Clim. Past, 18, 2155–2180, 2022
https://doi.org/10.5194/cp-18-2155-2022

Climate of the Past
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EGU

Meteorological and climatological triggers of notable past and present bark beetle outbreaks in the Czech Republic

Rudolf Brázdil[1,2], **Petr Zahradník**[3], **Péter Szabó**[4,5], **Kateřina Chromá**[2], **Petr Dobrovolný**[1,2], **Lukáš Dolák**[1,2], **Miroslav Trnka**[2,6], **Jan Řehoř**[1,2], **and Silvie Suchánková**[4]

[1]Department of Geography, Faculty of Science, Masaryk University, Brno, Czech Republic
[2]Global Change Research Institute, Czech Academy of Sciences, Brno, Czech Republic
[3]Research Institute of Forestry Economics and Gamekeeping, Jíloviště, Czech Republic
[4]Department of Vegetation Ecology, Institute of Botany, Czech Academy of Sciences, Brno, Czech Republic
[5]Department of Environmental Studies, Faculty of Social Studies, Masaryk University, Brno, Czech Republic
[6]Department of Agrosystems and Bioclimatology, Mendel University in Brno, Brno, Czech Republic

Correspondence: Rudolf Brázdil (brazdil@sci.muni.cz)

Received: 10 June 2022 – Discussion started: 13 June 2022
Revised: 6 September 2022 – Accepted: 7 September 2022 – Published: 28 September 2022

Abstract. Based on documentary evidence, a chronology of bark beetle outbreaks in the Czech Republic from 1781 to 1963 CE was created, continuing from 1964 through 2021 by bark beetle salvage felling data. The spatial distribution of bark beetle events concentrates on the border mountains of Bohemia and in the northern parts of Moravia and Silesia. The temporal distribution of the most important bark beetle outbreaks is concentrated in the 1830s, 1870s, 1940s–1950s, 1980s, 1990s, 2000s, and 2010s. Each of these notable calamities was analysed in detail with respect to their spatial extent, the volume of damaged wood, and their meteorological patterns. While meteorological triggers of the largest outbreaks of the 19th century were attributed especially to the slow procession of disastrous volumes of damaged wood after large windstorm events sometimes intensified by dying trees in subsequent dry years, the recent warming with relatively stable precipitation from the 1980s moves the main meteorological and climatological triggers to more frequent warm and dry meteorological patterns, acting simultaneously in interaction with severe windstorms. The last bark beetle outbreak from 2015 was evaluated as the most disastrous disturbance to spruce forest over the territory of the Czech Republic in documented history. The paper also discusses uncertainties in bark beetle data, responses to past bark beetle events, and relationships between environment, climate, and bark beetle outbreaks.

1 Introduction

Recent warming with relatively stable precipitation totals was accompanied by important drought episodes during the 2010s at the central European scale, reflected in the appearance of severe meteorological, agricultural, and hydrological droughts (Zahradníček et al., 2015; Hoy et al., 2017, 2020; Ionita et al., 2017; Zscheischler and Fischer, 2020). One of the impacts of long drought of the 2010s across much of central Europe has been the population growth of bark beetle (especially *Ips typographus*) devastating the Norway spruce forests (e.g. Hlásny et al., 2021a, b; Jaime et al., 2022). The reason is that dry episodes with high temperatures decrease the vitality and structure of spruce, which has shallow roots; these characteristics result in less resistance to bark beetle attacks. In addition, droughts with high temperatures accelerate bark beetle evolution and increase the number of generations per breeding season (summer) to three at lower altitudes and two at higher ones (e.g. Pfeffer and Skuhravý, 1995; Jönsson et al., 2009, 2011; Netherer et al., 2019; Hlásny et al., 2021a). Besides dry and warm patterns, other meteorological disturbances also play an important role. This is especially the case after severe windstorms with large numbers of uprooted or broken trees, as bark beetles use fallen, freshly dead trees – if such wood is not processed and removed from the forest stands relatively fast – as they propagate prodigiously and then invade healthy trees, significantly increasing the damage (e.g. Temperli et al., 2013; Thom et al., 2013; Stadelmann et al., 2014).

Bark beetle outbreaks have become a serious problem for spruce forests at the European scale. For example, Schelhaas et al. (2003), quantitatively analysing the role of natural disturbances in European forests from 1950–2000, attributed 16 % of the mean annual damage (35×10^6 m^3 of wood) to biotic factors, half of which were caused by bark beetles. The most comprehensive recent study of the state of knowledge on drivers and impacts of bark beetle outbreaks in Europe comes from Hlásny et al. (2021a) with an extensive list of references. Among different aspects of bark beetle outbreaks, several papers analysed in great detail the effect of temperatures on the duration of the egg, larval, and pupal stages of the spruce bark beetle and adult maturation feeding (e.g. Annila, 1969; Wermelinger and Seifert, 1998, 1999). Besides temperatures, windstorms interact importantly with bark beetle disturbances (e.g. Temperli et al., 2013; Thom et al., 2013; Stadelmann et al., 2014), and this interaction can be amplified by climate change (e.g. Seidl and Rammer, 2017). Moreover, windstorms coupled with bark beetle outbreaks remain the most damaging agents in Norway spruce stands as shown, for example, in Slovakia (Kunca et al., 2019). Acute droughts appear to be another important driver of bark beetle infestation as shown by the example of Austria (Netherer et al., 2019), and the influence of droughts on bark beetle outbreaks will even threaten the persistence of European coniferous forests (Jaime et al., 2022). Droughts limiting soil water content contribute to tree transpiration deficit, increasing host susceptibility to bark beetle attacks (Matthews et al., 2018). Effects of summer temperatures, droughts, and windstorms on the dynamics of bark beetle outbreaks in Norway spruce forests were analysed across eight European countries by Marini et al. (2017). Great research attention concentrated also on effects of future climate change, represented by various climate scenarios, on different aspects of bark beetle occurrences focusing, for example, on Sweden (Jönsson et al., 2009), Scandinavia (Jönsson et al., 2011), Switzerland (Jakoby et al., 2019), or the Bavarian Forest National Park in Germany (Sommerfeld et al., 2020).

Information about past bark beetle occurrences is a part of Czech forestry literature (e.g. Chadt-Ševětínský, 1913; Nožička, 1957; Hošek, 1981). Some papers concentrated on focal areas of bark beetle outbreaks like the Šumava Mts after the disastrous windstorm of 26–27 October 1870 (Záloha, 1970) and during the 1870s (Jelínek, 1988), while Zatloukal (1998) analysed factors of past and present bark beetle calamities. The PHENIPS model was used to analyse the influence of future climate change on the country bark beetle distribution (Hlásny et al., 2011) and bark beetle dynamic in the Bohemian Forest (Berec et al., 2013). Lubojacký (2012) described the Czech legislation related to protection against bark beetle. Zahradník and Zahradníková (2019) assessed salvage felling caused by bark beetle and other abiotic/biotic factors for 1998–2017. Past and recent bark beetle outbreaks in the Czech Republic after 1980 CE were described, for example, by Skuhravý and Šrot (1988), Mrkva (1993), Skuhravý (2002), and Hlásny et al. (2021b).

An unprecedented bark beetle outbreak began in the Czech Republic from about 2003 (Zahradník and Zahradníková, 2019; Hlásny et al., 2021b). Two questions arise. First, how does this outbreak appear in the context of preceding bark beetle outbreaks? And second, does recent climate change completely alter the conditions of such events? We must then analyse not only the conditions of more recent events but also similar situations from the past. This is the aim of the article, covering the period from the 18th through the 21st centuries. In order to fulfil this request, the most comprehensive and unique series of bark beetle outbreaks in the Czech Republic was created for this study and used to analyse and discuss meteorological and climatological triggers accompanying the notable bark beetle outbreaks. Having in mind that these outbreaks are the result of complicated human–environment–climate interactions, this study concentrates only on one part of this interaction.

2 Data

2.1 Bark beetle data

Different data sources were used to create a bark beetle database for the territory of the former Czech Lands, i.e. now the Czech Republic (further CR). Much bark beetle information was obtained from a large project called Forest History Research (Historický průzkum lesů). It was initiated in the early 1950s by Lesprojekt in Brandýs nad Labem (recently the Forest Management Institute, Ústav pro hospodářskou úpravu lesů) (for locations of places and regions in the CR see Fig. S1 in the Supplement). A collection of detailed historical information about each forest district was contributed for the economic improvement in forests (Hošek, 1983). In total, 544 unpublished volumes continuing until the late 1980s are now kept in the Forest Management Institute archive in Brandýs nad Labem (Novotný, 2011). An example of the bark beetle information in these volumes is a report of a forester Franz Loschan from the Telč domain who recorded dry spruce trees invaded by bark beetle in the forest district Rosičky in the autumn of 1807 (unpublished source US1, p. 65). The forest officer Vinzenz Tibl on 5 September 1808 from Červené Poříčí wrote that "the bark beetle occurred in all forest districts, especially on the line Dubí in the Doupov district (a group of 16 dry trees and 45 heavily invaded) and on the line Horní Stropecko in the Kbely district (12 dry trunks and 30 invaded in the surroundings)" (US2, p. 76). In the Loket domain, the forest stage manager Jan Wildt provided the information in a letter to a burgomaster office on 24 July 1870 that "many trees are invaded by the bark beetle, partly dry, in forest districts Kozí hřbet and Kovářská" (US3, p. 77). Bark beetle occurrences were often mentioned in connection with other natural disturbances like windstorms, snowstorms, and droughts. Reports also included various mitigation measures to prevent possible future bark beetle outbreaks. For example, after an 1870 windstorm, the purchase of new horses to remove the windthrow wood from forests, a prohibition on logging healthy trees or selling the redundant trunks to merchants for processing were applied in the Prášily domain (US4, p. 68).

