Evaluation of insect pest occurrence in areas of calamitous mortality of Scots pine

Jan Liška, Miloš Knížek, Adam Vele*

Forestry & Game Management Research Institute, Strnady 136, CZ – 252 02 Jíloviště, Czech Republic

Abstract

Pinus sylvestris is an important production tree. In recent years, there has been a sharp increase in the mortality of pine trees due to insect pests. It is obvious that some pests profit from climatic changes, increase their aggressiveness and spread to new localities. The study aimed to investigate the spectrum of more abundant insect pest species in pine plantations of Czechia. The occurrence of species and intensity of their infestation were studied at 77 localities situated in six regions. Any abundant foliophagous insect species were noticed. Bark beetles and wood-boring insects were found to be prevalent. Namely, *Ips acuminatus*, *Ips sexdentatus*, *Phaenops cyanea* and *Sirex noctilio* seem to be the most dangerous. These species are now better competitors than species previously considered as main pests. Their aggressiveness, expansion to new areas and interspecies co-occurrence are alarming. Due to the advancing climate change, pine mortality due to bark beetles and wood-boring pests will probably continue to increase.

Key words: *Pinus sylvestris*; biotic stressors; Coleoptera; Hymenoptera; Lepidoptera; central Europe

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1. Introduction

Scots pine (*Pinus sylvestris*) has a wide range of applications. Among others, it is used as construction timber and as raw material for pulpwood and paper. Therefore, from the mid-19th century, it began to be artificially cultivated on plantations in central Europe, which greatly expanded its occurrence even outside the original poor soil (Ruotsalainen & Persson 2013). The current proportion of pine trees in the forests of Czechia is 16.1%, while in the recommended composition of forests, their representation is higher by 0.7% (MZe 2020). This remains the recommended proportion despite continuing discussions about the negative impact of coniferous plantations on other components of the ecosystem and proposals for their transformation into deciduous forests (Chiarucci & de Dominicis 1995; Augusto et al. 2002; Poštulka & Bláha 2008; Hartmann et al. 2010). The decline of pine forests may not be the result of a targeted human effort but a consequence of natural processes. Like spruces, pine plantations are susceptible to damage by factors both abiotic (wind, drought, snow) and biotic (herbivorous, bark- and wood-destroying insects). These factors are interconnected by mutually reinforcing relationships (Dobbertin et al. 2007; Sierota et al. 2019).

Climate change and insufficient implementation of pest management can be identified as the main causes of the increase in damage of pine populations (Lindner et al. 2010; Lubojacký et al. 2019). Climate change facilitates the development of pests in several ways. It weakens trees by a lack of rainfall, higher temperatures and changes in the nutrient cycles. At the same time, it accelerates the development of insects and allows the spread of non-native species (see Lindner et al. 2008). A shortening of the gradation cycles of herbivorous insects can be expected in the future, but it has the “advantage” of predictable population collapse after a few years (Berryman 1996; Haynes et al. 2014). However, this is not the case of bark beetles (Biedermann et al. 2019), which is why we can expect the problem of bark beetles and wood-boring insects to worsen in the future. This prediction is corroborated by data comparisons, which show that the damage caused by bark beetles has been gradually increasing in recent years. For example, in 2009, bark beetles caused damage of about 10,000 m³, while in 2019, damages exceeded 80,000 m³ of pine wood (Knížek 2010; Knížek & Liška 2020). Furthermore, these official figures are underestimated. Forest managers often do not want to draw attention to their inaction in forest protection and provide distorted statistical data.

*Corresponding author. Adam Vele, e-mail: adam.vele@centrum.cz, phone: +420 737 309 406

Experts warned that climate change would cause a decline of pine forests more than a decade ago (Dobbertin et al. 2005; Lindner et al. 2008). These expectations have been fulfilled, and in recent years, extensive drying of pine trees started to be observed in Czechia (e.g. Knízek & Liška 2019, 2020).

Widespread mortality of trees associated with the formation of large clearings is undesirable from ecological and socio-economic points of view (Andréassian 2004; Weis et al. 2006; Lindner et al. 2008; Schelker et al. 2014). Rather than creating clearings, it is more advantageous to gradually increase the admixtures of other woody plants (Souček et al. 2018). Therefore, it is necessary to reduce the impact of harmful biotic agents. Appropriate forest protection methods can be planned and applied only with a detailed knowledge of pest agents along with a prognosis of their development (Southwood 1978). For this reason, we tried to assess the current condition of major insect pests in a pine forests and determine the pest distribution in Czechia.

