of research with a different focus.

There was general consensus about the importance of vegetation management-based measures in both ESBB and MPB that aim to transform forest stands and landscapes to increase structural and species heterogeneity, and thereby reducing vulnerability and increasing resilience and adaptive capacity (Bentz et al., 2005; Dhar et al., 2016; Dobor et al., 2020b; Dymond et al., 2014; Halofsky and Peterson, 2016; Honkaniemi et al., 2020). Importance of thus oriented management is highlighted by its adherence to climate change adaptation objectives and that it addresses a broader range of risks, extending beyond bark beetles (Hessburg et al., 2019; Jactel et al., 2009; Seidl et al., 2016b). Still, a consistent framework for the use of vegetation management aimed at reducing susceptibility to bark beetle outbreaks amplified by climate change is yet to be formulated. We identified several important knowledge gaps in this regard, including: 1) potential conflict between vegetation management aimed at outbreak prevention (i.e., diversifying forest species and structure) and forest productivity (i.e., replacing profitable but vulnerable tree species with less vulnerable species that may generate lower timber profit), 2) interaction of vegetation management (such as rotation length reduction and promotion of non-host species) with direct measures for bark beetle control (such as trapping and sanitation logging), 3) issues related to scaling between stand- and landscape-oriented vegetation management, and 4) uncertainty in climate change projections and the impact of increasing climate variability on the interaction among vegetation (including effects on host tree vigour and host availability), bark beetles, and their community associates. Our literature search suggests that some progress has been made in understanding the direct effects of changing climate on bark beetle population success, although the other issues have not been sufficiently addressed in the scientific literature and may represent key limitations to the transition to new management systems.

The situation was less clear in the case of measures aimed at direct control of bark beetles, which particularly concerns ESBB. As outbreaks increase in size and severity and warming boosts bark beetle populations, these conditions raise concerns about the efficacy of control measures such as massive beetle trapping and large-scale salvaging of windfelled trees. The information identified in the reviewed papers, however, is rather incomplete in this regard. While some studies based on mechanistic ecosystem models demonstrated a declining performance of such measures under a warming climate (e.g. Dobor et al., 2020a, 2020b, 2019), empirical studies are scarce and limited in clear management recommendations (e.g., Marini et al., 2017). Although there are studies on the performance of salvage and sanitation logging, and beetle trapping conducted under past climate (i.e. not considering climate change-modified ecosystem dynamics), their conclusions are ambiguous and transferability of these findings to new conditions is questionable (Faccoli and Stergulc, 2008; Holuša et al., 2017; Leverkus et al., 2020; Mezei et al., 2017; Stadelmann et al., 2013).

We note, however, that some changes in outbreak management strategies have been recently adopted in both continents. In Europe, for example, the use of pheromone traps for large-scale population control has been abandoned in many countries, mainly because of poor cost-benefit ratios. The traps are now being predominantly used for general monitoring of bark beetle populations (e.g. Galko et al., 2016). The traditional practice of high-intensity salvage and sanitation logging has been revisited in some countries, aiming to better balance multiple objectives such as the prevention of secondary disturbance from bark beetles, dead wood retention for biodiversity reasons, and economic profit (Augustynczik et al., 2021; Leverkus et al., 2020). In the USA, direct control using semiochemicals is an increasingly important tool in monitoring and suppression of MPB populations (Progar et al., 2014;

Seybold et al., 2018). While the adopted changes on both continents highlight progress in management of ESSB and MPB, they in large part represent adjustments of existing practices rather than full transition to new management systems (Hlásny et al., 2021a; Leverkus et al., 2021).

Although the studies reviewed in this synthesis provide pathways for action, significant knowledge gaps remain when it comes to on-the-ground implementation into forest management guidelines. We note, however, that there is a large body of scientific literature on managing forests under intensified disturbance regimes (in a broad sense) and improving management and policies accordingly, which were not included in our literature search (e.g. Hessburg et al., 2019; Leverkus et al., 2021; Messier et al., 2019; Timberlake et al., 2020). Additionally, tools for incorporating climate change adaptation into forest management are becoming increasingly available ("Climate Change Resource Center. [online]," n.d., "Forest Change adaptation tools. [online]," 2020; Jandl et al., 2019; Sousa-Silva et al., 2018; Swanston et al., 2016; Tkacz et al., 2011), although specific strategies for bark beetle management are not included. As bark beetle outbreaks are often considered the most important disturbance agent in coniferous forests of Europe and North America, it is increasingly important to include their impacts in the broader framework of relevant literature and to evaluate implications for management and policy-making from a more comprehensive perspective. As forest and climate conditions change, tools and tactics for managing ESBB and MPB will need to evolve and adapt, and their application must account for the overall increase in forest susceptibility, emerging social-ecological contexts, resource availability, and market conditions (Hlásny et al. 2021a).