Annual forest reports with information on forest pests were published for a few estates (domains) in *Neue Schriften* of the Imperial Royal Patriotic-Economic Society of Bohemia, together with meteorological and phenological observations (Brázdil et al., 2011) as well as agricultural reports for the years 1828–1846. For example, in 1833 on the Plasy estate, there was a bark beetle outbreak "which, aided by the weather, caused great damage." The local foresters tried to contain the outbreak by laying out spruce trunks without the bark to attract the beetles. In this way they destroyed more than a million bark beetles (Neue Schriften der kais. königl. patriotisch-ökonomischen Gesellschaft im Königreiche Böhmen, 1836, p. 217).

Among other documentary sources are monographs (e.g. Nožička, 1957; Hošek, 1981; Jelínek, 1988; Skuhravý, 2002) and professional papers (e.g. Kalandra et al., 1957; Kudela, 1980; Skuhravý and Šrot, 1988; Zatloukal, 2003; Simanov, 2014). Further bark beetle information has also been found in newspapers (e.g. *Rudé Právo*, 29 June 1966, p. 4; *Rudé Právo*, 31 August 1983, p. 2), or via internet sources (e.g. Historie lesních kalamit v ČR, 2018).

Systematic quantitative data related to bark beetle forest damage for the 1964–2021 period were compiled by the Research Institute of Forestry Economics and Gamekeeping (Výzkumný ústav lesního hospodářství a myslivosti) at Jíloviště-Strnady in the form of annual volumes of salvage felling attributed to bark beetle impacts. These data were collected from reports of individual forest districts (foresters) in the CR.

2.2 Meteorological and climatological data

Because meteorological and climatological factors influence the evolution of bark beetle outbreaks and are important triggers in the CR, the following climatological data for the 1781–2021 period were used in this study:

i. mean monthly areal temperature series for the CR (Brázdil et al., 2012), extended to 2021

ii. mean monthly areal precipitation series for the CR (Brázdil et al., 2012), extended to 2021 and completed with seasonal and annual reconstructed precipitation totals before 1804 (Dobrovolný et al., 2015)

iii. mean monthly areal self-calibrated Palmer Drought Severity Index (scPDSI) series for the CR (Brázdil et al., 2022a)

iv. the chronology of severe windstorms in the CR derived from documentary and instrumental data for 1801–2015 (Brázdil et al., 2018b) and extended to 1781 and 2021.

3 Methods

Different documentary data of bark beetle occurrences (see Sect. 2.1) were critically evaluated to create a database containing information about the time (year), place, special bark beetle information (occurrence, type of damage, damaged volume of wood, measures against bark beetle), and source of report. Information about place was divided according to ownership of forest stands such as estates (domains) or towns, sometimes specified to the corresponding forest district or even individual forest stand. Because some older quantitative data about the felling of wood invaded by bark beetle as well as the area of such affected stands were expressed in older units, they were recalculated to recent units as follows: the volume unit 1 fathom (*sáh*) equals 2.842 m^3 of stacked wood or 1.8954 m^3 of solid wood (i.e. without the air between the logs); the areal unit 1 square measure (*jitro*) equals 0.5754 ha.

The created new database was used to describe long-term spatiotemporal variability in bark beetle occurrences across the CR between 1781 and 1963 CE, from which the three most outstanding bark beetle outbreaks based on the spatial extent and estimated volume of damaged wood were selected for detailed analyses. These outbreaks were complemented by four events identified as having the highest volumes of bark beetle salvage felling since 1964. The spatial distribution of bark beetle occurrences during the two outbreaks from the 19th century are characterized by estates (domains) and localities with invaded forest stands, while selected outbreaks after 1963 were spatially attributed to 77 newly established administrative districts (*okres*), expressing total volumes of bark beetle salvage felling for them as well as volumes in the individual years of a given outbreak. For the description of meteorological and climatological patterns, annual and summer (June–August) anomalies of air temperature, precipitation totals, scPDSI-3 (summer), and scPDSI-12 (annual) with respect to the 1961–1990 reference period were expressed. This reference period was preferred to the more recent 1991–2020 period because of more stable climatic patterns and a weaker effect of recent warming (Brázdil et al., 2022b). For corresponding monthly anomalies, their cumulative sums were calculated starting from the January anomaly of the first year of the related bark beetle outbreak and finishing by the addition of the December anomaly of the last year. A description of climatological patterns was complemented by the reporting of windstorms as a meteorological disturbance, taken from our historical climatological database. The events from 1964 were further complemented by annual volumes of salvage felling, separately attributed to bark beetle and windstorms.

In order to characterize the general climatological conditions of all seven selected bark beetle outbreaks together, a composite or superposed epoch analysis was applied (Haurwitz and Brier, 1981), calculating the mean summer and annual anomalies of temperatures, precipitation, scPDSI-3, and scPDSI-12 5 years before and 5 years after the first year of the corresponding outbreak (see Sect. 4.2.8). The statistical significance ($p < 0.05$) of these anomalies was estimated using a random bootstrapping approach (Rao et al., 2019). The method uses a composite matrix in which the rows represent the years of the bark beetle outbreak (event years) and the columns are analysed data (temperature, precipitation, scPDSI) for 5 years before and after the event (lag years). In a random bootstrapping approach, 500 unique versions of composite matrices were created drawing unique subsets of event years at random without replacement. For each column (that is for years from lag −5 to lag +5) and for each normalized composite matrix the density function and its percentiles were calculated. For each lag year the mean data anomaly (temperature, precipitation, scPDSI) that exceeded the 95th percentile, was considered statistically significant (see, e.g., Adams et al., 2003, or Rao et al., 2019, for more details).

To analyse large-scale circulation patterns corresponding to years around bark beetle outbreaks, we used an objective classification of circulation types based on flow strength, flow direction, and vorticity (Jenkinson and Collison, 1977; Plavcová and Kyselý, 2011), calculated with respect to the geographic midpoint of the CR from sea level pressure data in an NCEP/NCAR reanalysis (Kalnay et al., 1996). This classification defines nine anticyclonic types, nine cyclonic types, and eight directional types; the type U stands separately for unclassified patterns (see Řehoř et al., 2021a, for more details). Relative frequencies of circulation types in years around outbreaks were expressed as differences with respect to corresponding mean frequencies of the 1961–1990 reference period. These relative differences were further tested by the two-proportion Z test (Sprinthall, 2011) for their statistical significance ($p < 0.05$).

4 Results

4.1 Bark beetle outbreaks during the 18th–21st centuries

The spatiotemporal chronology of bark beetle occurrences on the territory of the CR covers the period from the 1780s to the early 1960s CE. The beginning of this series is characterized by a few reports before 1780 and a lack of spatial details after 1950, reporting rather larger areas like the borderland mountains. Fluctuations in the number of places with bark beetle occurrence follow from Fig. 1 and reported locations across the CR appear in Fig. S1. After 1963, bark beetle occurrences are presented generally for the whole CR according to corresponding volumes of salvage felling (see Fig. 2).

4.1.1 The 18th century

The first, but only general, reports of bark beetle occurrences in the CR appear for the years 1720, 1733, and 1748 CE (Nožička, 1957). The number of related reports increased during the 1780s and 1790s. For example, in 1782–1785 bark beetle occurrence was documented in the western half of Bohemia (e.g. the Křivoklát, Loket, Plzeň, Toužim, and Zbiroh estates). After a windstorm on 5–6 November 1786, the trees of the Jizerské hory, the Krkonoše Mts, and the Orlické hory were processed for 15 years. Around 1790 a farm estate in Jindřichovice in the Krušné hory reported around 20 000 fathoms (56 840 m^3) of bark beetle wood. Further bark beetle reports between 1793 and 1798 appear for several other estates, having in their possession forest stands in Bohemia (e.g. Horšovský Týn, Kynžvart, Opočno, Přísečnice, Zbiroh). On 20 April 1799, the forester Ehrenwert reported to the *Gubernium* in Prague that bark beetles in the Loket region invaded 5469 cadastral *jitro* (3147 ha) of forest stands, as a result of which it was necessary to cut down 321 828 trees (US5, p. 93).