2. Material and methods

The occurrence of beetles was monitored by observing their galleries on dead and dying trees, which were determined by the colour change of their needles. Only trees in a group of at least five dying trees were included in our study. On all trees (max. 15 at one locality), the bark in the trunk part was peeled off at three sections, with each section comprising an area of about 1,000 cm². To determine pest presence, galleries, halls or entrances were used. Galleries or entrances in the crown sections of standing trees were determined using high-brightness binoculars. The intensity of infestation was recorded on a scale of 0 (no infestation), 1 – weak (a rare occurrence), 2 – medium (only a few galleries on the peeled plot) and 3 – strong (galleries covering more than 75% of the bark area). In the case of horntails (Siricidae), the number of boreholes was similarly evaluated on a scale of 0 – no hole, 1 – one hole, 2 – two to five holes and 3 – more than five holes. We also looked for the presence of needles damaged by foliophagous insects on the investigated trees as well as on the surrounding ten trees. Observations were made separately at the pole timber stands (23

localities) and mature stands (54 localities). The studied areas were located in central, northern, eastern, western and southern Bohemia, respectively, and western and southern Moravia. Approximately one-third of the trees were monitored in autumn and winter of 2019, the rest in spring and autumn of 2020. We used unconstrained principal correspondence analysis (PCA) for visualisation of species co-occurrence. Both ordination analyses were performed in Canoco 5 (Šmilauer & Lepš 2014). The differences in the abundance of species between forest stands were evaluated by Mann–Whitney tests in Statistica 10.

3. Results

A total of 10 taxa with more than two occurrences were recorded (Table 1). All of these species belonged to wood-boring or bark insects. No strong damage caused by a foliophagous insect was observed. *Ips acuminatus*, *Phaenops cyanea*, *Sirex noctilio* and *Tomicus piniperda* were found in all the examined regions. *I. acuminatus* was the species that most often manifested a strong infestation in both forest types. It was detected in all of pole timber stands and majority of mature stands. It was present mainly in the strong intensity of the attack. In both forest types, it often occurred together with *Ips sexdentatus* (Fig. 1). This species was found only in a few localities, but mainly in the strong intensity of the infestation. The occurrence of both mentioned species in the mature forests was negatively correlated with the occurrence of two other species of bark beetles, which, in contrast, often occur together: *Tomicus minor* and *T. piniperda*. We found *T. piniperda* in 61% of mature stands, most often only in weak or medium infestation. *T. minor* occurred in only 17% of localities, also in weak and medium infestation intensities, hence it was not responsible for any strong attacks. Together with these, two other beetle species, namely *P. cyanea* and *Monochamus galloprovincialis*, occurred. *P. cyanea* was found in 70% of pole timber stands, where the infestation intensities were comparable, and in almost all the studied mature stands, where medium infestation intensities were prevalent. It was significantly more numerous in mature forests ($p = 0.04$).

Table 1. Occurrence and percentage frequency of infestation intensity (0–3) of 10 monitored species. CB – central Bohemia, EB – eastern Bohemia, NEB – north-eastern Bohemia, SM – southern Moravia, WB – western Bohemia, WM – western Moravia.

	Regional species occurrence						Intensity of infestation							
	SM	CB	NEB	EB	WB	WM	Mature stands				Pole timber stands			
							0	1	2	3	0	1	2	3
<i>Chalcophora mariana</i>		x	x				85.2	13.0	1.9	0	95.7	4.3	0	0
<i>Ips acuminatus</i>	x	x	x	x	x	x	3.7	11.1	25.9	59.3	0	30.4	26.1	43.5
<i>Ips sexdentatus</i>	x	x					92.6	1.9	1.9	3.7	82.6	0	4.3	13
<i>Monochamus galloprovincialis</i>		x	x	x			92.6	7.4	0	0	100	0.0	0	0
<i>Orthotomicus longicollis</i>		x					96.3	1.9	0	1.9	100	0.0	0	0
<i>Phaenops cyanea</i>	x	x	x	x	x	x	5.6	24.1	40.7	29.6	30.4	21.7	26.1	21.7
<i>Pissodes</i> spp.		x		x			88.8	1.9	5.6	3.7	82.6	17.4	0	0
<i>Sirex noctilio</i>	x	x	x	x	x	x	20.4	25.9	48.1	5.6	26.1	43.5	30.4	0
<i>Tomicus minor</i>		x	x	x			83.3	9.3	7.4	0	91.3	4.3	4.3	0
<i>Tomicus piniperda</i>	x	x	x	x	x	x	38.9	51.9	7.4	1.9	43.5	47.8	8.7	0