4.3. Policy implications

Our review highlights the cultural, institutional, and personal barriers that separate scientists and policy makers, which are recognized across multiple disciplines (Cvitanovic et al., 2015; Guston, 2001; Rose, 2015). In the case of ESBB, for example, key strategic documents such as the EU Forest Strategy and the EU Adaptation Strategy were not mentioned at all although they address, directly or indirectly, reducing forest damage and promoting resilience to natural disturbances. Due to the increasing pressure on policy-makers to address the intensifying disturbances in Europe, several Member States requested in 2018 a report that summarized the current understanding of bark beetle outbreak dynamics and management recommendations for use in formulating future EU and national forestry policies (Hlásny et al., 2019). While a good first step, this request likely reflects the chronic lack of knowledge transfer between forest research and forest management policies identified in our review. Stakeholder and community engagement and communication are key to successful implementation of proactive land management (Halofsky et al., 2018a; Hessburg et al., 2019), as highlighted in a similar case described by Siders (2019) wherein activity fragmentation, and lack of consensus and debate constrained adaptive capacity research to inform adaptation practice.

Much of the integration – both in Europe and North America has been focused on fine tuning existing practices and advancing policy that was in place prior to recent outbreaks, rather than providing tools for longer-term forest adaptation and resilience focused specifically on novel outbreak dynamics (Abrams et al., 2018; Halofsky and Peterson, 2016). Moreover, Abrams et al. (2018) found that no bills introduced into the US Congress mentioned the link between MPB and climate change despite evidence in the scientific literature. By contrast, a direct link between MPB outbreaks and increased wildland fire risk, which is less supported or straightforward in the scientific literature, appeared in a majority of the bills that were analyzed. Overall, their analyses suggest little evidence of a legislative response to recent MPB outbreaks (Abrams et al. 2018), a situation that is similar to policy responses to bark beetle outbreaks in Canada and Europe (e.g. Keskitalo et al., 2016; Nelson, 2007). Adaptation of existing policies that address emerging patterns of climate-induced environmental change, including intensifying bark beetle outbreaks, appears to be limited globally. A challenge for forest agencies is to build organizational capacity to address the long-term and complex issues that affect multiple resources, and allocating adequate resources for research that connects bark beetle outbreak dynamics and adaptive management is a critical part of this need (Cottrell et al., 2020).

One option for alleviating this fragmentation is for publishers to proactively request that bark beetle research is placed in the context of relevant forest management and policy. Novel concepts such as the boundary spanning approach (Bednarek et al., 2018; Posner and Cvitanovic, 2019) should also be increasingly exploited to further accelerate the pace of knowledge transfer. A potentially important initiative in Europe is the establishment of a European Risk Facility, which is gaining increasing political support (European Forest Institute and Forest Europe Liaison Unit Bratislava, 2019; Schuck et al., 2015). This initiative strives to promote a science-policy dialogue in the field of forest disturbance management and strengthen the collaboration in the pan-European level, including scientists, policy- and decision-makers. In US and Canadian forest agencies, science-management partnerships have developed vulnerability assessments and identified adaptation options for integration into climate-informed forest planning and management (Halofsky et al., 2018a, 2018b).

5. Conclusions

We found that studies on ESBB and MPB have increased in the past two decades, likely in response to the increasing rate of climate change-induced disturbances and a cascade of related social and ecological impacts. Many studies were focused on direct impacts of climate change on insect population outbreak dynamics and changes in distribution ranges, contributing to a mechanistic knowledge base for predicting future impacts. Only a small number of studies, however, were specifically aimed at informing novel forest management and policies required for responding to the emergent natural dynamics. While there is a broad consensus on the importance of vegetation management in responding to ESBB and MPB outbreaks amplified by climate change, strategies on how to embed these tactics into the broader agenda of climate change adaptation in forest agencies differ between the two continents and largely remain unresolved. We conclude that research on bark beetle management under climate change has received inadequate attention and it lags behind observed and foreseen global-scale impacts. Applied, targeted, and systematic research that integrates and evaluates forest management strategies aimed at novel bark beetle outbreaks is needed to advance policies that encompass social, economic, and ecological aspects in a consistent and comprehensive manner.

CRediT authorship contribution statement

T. Hlásny: Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Supervision. **S. Zimová:** Investigation, Formal analysis. **B. Bentz:** Writing – original draft, Writing – review & editing.

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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Appendix A. Supplementary material

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