4.1.2 The 19th century

In the 19th century, the first bark beetle infestation occurred after fallen trees following several meteorological disturbances between 1807 and 1809, when the estates and regions of Bechyně, Červené Poříčí, Choceň, Jáchymov, Kumburk, Litoradlice, Plzeň, Rokycany, and Slapy in Bohemia and Fulnek, Krnov, and Telč in Moravia and Silesia were affected. Overall 60 000 trees were infested in the Častolovice and Choceň forests (US6, p. 78). Further regions infested by bark beetle were reported in 1811–1813 for the Krušné hory and the estates Chrudim, Heřmanův Městec, Jičíněves-Veliš-Vokšice, Kumburk, and Třeboň.

An important expansion of bark beetles was recorded in the 1820s; starting in 1822 they were reported in each year of this decade for different estates or localities of Chodová Planá, Jáchymov, Jezeří, Jindřichův Hradec, Kardašova Řečice, Lovosice, Nepomyšl-Krásný Dvůr, Nové Hrady, Orlík, Ostrov, Přísečnice, Rokytnice, Rychmburk, Toužim, and Třeboň in Bohemia, while in Moravia and Silesia it was Hranice, Libava, Lipník nad Bečvou, Potštát, and Žďár nad Sázavou. For example, in Prášily forests in the Šumava Mts area, 14 671 fathoms (41 695 m^3) of thrown and fallen good trees and 5000 fathoms (14 210 m^3) of trunks of over-aged trees appeared after the 20–25 November 1821 windstorm. To avoid the expansion of the bark beetle population, a holder of a corresponding domain asked in August 1822 to speed up the processing of the wood, even at the increased labour costs this would entail (US4, p. 67).

Windstorms in December 1833 and January 1834 followed by subsequent summer droughts in 1834–1835 were triggers of the next and much larger bark beetle outbreak during the 1830s, which was documented in forest stands of 50 estates

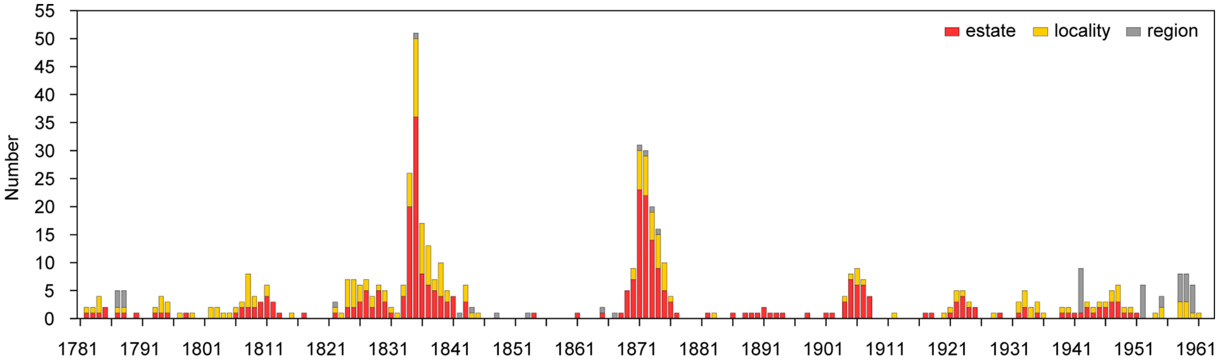

Figure 1. The annual numbers of locations with bark beetle outbreaks over the territory of the Czech Republic during the 1781–1963 period extracted from documentary evidence.

and 28 other localities (see Fig. 1 and Sect. 4.2.1 for more details).

The beginning of the 1840s signalled a subsiding of the bark beetle infestation with beetle occurrence record in a few estates (e.g. Loket, Manětín-Rabštejn, Okrouhlice, Přísečnice, Toužim, Uhrov, Želiv, Žichovice), mainly in 1841 and 1843 (in the Písek region until 1845). For the next 2 decades, bark beetle occurrences were reported only for the estates of Jezeří (1854), Branná (1861), and Bruntál (1865). But after two extreme windstorms in 1868 and 1870, the most disastrous bark beetle outbreak of the 19th century occurred, continuing until 1875–1877. Our database documents this event in the forest stands of 35 estates and 10 other localities, focused on the area of the Šumava Mts (see Fig. 1 and Sect. 4.2.2 for more details).

After this bark beetle infestation there are few accounts in the years up to the end of the 19th century. For example, the increased occurrence of bark beetles around 1883 in the Vysoké Mýto region was eliminated by peeling affected trees and by bark burning (US6, p. 240). In the forests of the Maršov domain, the bark beetle was kept in harmless boundaries using catchers in 1888–1894, with the annual felling only between 55 and 167 m^3 of solid wood (US7, p. 43).

4.1.3 The 1901–1963 period

Hošek (1981) estimated bark beetle calamities on the territory of the CR during 1900–1940 for 2.2×10^6 m^3 of wood. The first portion of bark beetle reports appeared after snow-fallen trees in 1904 and some blowdown especially in 1905–1908 for different estates in Bohemia like Ahníkov, Cvikov, Červený Hrádek, Debrné, Hořice, Hůzová, Jirkov, Náchod, Rokytnice, Rychnov-Černíkovice, and Skály. In the following decade, the 1910s, only sporadic bark beetle records occurred. In the 1920s, bark beetle occurrences were reported particularly after damage caused by nun moths (*Lymantria monacha*). To this is attributed damage in spruce and pine forests of ca. 20×10^6 m^3 of wood across an area of 62 000 ha during the years 1917–1927 (Komárek, 1931; Simanov, 2014). But bark beetles did not achieve any broader expansion. Only Kudela (1980) reported ca. 22 000 m^3 of bark beetle wood for 1922 in the surroundings of Nové Hrady and České Velenice in southern Bohemia after neglected blowdown trees from 1920. Skuhravý (2002) estimated the volume of damaged wood by nun moth and bark beetle in the mountain positions at 300 000 m^3 of wood between 1922–1927.

As for the 1930s, greater expansions of bark beetles were reported for only some estates or localities in Bohemia (e.g. Boleboř, Přísečnice, Rychmburk, Rychnov-Černíkovice, Skály) and Moravia and Silesia (e.g. the areas around Velké Losiny and Velké Vrbno). A lack of forest workers during World War II (1939–1945) led to the slow processing of blowdown trees in forest stands after several meteorological disturbances; in 1946 a bark beetle outbreak affected nearly all mountainous forest stands across the territory of the CR and their elimination continued until 1954 (see Sect. 4.2.3 for more details).

Further quantitative estimates from the 1950s include for 1953–1955 only 200 000 m^3 of bark beetle wood in the border mountains and the Doupovské hory and 120 000 m^3 for 1959–1960, again in the border mountains (Kudela, 1980). Fewer volumes were reported in annual overviews of insect pests and diseases: 40 000 m^3 in 1958 (Pivetz et al., 1959), 43 500 m^3 in 1959 (Šrot et al., 1960), and 75 000 m^3 in 1960 (Martinek and Šrot, 1961). Hošek (1981) estimated bark beetle salvage felling during 1961–1963 at ca. 60 000 m^3 of wood annually.

4.1.4 The 1964–2021 period

Systematic quantitative data of bark beetle salvage felling for the entire CR territory appears since 1964, with 287 000 m^3 of wood in that year. Harvested volumes of wood did not achieve a 0.5×10^6 m^3 until 1982 (Fig. 2). But in 1983–1984 and 1986–1987 they exceeded 1×10^6 m^3 annually. In 1993–1995 they were already above 1.5×10^6 m^3 per year, similar to 2008–2010. Then from 2012, with the value of

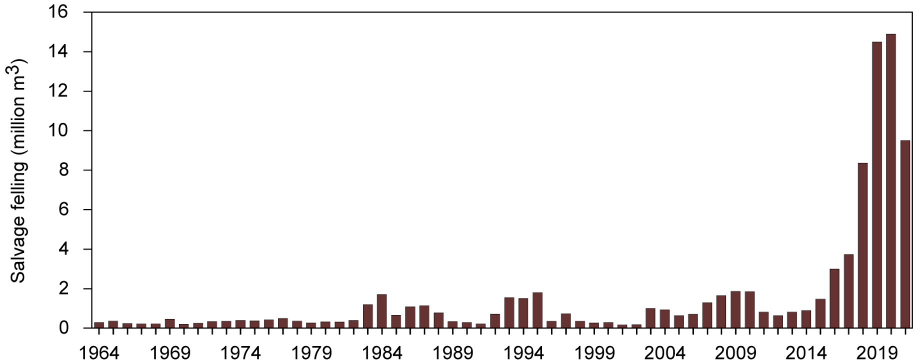

Figure 2. Fluctuations in bark beetle salvage felling ($\times 10^6$ m^3 of wood) for the Czech Republic in the 1964–2021 period (source of data: Research Institute of Forestry Economics and Gamekeeping).