Fig. 1. Unconstrained PCA ordination results for the co-occurrence of 10 species in (a) mature stands and (b) pole timber stands. IA – *Ips acuminatus*, TM – *Tomicus minor*, SN – *Sirex noctilio*, PC – *Phaenops cyanea*, IS – *Ips sexdentatus*, TP – *Tomicus piniperda*, PP – *Pissodes* spp., CHM – *Chalcophora mariana*, MG – *Monochamus galloprovincialis*, OL – *Orthotomicus longicollis*.

Monochamus galloprovincialis was detected in only 7.5% of mature pine forest stands and only in the weak infestation intensity. Also recorded was a mostly weak attack of *Chalcophora mariana*. Representatives of *Pissodes* were found more often in pole timber stands and only in weak infestation. The only representative of the Hymenoptera was *S. noctilio*. It was recorded in 80% of mature stands and in 74% of pole stands, and was more numerous in mature stands ($p = 0.02$). In the mature stands, medium infestation prevailed, while in the pole timber stands, weak infestation was prevalent. Co-occurrence was recorded only with *Pissodes* in mature stands and with *T. piniperda* and *P. cyanea* in pole timber stages.

Other species were detected only in rare occurrences and in low abundances. However, the strong occurrence of the invasive bark beetle *Gnathotrichus materiarius* near Kardašova Řečice (southern Bohemia) is worth mentioning.

4. Discussion

Ips acuminatus was identified as the most common species with strong infestation. A similar incidence in both tree age categories is consistent with the findings of other studies. For example, Siittonen (2014) found it on trees with a diameter of 8–49 cm. During outbreaks, *I. acuminatus* can attack even stronger trees otherwise not prone to infestation (Colombari et al. 2013). This species has long been considered a typically secondary pest with a limited effect on tree mortality (Siittonen 2014). At the beginning of the millennium, it began to grow in aggression. Its harmful effects increase not only in central

Europe but also elsewhere (Foit 2007; Grégoire & Evans 2007; Wermelinger et al. 2008; Colombari et al. 2013; Siittonen 2014). In the conditions of central Europe, *I. acuminatus* is now one of the first colonizers of weakened trees (Foit & Čermák 2014).

The change in the harmfulness of *I. acuminatus* can be caused by higher spring temperatures (Chinellato et al. 2014). We observed it mostly in a strong infestation. In this case, the galleries can occupy more than 90% of the bark area in crowns (Siittonen 2014). With respect to population, the recorded incidence of *I. acuminatus* appears as outbreaks. Outbreaks are characteristic by the occurrence of infested trees in foci, while in periods of low abundance, the distances between infested trees are higher (Colombari et al. 2013). The number of killed trees in the studied areas reflects the state of the population well, as the numbers of infested trees in one plot do not increase year-on-year because the beetles fly to new areas up to hundreds of meters away in spring. It is precisely this first generation of beetles that causes the greatest damage (Colombari et al. 2013). In the examined areas, *I. acuminatus* often co-occurred together with *I. sexdentatus*. Both species have much in common: by means of aggregation pheromones, they undertake mass attack, and they are associated with *Ambrosiella* species that are phylogenetically related to *Ophiostoma*, which trigger hypersensitive response in plants. Both these bark beetle species use mycangia for fungal transport (Kirisits 2007; Lieutier 2007). The occurrence of *I. sexdentatus* in the studied areas was relatively rare. Historically, its presence is known especially in south-eastern Moravia (Pfeffer 1955), which corresponds with our results. Our unique findings of this species in Bohemia confirm its

expansion (Knížek 2020). The strong intensity of the infestation together with the observed spread in Bohemia ranks both species among the taxa that require attention.