633 000 m^3, a continuous increase in bark beetle salvage felling started and amounted to nearly 1.5×10^6 m^3 in 2015. Later during 2016–2017 it went beyond 3×10^6 m^3 per year, in 2018, 8×10^6 m^3, and in 2019–2020 14×10^6 m^3 (to the maximum of 14.9×10^6 m^3 in 2020). In 2021 related salvage felling declined to 9.5×10^6 m^3 of wood. Bark beetle calamities of the 1980s, 1990s, 2000s, and 2010s–2020s are analysed in detail in Sect. 4.2.4–4.2.7.

4.2 Meteorological and climatological triggers

Figure 3 demonstrates long-term fluctuations in the mean annual and summer series of air temperature, precipitation totals, scPDSI, and windstorms over the territory of the CR during the 1781–2021 CE period. The mean annual temperatures slightly declined from the warmer 1790s to ca. 1890, with a following continuous increase, particularly rapid from the late 1980s (Fig. 3a). The mean annual precipitation totals are lower before ca. 1810 and experienced a slight decrease from the 1810s to the 1860s and afterwards an increase in the 1870s, with the maximum of the entire series occurring around 1940 CE. Afterwards, totals kept a relatively similar level to before (Fig. 3b). Annual scPDSIs show similar behaviour to fluctuations in precipitation totals as high as the maximum (wet patterns) around 1940, but afterwards a clear decreasing trend (i.e. increasing dryness) was well expressed, ending with an extremely sharp drop in the 2010s (Fig. 3c). This last, sharply enhanced dryness has no analogue in the entire scPDSI series. As for summer series, they slightly differ from annual series in individual values and in the amplitude of smoothed local extremes, but otherwise they express very similar temporal changes. Periods of relatively higher annual frequency of severe windstorms (Fig. 3d) were identified in the 1820s–1840s, 1900s–1930s, and 1960s–2000s, while they were less frequent in the second half of the 19th century (particularly in the 1850s) and in the 1940s–1950s.

Because of the importance of meteorological and climatological triggers for the origin and course of bark beetle outbreaks, the most notable bark beetle events in the whole chronology since 1781 CE with respect to their meteorological and climatological conditions in the CR are characterized in greater detail in the following sections.

4.2.1 The bark beetle outbreak of the 1830s

Locations of 78 estates and localities whose forest stands were affected by the bark beetle outbreak in 1834–1839 are shown in Fig. 4a. Affected locations occur especially in southern, western, northwestern, and eastern Bohemia and in northeastern Moravia and Silesia.

The meteorological trigger of this bark beetle outbreak was primarily a heavy windstorm that occurred on 18–19 December 1833, followed by high winds on 22 and 26 December and then by another windstorm on 31 December 1833–1 January 1834 (Brázdil et al., 2018b). Vicena (1964) estimated related damage to 4.2×10^6 m^3 of wood for the first windstorms and 0.3×10^6 m^3 for the second windstorm. Hošek (1981) reported the same volume of damaged wood for the first event, divided into 3.7×10^6 m^3 in Bohemia and 0.5×10^6 m^3 in Moravia and Silesia (mainly in the Jeseníky Mts). A large number of fallen and broken trees being processed together with a warm (especially summer) and dry year in 1834 and another dry year in 1835 (the lowest scPDSI) compared to the 1961–1990 reference (Fig. 4b) created good conditions for the bark beetle outbreak. For example, while the January windstorm felled 21 978 m^3 of wood in the Vimperk domain, the subsequent bark beetle outbreak infested nearly 10 times more (202 653 m^3 of wood until 1839). In the forest of Volary town, a lax approach to blowdown tree processing finally led to 151 603 m^3 of damaged wood, of which more than half are attributed to bark beetle infestation (Jelínek, 1988). Zatloukal (2003) reported ca. 300 000 m^3 of bark beetle spruce wood for the Šumava Mts area. Cumulative monthly precipitation anomalies showed a stable deficit between 250 and 300 mm from the summer of 1835 to the autumn of 1837, while decreasing cumulative monthly anomalies of scPDSI from late 1834 document increasing dryness which culminated in 1836, being continuously reduced af-

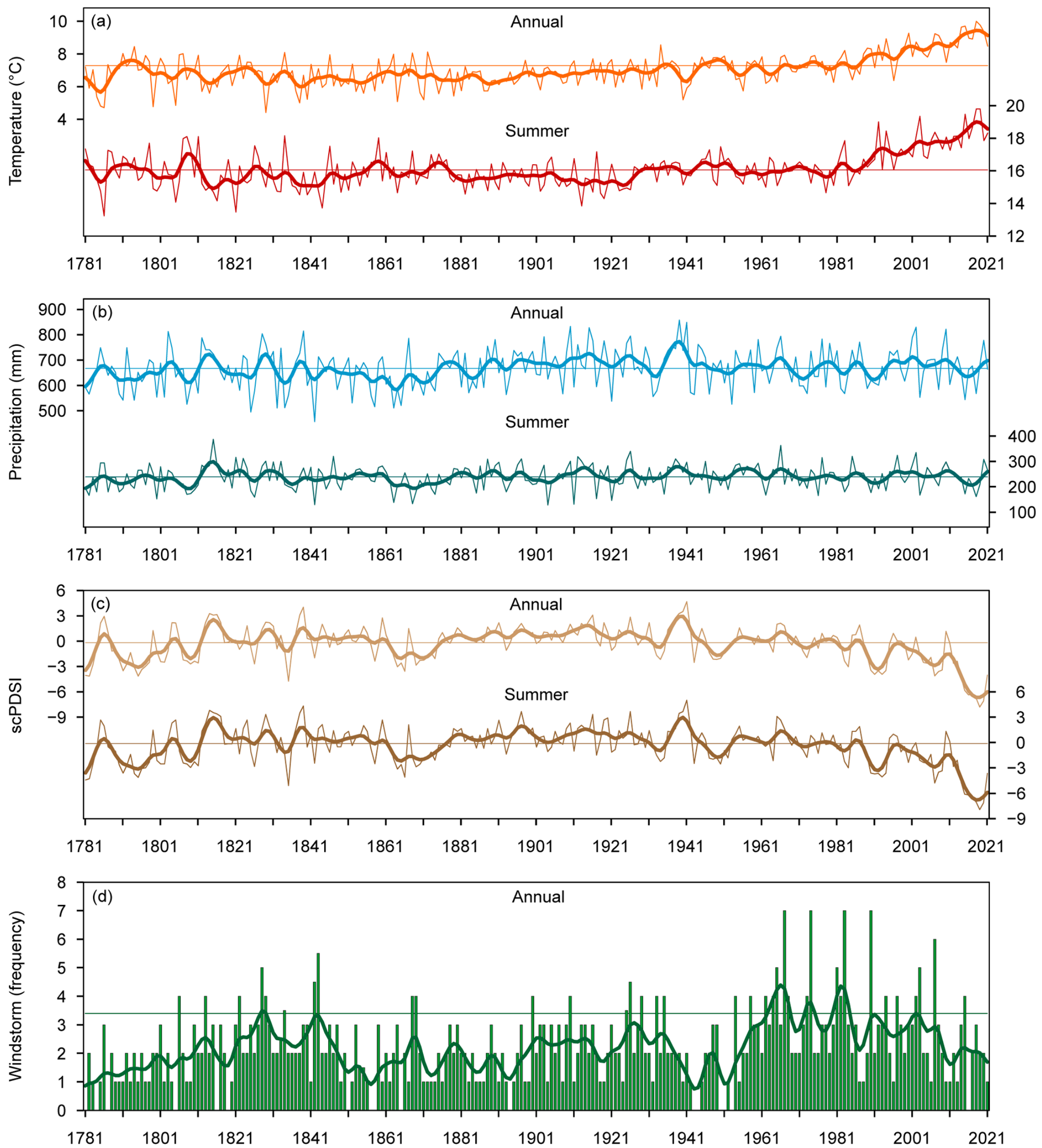

Figure 3. Fluctuations in annual and summer series of **(a)** mean air temperatures, **(b)** precipitation totals, **(c)** scPDSI-3 (summer) and scPDSI-12 (annual), and **(d)** severe windstorms for the territory of the Czech Republic during the 1781–2021 period. The values are smoothed by a 10-year Gaussian filter (bold line) and complemented by horizontal lines corresponding to related means of the 1961–1990 period.

terwards by subsequent colder and wetter years until 1839 (Fig. 4c).