Tomicus minor is also a mycophagous species, but this beetle does not have mycangia, and its mycobionts differ considerably (Francke-Grosman 1963; Kirisits 2007). This could partly explain the negative dependence on *I. acuminatus* and *I. sexdentatus* that was found in the studied mature forest stands. *Ophiostoma canum*, which is primarily used by *T. minor*, develops relatively slowly and does not benefit from higher temperatures as much as other fungi (Solheim et al. 2001; Kirisits 2007). Species of *Ips* can fly over longer distances (Jactel & Gaillard 1991; Bouhot et al. 1988; Lieutier & Faccoli 2015) and thus better occupy freshly weakened trees. *T. minor* is probably not able to compete sufficiently with the above species. The existing competition among *T. minor* and species of *Ips* is obvious. A comparison of habitat parameters further shows that *T. minor* competes partially with *I. sexdentatus* and strongly with *I. acuminatus* (Sauvard 2007).

The positive correlation found between *T. minor* and *T. piniperda* is not surprising. These species commonly occur together on one tree, as their habitat demands do not overlap (Sauvard 2007). *T. minor* is considered to be the secondary colonizer of the subsequent *T. piniperda* (Långström & Hellqvist 1993). Neither of these species showed strong aggression. This confirms the assumption that species aggressiveness also depends on the virulence of associated blue-stain fungi, and the fungi used by *Tomicus* have low virulence (Krokene & Solheim 1998; Solheim et al. 2001).

Along with *Tomicus* species, also *P. cyanea* was very numerous and recorded in all regions. It occurred in majority of mature forest stands, where the intensity of infestation was most often medium, and in more than two thirds of the studied pole timber stands. It is a common aggressive species, which can successfully attack older and only slightly weakened pines (Wermelinger et al. 2008; Sowińska et al. 2000; Foit & Čermák 2014). Research conducted in German forests has confirmed that the species responds positively to global warming (Wulf 1995). It is one of the most common pests in Switzerland, where it periodically causes significant pine damages (Dobbertin et al. 2007). During pest monitoring in the second half of the 1980s, Kolk (1992) recorded the presence of *P. cyanea* on more than 20% of trees and predicted an abundance increase in damaged and weakened trees. From our results and the results of the above studies, it is clear that the abundance of this beetle indeed increases. Infested trees show a decrease in xylem flow, reduced content of wood moisture and increased heartwood/sapwood ratio (Apel et al. 2000), thus enabling a successful invasion of other species (Lindner et al. 2008).

The only recorded species in our study not belonging to the beetles is *S. noctilio*. It was detected in approxi-

mately three quarters of the studied localities, most often in a weak and medium degree of infestation. It occurred independently from all the other more abundant species. Co-occurrence was recorded with *Pissodes* spp. in mature stands and with *T. piniperda* and *P. cyanea* in pole timber stands. The co-occurrence of *S. noctilio* with *T. piniperda* and *Pissodes* is described in a Swiss study published by Wermelinger et al. (2008). The same authors state that the links to other insect species are weak. The independent occurrence of *S. noctilio* from other species can be explained by its ability to attack almost healthy trees and partly also by the competition between fungal associates of *S. noctilio* and bark beetles (Bordeaux & Dean 2012; Ryan et al. 2012). *S. noctilio* is a major pest in the Southern Hemisphere, where it was introduced, but until recently it was considered an economically insignificant species in Europe (see Hurley et al. 2007; Wermelinger et al. 2008). It benefits from the weakening of pines by drought, as well as their partial regeneration after short rains, which enhances the development of larvae (Madden 1988). The infestation of trees is characterized by a markedly focal character, while the area of foci is constantly increasing (Corley et al. 2007). This wasp has eruptive population dynamics (Madden 1988; Corley & Villacide 2012). Due to its relatively abundant occurrence in our studied areas, it can be concluded that *S. noctilio* is now in the outbreak phase and owing to its excellent flight abilities, we expect rapid spread to new localities.

5. Conclusion

In recent years, there has been an increase in temperatures and a decrease in the amount of precipitation during the growing season (Hanel et al. 2011). Higher temperatures are associated with increased stress on trees and shorter development time of economically undesirable organisms, thereby prolonging the reproductive season and increasing voltinism. Shorter development times also reduce the exposure time of larvae to their natural enemies (Chinellato et al. 2014). The results of this study confirm the significant influence of insect pests, especially *I. amitinus*, *I. sexdentatus*, *P. cyanea* and *S. noctilio*. What is alarming is the abundance and co-occurrence of aggressive species or their expansion to new areas. Due to the advancing climate change, pine mortality due to bark beetles and wood-boring pests will probably continue to increase. Therefore, pest management should become a necessary priority in pine plantations in the face of climate change.

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References

- Andréassian, V., 2004: Waters and forests: from historical controversy to scientific debate. *Journal of Hydrology*, 291:1–27.
- Apel, K. H., Katzel, R., Luttschwager, D., Schmitz, H., Schutz, S., 2000: Investigations on possible mechanisms of the host finding by *Phaenops cyanea* F. (Col., Buprestidae). *Mitteilungen der Deutschen Gesellschaft für allgemeine und angewandte Entomologie*, 12:23–27.
- Augusto, L., Ranger, J., Binkley, D., Rothe, A., 2002: Impact of several common tree species of European temperate forests on soil fertility. *Annals of Forest Science*, 59:233–253.
- Berryman, A. A., 1996: What causes population cycles of forest Lepidoptera? *Trends in Ecology & Evolution*, 11:28–32.
- Biedermann, P. H. W., Müller, J., Grégoire, J.-C., Gruppe, A., Hagge, J., Hammerbacher, A. et al., 2019: Bark Beetle Population Dynamics in the Anthropocene: Challenges and Solutions. *Trends in Ecology & Evolution*, 34:914–924.
- Bordeaux, J. M., Dean, J. F. D., 2012: Susceptibility and Response of Pines to *Sirex noctilio*. In: Slippers, B., de Groot, P., Wingfield, M. (eds.): *The Sirex Woodwasp And Its Fungal Symbiont*. Springer Netherlands, Dordrecht, p. 31–50.
- Bouhot, L., Lieutier, F., Debouzie, D., 1988: Spatial and temporal distribution of attacks by *Tomicus piniperda* L. and *Ips sexdentatus* Boern. (Col., Scolytidae) on *Pinus sylvestris*. *Journal of Applied Entomology*, 106:356–371.
- Bruzzzone, O. A., Villacide, J. M., Bernstein, C., Corley, J. C., 2009: Flight variability in the woodwasp *Sirex noctilio* (Hymenoptera: Siricidae). *Journal of Experimental Biology*, 212:731–737.
- Colombiari, F., Schroeder, M. L., Battisti, A., Faccoli, M., 2013: Spatio-temporal dynamics of an *Ips acuminatus* outbreak and implications for management. *Agricultural and Forest Entomology*, 15:34–42.
- Corley, J. C., Villacide, J. M., 2012: Population Dynamics of *Sirex noctilio*: Influence of Diapause, Spatial Aggregation and Flight Potential on Outbreaks and Spread. In: Slippers, B., de Groot, P., Wingfield, M. (eds.): *The Sirex Woodwasp And Its Fungal Symbiont*. Springer Netherlands, Dordrecht, p. 51–64.
- Corley, J. C., Villacide, J. M., Bruzzzone, O. A., 2007: Spatial dynamics of a *Sirex noctilio* woodwasp population within a pine plantation in Patagonia, Argentina. *Entomologia Experimentalis et Applicata*, 125:231–236.
- Dobbertin, M., Mayer, P., Wohlgemuth, T., Feldmeyer-Christe, E., Graf, U., Zimmermann, N. E. et al., 2005: The Decline of *Pinus sylvestris* L. Forests in the Swiss Rhone Valley – a Result of Drought Stress? *Phyton*, 45:153–156.