4.2.2 The bark beetle outbreak of the 1870s

The location of 45 documented estates and localities over the territory of the CR, whose forest stands were affected by a bark beetle outbreak in 1870–1875, is shown in Fig. 5a. Especially affected was the area of the Šumava Mts in southwestern Bohemia. For example, Jelínek (1988) reported that the Vimperk domain had bark beetle salvage felling in the volume of 1 079 115 m^3 of wood during 1868/1869–1877/1878 decade. Further documented places were located in western Bohemia, in the Krušné hory, and the Krkonoše Mts. It is interesting to note the location of affected localities in a line from southern Bohemia to the northeast, with further occurrences in the broader Jeseníky Mts area (Fig. 5a).

The bark beetle outbreak in the 1870s had its meteorological triggers in two disastrous windstorms following shortly after each other. The first windstorm on 7 December 1868 resulted in 6×10^6 m^3 of solid wood, according to Hošek (1981). However, based on hard data from 273 forest

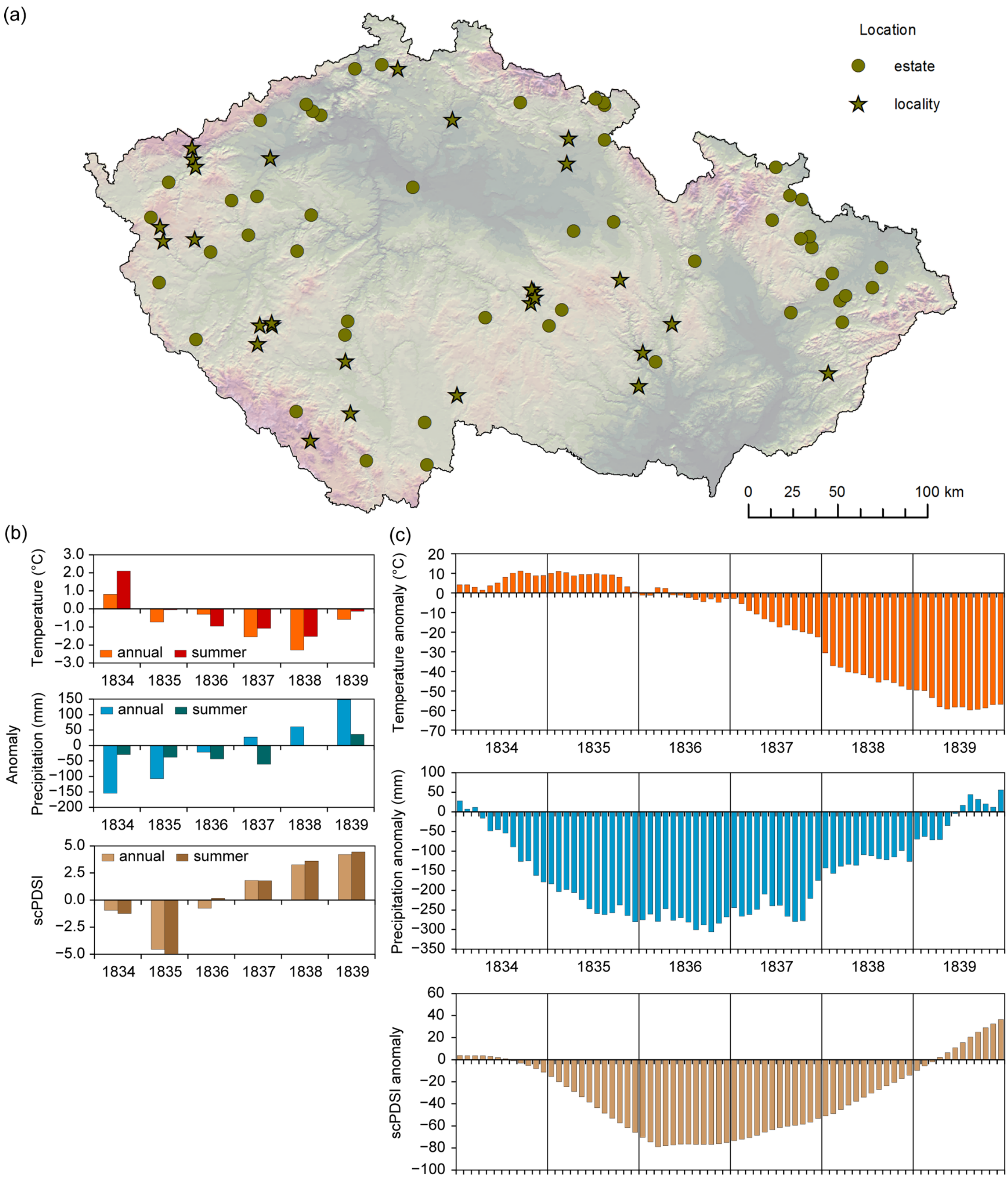

Figure 4. Bark beetle outbreak of the 1830s on the territory of the Czech Republic: **(a)** locations with the occurrence of bark beetle; **(b)** annual and summer anomalies of temperature, precipitation, scPDSI-12, and scPDSI-3 in 1834–1839; **(c)** cumulative monthly anomalies of temperature, precipitation, and scPDSI in 1834–1839 (1961–1990 reference period).

districts throughout the Czech Lands, Brázdil et al. (2017) disclosed only 4.89×10^6 m^3 of solid wood. The subsequent disastrous windstorm on 26–27 October 1870 completely devastated many forested areas, especially in the Šumava Mts in southwestern Bohemia (Brázdil et al., 2018a). Hošek (1981) estimated total forest damage during this windstorm at 4×10^6 m^3 of solid wood. A huge number of uprooted and broken trees that could not be processed relatively fast created optimal conditions for bark beetle spread during generally cooler years and more or less normal sum-

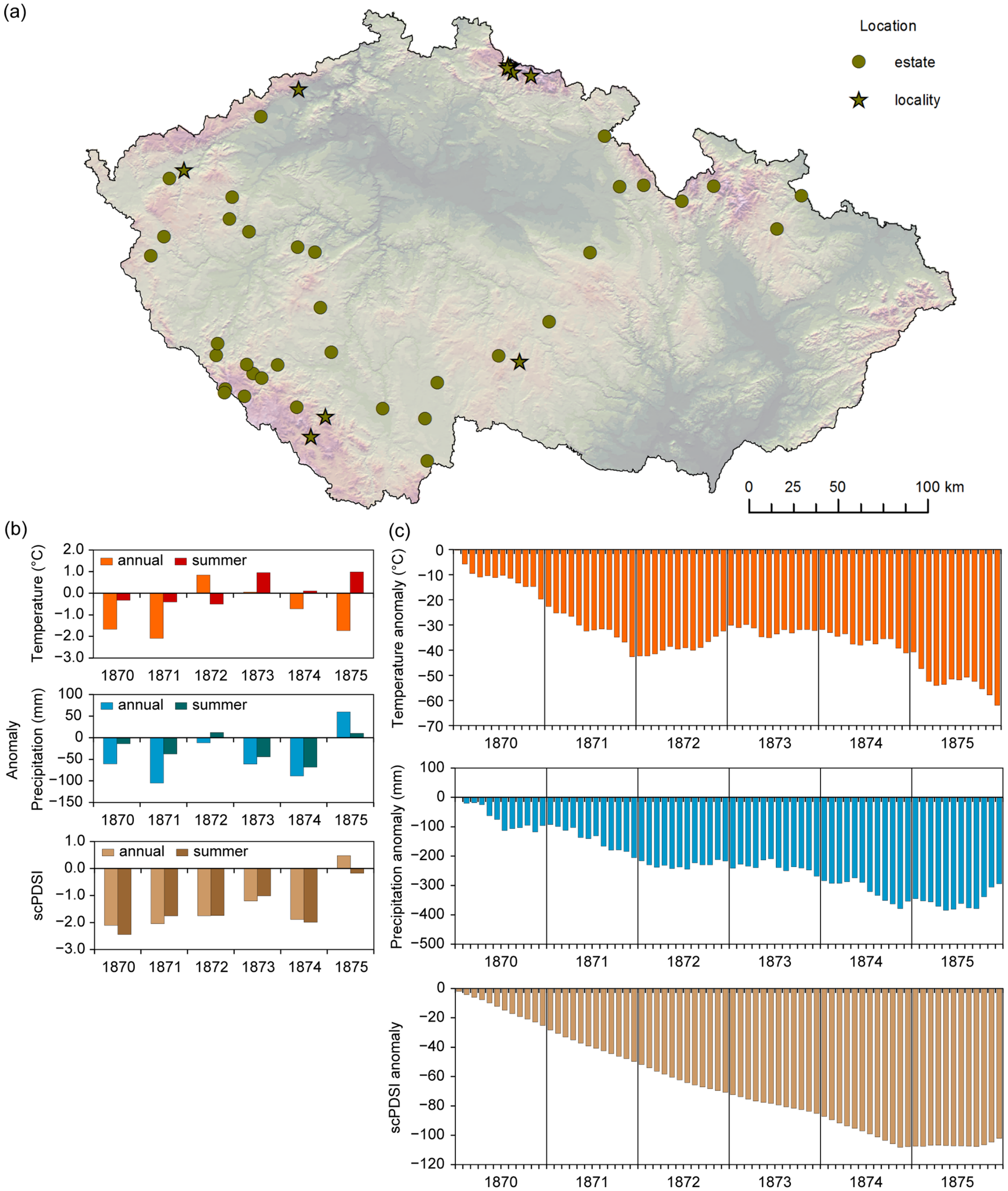

Figure 5. Bark beetle outbreak of the 1870s on the territory of the Czech Republic: **(a)** locations with the occurrence of bark beetle; **(b)** annual and summer anomalies of temperature, precipitation, scPDSI-12, and scPDSI-3 in 1870–1875; **(c)** cumulative monthly anomalies of temperature, precipitation, and scPDSI in 1870–1875 (1961–1990 reference period).

mers but also during drier years 1870–1871 (the lowest scPDSI already in 1870) compared to the 1961–1990 reference (Fig. 5b). The cumulative monthly precipitation deficit was above 200 mm in 1872–1873 and increased by more than 350 mm from autumn 1874 to summer 1875 (Fig. 5c). The dryness expressed by cumulative monthly scPDSI anomalies was enhanced until 1874, while in the next year 1875 cumulative anomalies remained more or less constant.