- Dobbertin, M., Wermelinger, B., Bigler, C., Bürgi, M., Carron, M., Forster, B. et al., 2007: Linking Increasing Drought Stress to Scots Pine Mortality and Bark Beetle Infestations. *The Scientific World Journal*, 7:231–239.
- Foit, J., 2007: The fauna of cambioxylophagous insects on Scots pine trees declined after spells of drought in 2003. *Journal of Forest Science*, 53:334–339.
- Foit, J., Čermák, V., 2014: Colonization of disturbed Scots pine trees by bark- and wood-boring beetles. *Agricultural and Forest Entomology*, 16:184–195.
- Francke-Grosmann, H., 1963: Some New Aspects in Forest Entomology. *Annual Review of Entomology*, 8:415–438.
- Grégoire, J. C., Evans, H. F., 2007: Damage and control of BAWBILT organisms an overview. In: Lieutier, F., Day, K. R., Battisti, A., Grégoire, J.-C., Evans, H. F. (eds.): *Bark And Wood Boring Insects in Living Trees in Europe, A Synthesis*. Springer, Dordrecht, p. 19–37.
- Hanel, M., Kašpárek, L., Mrkvíčková, M., 2011: Odhad dopadů klimatické změny na hydrologickou bilanci v ČR a možná adaptační opatření. Praha, Výzkumný ústav vodohospodářský T. G. Masaryka, 108 p.
- Hartmann, H., Daoust, G., Bigué, B., 2010: Negative or positive effects of plantation and intensive forestry on biodiversity: A matter of scale and perspective. *The Forestry Chronicle*, 86:354–364.
- Haynes, K. J., Allstadt, A. J., Klimetzek, D., 2014: Forest defoliator outbreaks under climate change: effects on the frequency and severity of outbreaks of five pine insect pests. *Global Change Biology*, 20:2004–2018.
- Hurley, B. P., Slippers, B., Wingfield, M. J., 2007: A comparison of control results for the alien invasive woodwasp, *Sirex noctilio*, in the southern hemisphere. *Agricultural and Forest Entomology*, 9:159–171.
- Chiarucci, A., De Dominicis, V., 1995: Effects of Pine Plantations on Ultramafic Vegetation of Central Italy. *Israel Journal of Plant Sciences*, 43:7–20.
- Chinellato, F., Faccoli, M., Finozzi, V., Battisti, A., 2014: Better today but worse tomorrow: how warm summers affect breeding performance of a Scots pine pest. *Agrochimica Pisa*, 58:133–145.
- Jactel, H., Gaillard, J., 1991: A preliminary study of the dispersal potential of *Ips sexdentatus* (Boern) (Col., Scolytidae) with an automatically recording flight mill. *Journal of Applied Entomology*, 112:138–145.
- Kirisits, T., 2007: Fungal associates of European bark beetles with special emphasis on the Ophiostomatoid fungi. In: Lieutier, F., Day, K. R., Battisti, A., Grégoire, J.-C., Evans, H. F. (eds.): *Bark And Wood Boring Insects in Living Trees in Europe, A Synthesis*. Springer, Dordrecht, p. 181–236.
- Knížek, M., 2020: Lýkožrout borový (*Ips sexdentatus*). *Lesnická práce*, 99:4, příloha.

- Knížek, M., Liška J. (eds.), 2019: Výskyt lesních škodlivých činitelů v roce 2018 a jejich očekávaný stav v roce 2019. Strnady, Výzkumný ústav lesního hospodářství a myslivosti, Zpravodaj ochrany lesa. Supplementum, 74 p.
- Knížek, M., Liška, J. (eds.), 2020: Výskyt lesních škodlivých činitelů v roce 2019 a jejich očekávaný stav v roce 2020. Strnady, Výzkumný ústav lesního hospodářství a myslivosti, Zpravodaj ochrany lesa. Supplementum, 76 p.
- Knížek, M. (ed.), 2010: Výskyt lesních škodlivých činitelů v roce 2009 a jejich očekávaný stav v roce 2010. Zpravodaj ochrany lesa. Supplementum, 70 p.
- Kolk, A., 1992: Impact of bark beetles on forest management in Poland in 1981–1990. *Journal of Applied Entomology*, 114:425–430.
- Krokene, P., Solheim, H., 1998: Pathogenicity of Four Blue-Stain Fungi Associated with Aggressive and Nonaggressive Bark Beetles. *Phytopathology*, 88:39–44.
- Långström, B., Hellqvist, C., 1993: Induced and spontaneous attacks by pine shoot beetles on young Scots pine trees: tree mortality and beetle performance. *Journal of Applied Entomology*, 115:25–36.
- Lieutier, F., 2007: Host resistance to bark beetles and its variations. In: Lieutier, F., Day, K. R., Battisti, A., Grégoire, J.-C., Evans, H. F. (eds.): *Bark And Wood Boring Insects in Living Trees in Europe, A Synthesis*. Springer, Dordrecht, p. 135–180.
- Lieutier, F., Faccoli, M., 2015: The Genus *Tomicus*. In: Vega, F. E., Hofstetter, R. V. (eds): *Bark Beetles: Biology And Ecology Of Native And Invasive Species*. Elsevier, London, p. 371–425.
- Lindner, M., Garcia-Gonzalo, J., Kolström, M., Green, T., Reguera, R., Maroschek, M. et al., 2008: Impacts of climate change on European forests and options for adaptation. Report to the European Commission Directorate-General for Agriculture and Rural Development, 173 p.
- Lindner, M., Maroschek, M., Netherer, S., Kremer, A., Barbati, A., Garcia-Gonzalo, J. et al., 2010: Climate change impacts, adaptive capacity, and vulnerability of European forest ecosystems. *Forest Ecology and Management*, 259:698–709.
- Lubojacký, L., Knížek, M., Zahradník, P., 2019: Podkořní hmyz. In: Knížek M., Liška J. (eds.): Výskyt lesních škodlivých činitelů v roce 2018 a jejich očekávaný stav v roce 2019. Strnady, Výzkumný ústav lesního hospodářství a myslivosti, Zpravodaj ochrany lesa. Supplementum 2019, p. 33–40.
- Madden, J. L., 1988: *Sirex* in Australasia. In: Berryman A. A. (ed.): *Dynamics of forest insect populations. Patterns, causes, implications*. Plenum Press, New York, p. 407–429.
- MZe, 2019: Zpráva o stavu lesa a lesního hospodářství České republiky v roce 2019. MZe, Praha, 128 p.
- Pfeffer, A., 1955: Fauna ČSR. Kůrovci – Scolytidae (Řád: Brouci – Coleoptera). Praha, Nakladatelství Československé akademie věd, p.121–123.
- Poštulka, Z., Bláha, J., 2008. Borové monokultury. Hnutí Duha. Brno.
- Ruotsalainen, S., Persson, T., 2013: Scots pine – *Pinus sylvestris*. In: Mullin, T. J., Lee, S. J. (eds.): *Best practices for tree breeding in Europe*. Skogforsk (The Forestry Research Institute of Sweden), Uppsala, p. 49–63.
- Ryan, K., de Groot, P., Smith, S. M., 2012: Evidence of interaction between *Sirex noctilio* and other species inhabiting the bole of *Pinus*. *Agricultural and Forest Entomology*, 14:187–195.
- Sauvard, D., 2007: General Biology of Bark Beetles. In: Lieutier, F., Day, K. R., Battisti, A., Grégoire, J.-C., Evans, H. F. (eds.): *Bark And Wood Boring Insects in Living Trees in Europe, A Synthesis*. Springer, Dordrecht, p. 63–88.
- Sierota, Z., Grodzki, W., Szczepkowski, A., 2019: Abiotic and Biotic Disturbances Affecting Forest Health in Poland over the Past 30 Years: Impacts of Climate and Forest Management. *Forests*, 10:75.
- Solheim, H., Krokene, P., Långström, B., 2001. Effects of growth and virulence of associated blue-stain fungi on host colonization behaviour of the pine shoot beetles *Tomicus minor* and *T. piniperda*. *Plant Pathology*, 50:111–116.
- Souček, J., Špulák, O., Dušek, D., 2018. Metodika přeměny a přestavby borových monokultur na stanovištích přirozených smíšených porostů: certifikovaná metodika, Lesnický průvodce. Strnady, Výzkumný ústav lesního hospodářství a myslivosti, 35 p.
- Southwood, T. R. E., 1978: *Ecological Methods*. Dordrecht, Springer Netherlands, 201 p.
- Sowińska, A., Kolk, A., Wolski, R., Janiszewski, W., 2000: Wyniki badań nad nowymi metodami prognozowania i zwalczania przypłaszczka granatka *Phaenops cyanea* (F.) (Coleoptera, Buprestidae). *Sylvan*, 9:17–32.
- Šmilauer, P., Lepš, J., 2014: *Multivariate Analysis of Ecological Data using CANOCO 5*. Cambridge, Cambridge University Press, 362 p.
- Wermelinger, B., Rigling, A., Schneider Mathis, D., Dobbertin, M., 2008: Assessing the role of bark-and wood-boring insects in the decline of Scots pine (*Pinus sylvestris*) in the Swiss Rhone valley. *Ecological Entomology*, 33:239–249.
- Wulf, A., 1995: Einfluss von Klimaänderungen auf die phytosanitäre Situation im Forst. Schriftenreihe des Bundesministeriums für Ernährung, Landwirtschaft und Forsten. *Angewandte Wissenschaft*, 442:71–79.