The 1870 windstorm also damaged more than 620 000 m^3 of wood on the German side of the southwestern border of the CR; together with the 1868 windstorm and the subsequent bark beetle outbreak, 12.3 % of all the forests were devastated there (Elling et al., 1987). On the Czech side, salvage logging amounted to 3.5×10^6 m^3 of solid wood between 1868 and 1882 (Jelínek, 2005). Analysing the effects of the two windstorms and the following bark beetle outbreak for the Šumava Mts and Bayerischer Wald together, Brůna et al. (2013) estimated damage to ca. 40 % of their 43 247 ha area, for which forests were at least partly disturbed (7725 ha totally, 4647 ha half). According to Svoboda et al. (2012), the effects of this disaster still remain visible in many stands in the Šumava Mts.

4.2.3 The bark beetle outbreak of the 1940s–1950s

While post World War II bark beetle outbreaks affected forest stands in all border mountains of the CR, information about volumes of damaged wood differs significantly. For example, Kalandra et al. (1957) reported ca. 10×10^6 m^3 of bark beetle wood during the first part of this outbreak in 1944–1947 and then in 1949–1954, emphasizing the weakening of spruce trees after a severe drought in 1947. Hošek (1981) mentioned 8×10^6 m^3 for the whole 1946–1954 period, giving annual felling data only for 1950–1954 of a total of 3.737×10^6 m^3 (1950 – ca. 957 000 m^3; 1951 – 720 000 m^3; 1952 – 740 000 m^3; 1953 – 800 000 m^3; 1954 – 520 000 m^3). The bark beetle outbreak especially affected the border mountain systems of the CR as the Šumava Mts, the Krušné hory, the Lužické hory, the Jizerské hory, the Krkonoše Mts, the Orlické hory and the Jeseníky Mts but also the Doupovské hory in western Bohemia. Besides these regions, bark beetle occurrences were documented in excerpted documentary sources only for 11 different localities (Fig. 6a).

Kudela (1980) reported a snow throw on 6–8 December 1939, especially in western, southern, and central Bohemia, a windstorm on 4 November 1941, and strong winds in 2 subsequent years as causes of ca. 10×10^6 m^3 of broken and fallen trees in Czech forest stands, which were only slowly processed due to problems with a lack of forest workers, who moved during the war to the arms industry. This created good conditions for the bark beetle outbreak that appeared in full intensity during 1945–1947 with 2×10^6 m^3 of invaded wood. A further 0.2×10^6 m^3 of wood was reported for 1953–1955. While in 1952 trees threatened by bark beetle were cut down from the Novohradské hory over the Šumava Mts, the Český les Highland, the Doupovské hory, and the Krušné hory to the Děčín region (Kalandra, 1953); small bark beetle pockets in the Ústí nad Labem region, the Jeseníky Mts, partly in the Moravskoslezské Beskydy Mts, and elsewhere were reported in 1955 (Kudler et al., 1956).

Compared to the 1961–1990 reference period, annual anomalies characterized the years 1945 and 1948–1951 as warmer (especially warm summers in 1947 and 1950), 1947 and 1953 as dry, and 1947–1950 with the highest scPDSI negative anomalies (Fig. 6b). While cumulative monthly temperature anomalies were positive through the whole 1945–1954 period except for the first half of 1947, cumulative monthly precipitation anomalies were both positive and negative, achieving ca. 100 mm in February–April 1947 and ca. −150 mm in the first half of 1954 (Fig. 6c). In the case of cumulative monthly scPDSI anomalies, the continuously increasing dryness appeared from the spring of 1947 to mid-1952 and did not change much afterwards until the end of 1954. Thanks to the wetter years of 1945–1946, cumulative values were not so strongly expressed as the known very dry year of 1947 (Brázdil et al., 2016).

Concerning this bark beetle outbreak, Skuhravý (2001) reported its occurrence in a broad central European area extending from Switzerland and Austria to northern Germany on the one hand and from the river Rhine in the west to southern Poland, Slovakia, and Hungary in the east on the other. Bark beetles invaded more than 30×10^6 m^3 of wood, especially in altitudes between 150 and 600 m a.s.l. This outbreak in southwestern Germany during 1944–1951, especially in Baden-Württemberg and Rheinland-Pfalz, was analysed in the volume of papers edited by Wellenstein (1954). Turček (1950) described the situation in Slovakia during 1947–1948.

4.2.4 The bark beetle outbreak of the 1980s

The bark beetle salvage felling in 1982–1987 amounted to 6.205×10^6 m^3 of wood according to data in Fig. 2. The highest values (Fig. 7a) were recorded especially in the border districts of Bohemia, with most of those in northern Bohemia (Liberec district 611 604 m^3), followed by three other districts with more than 250 000 m^3 in southwestern Bohemia in the Šumava Mts (Klatovy 334 080 m^3 and Prachatice 262 917 m^3) and in northwestern Bohemia (Karlovy Vary 262 517 m^3). In Moravia and Silesia, the highest bark beetle felling amounted to 198 341 m^3 in Šumperk district.

As follows from Fig. 7b and c, the warm and dry years 1982 and especially 1983 (1961–1990 reference period) led to a deficit in cumulative monthly precipitation anomalies achieving nearly 200 mm from late 1983 into the first half of 1985, which was reflected in continuously increasing dryness expressed by scPDSI to the end of 1984. Afterwards, the situation started to improve due to cooler and wetter patterns in 1985 and 1987. As for summers, those in 1982 and 1983 showed a positive anomaly of 1.1 and 1.8 °C respectively, while precipitation totals in the summer of 1983 were 58 mm below the long-term mean. But in this context, two extreme windstorms on 12–13 July and 23–24 November 1984 in the CR (Brázdil et al., 2018b) cannot be omitted, which were significantly reflected in the important increase in windstorm salvage felling in 1984–1985 with 12.43×10^6 m^3 of wood together (Fig. 7b). Another severe windstorm on 19–20 January 1986 (Brázdil et al., 2018b) had less influence on bark beetle outbreaks that had significantly increased related salvage felling in 1986–1987 (8.28×10^6 m^3 together).

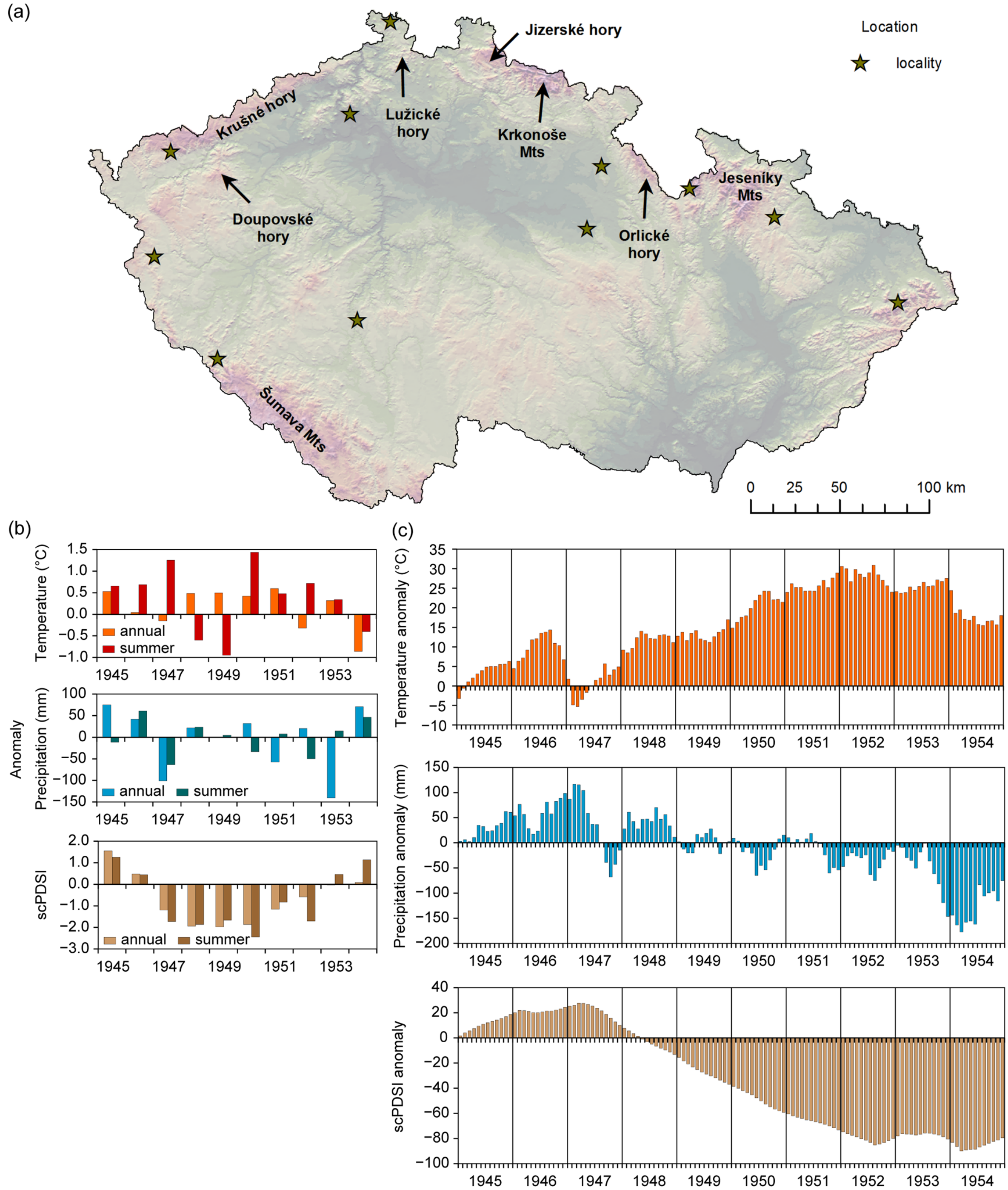

Figure 6. Bark beetle outbreak of the 1940s–1950s on the territory of the Czech Republic: **(a)** location of regions and localities with the occurrence of bark beetle; **(b)** annual and summer anomalies of temperature, precipitation, scPDSI-12, and scPDSI-3 in 1945–1954; **(c)** cumulative monthly anomalies of temperature, precipitation, and scPDSI in 1945–1954 (1961–1990 reference period).

Skuhravý and Šrot (1988), who analysed the same outbreak for 1982–1986 in detail, pointing out 5.081×10^6 m^3 of bark beetle wood, reported windstorm and snowstorm, dry episodes, and also air pollution among meteorological triggers. But they attributed this outbreak additionally to the neglect of cleaning and protecting spruce stands, to the underestimation of bark beetle danger in the early stage of its gradation (for example, the quantity of bark beetle increased 3.5 times between 1982 and 1983 in the whole CR

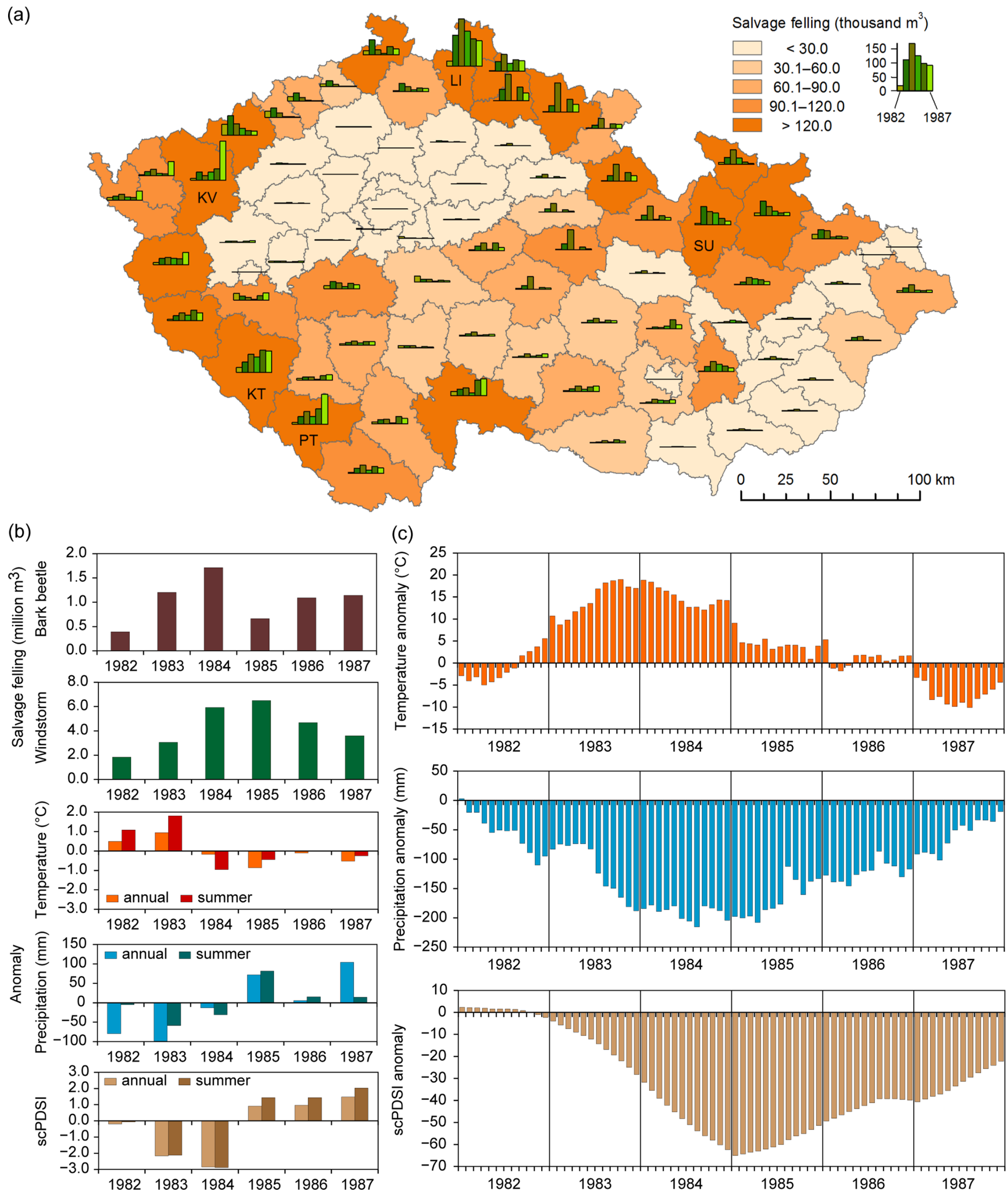

Figure 7. Bark beetle outbreak of the 1980s on the territory of the Czech Republic: **(a)** the volume of bark beetle salvage felling in 1982–1987 in individual districts; **(b)** annual bark beetle and windstorm salvage felling, annual and summer anomalies of temperature, precipitation, scPDSI-12, and scPDSI-3 in 1982–1987; **(c)** cumulative monthly anomalies of temperature, precipitation, and scPDSI in 1982–1987 (1961–1990 reference period). Abbreviations of districts: LI – Liberec; KT – Klatovy; KV – Karlovy Vary; PT – Prachatice; SU – Šumperk.

but 12.9 times in the East Bohemian region), and to the human factor.

4.2.5 The bark beetle outbreak of the 1990s

Taking into account bark beetle salvage felling in 1992–1995, the highest values were recorded especially in districts extending from southwestern Moravia to the northeastern part of the CR (Fig. 8a). Maximum volumes of bark beetle wood were felled in the Opava district with 513 382 m^3 of wood, followed by the districts of Brno-venkov (386 059 m^3), Bruntál (384 318 m^3), and Třebíč (364 999 m^3), with three other districts with more than 200 000 m^3. In Bohemia, the highest felling in Klatovy district amounted to only 120 377 m^3. The total volume of bark beetle salvage felling in the CR during 1992–1995 amounted to 5.59×10^6 m^3 of wood (Fig. 2).

The dry and warm patterns of 1992 (Fig. 8b and c) with a particularly warm summer created good meteorological conditions for the subsequent bark beetle outbreak as warned by Mrkva (1993). Although the cumulative deficit of monthly precipitation anomalies compared to the 1961–1990 reference was around 100 mm and more in some months of 1993–1994, increasing temperatures intensified the dryness significantly until the winter of 1994/1995. The situation slightly improved in the warmer but also wet year of 1995, but without any important changes in the cumulative monthly anomalies of scPDSI. This bark beetle event remained outside of the potential impacts of two disastrous windstorms in 1990 (Vivian on 26 February and Wiebke on 1 March) because related wood from these windstorms was already processed during 1990–1991 to a total of 12.51×10^6 m^3 (Brázdil et al., 2018b), and corresponding volumes of salvage felling in 1992–1995 were annually only ca. 2×10^6 m^3 or less (Fig. 8b). On the other hand, in 1993–1995 and 1997, a significant increase in salvage felling attributed to drought (6.72×10^6 m^3 together) was recorded (not shown).

4.2.6 The bark beetle outbreak of the 2000s

A herald of this bark beetle outbreak in the CR was already related to salvage felling in 2003–2004 with a total of 1.94×10^6 m^3, triggered by very warm and dry weather in the summer of 2003. Although some papers (e.g. Hlásny et al., 2021b) took this as a bark beetle event continuing until recent times, we are dividing it into two episodes with significantly increased bark beetle salvage felling, namely in 2007–2010 and after 2015. The first outbreak of 2007–2010 (Fig. 9a) was concentrated especially in the Šumava Mts in southwestern Bohemia (the district Klatovy with 796 706 m^3 of wood and Prachatice with 611 530 m^3) and in the districts in the northern part of Moravia and Silesia (Bruntál 498 726 m^3 and Opava 483 959 m^3). The salvage felling of over 200 000 m^3 of wood was also recorded in three other districts in southern (Český Krumlov) and eastern (Chrudim) Bohemia and in northern Moravia (Frýdek-Místek). The total volume of bark beetle salvage felling in the whole CR during 2007–2010 amounted to 6.66×10^6 m^3 of wood (Fig. 2).

While annual mean temperatures experienced high positive anomalies in 2007–2010 compared to the 1961–1990 reference, reflected in the continuous increase in cumulative monthly temperature anomalies in 2007–2009, cumulative monthly precipitation totals fluctuated only between −50 and 50 mm during these 3 years, being followed by the wet year of 2010 (Fig. 9b and c). Despite this, continuously growing dryness expressed by cumulative scPDSI anomalies was well pronounced in 2007–2009, and it improved only slightly in the following year 2010. But the total situation was negatively influenced especially by the disastrous Kyrill windstorm on 18–19 January 2007 followed by Emma on 1–2 March 2008 (Hostýnek et al., 2008; Brázdil et al., 2018b), which were reflected in wind-related salvage felling of 8.842×10^6 m^3 of wood in 2007 and 4.855×10^6 m^3 in 2008, i.e. 13.697×10^6 m^3 together.

4.2.7 The bark beetle outbreak of the 2010s–2020s

According to bark beetle salvage felling, the outbreak of 2015–2021 affected a broad belt of the districts spanning from the Šumava Mts easterly to Moravia and turning there to the Jeseníky Mts region, where in the Bruntál district felling amounted to 4.845×10^6 m^3 of wood (Fig. 10a). But the most affected area was the Bohemian–Moravian Highlands with districts located there or in their broader neighbourhood (Jihlava 3.517×10^6 m^3, Jindřichův Hradec 2.746×10^6 m^3, Blansko 1.928×10^6 m^3, Havlíčkův Brod 1.887×10^6 m^3, Třebíč 1.883×10^6 m^3, Žďár nad Sázavou 1.824×10^6 m^3). Other highly affected districts included also Písek in southern Bohemia (1.817×10^6 m^3) and Děčín in northern Bohemia (1.776×10^6 m^3). The bark beetle felling overcame 1×10^6 m^3 of wood in a further five districts in Bohemia and a further six districts in Moravia and Silesia. The total amount of bark beetle salvage felling in the whole CR during 2015–2021 amounted to 55.46×10^6 m^3 of wood (Fig. 2).

Temperature patterns during 2015–2021 were characterized by highly positive anomalies compared to the 1961–1990 reference (with especially warm summers), which was expressed in continuously growing cumulative monthly anomalies (Fig. 10b and c). Annual precipitation totals were deeply below the mean in 2015 and 2018 when cumulative monthly anomalies amounted to ca. −250 mm from autumn 2018 to spring 2020. Prevailing negative precipitation anomalies combined with increasing temperatures resulted in growing dryness expressed by cumulative scPDSI anomalies. Above-mean precipitation in 2020 and mean totals in 2021 did not improve dry patterns too much. The heavy windstorm Herwart on 29 October 2017 (Hujslová and Šimandl, 2018) complicated the situation by correspondingly high salvage felling in 2018 (4.62×10^6 m^3). But already from 2016 volumes of annual salvage felling due to strong winds were deeply below the related annual volumes for bark beetle felling (Fig. 10b).

4.2.8 Composite analysis of outstanding bark beetle outbreaks

In order to characterize general climatological conditions of all seven outstanding bark beetle outbreaks together, mean

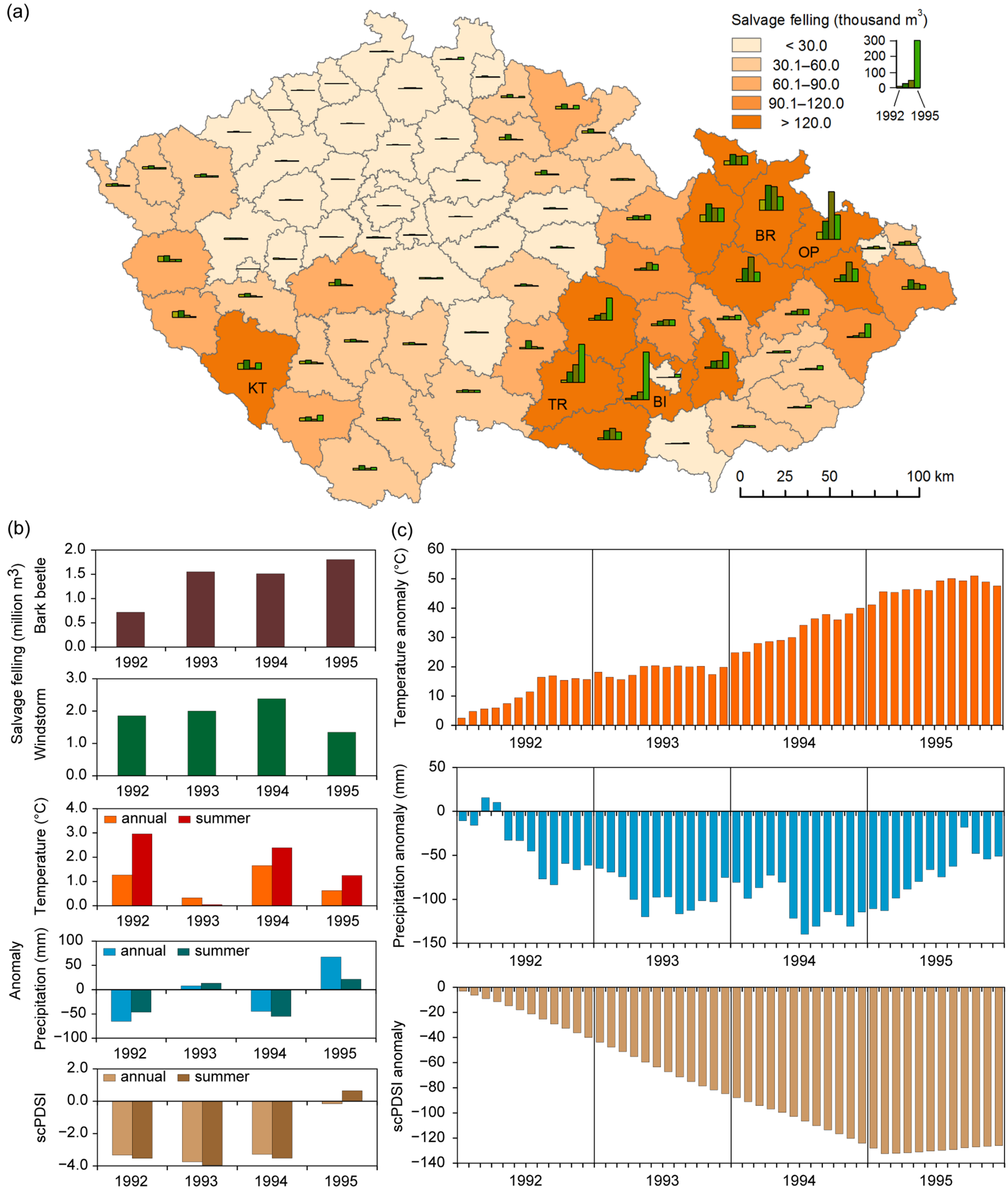

Figure 8. Bark beetle outbreak of the 1990s on the territory of the Czech Republic: **(a)** the volume of bark beetle salvage felling in 1992–1995 in individual districts; **(b)** annual bark beetle and windstorm salvage felling, annual and summer anomalies of temperature, precipitation, scPDSI-12, and scPDSI-3 in 1992–1995; **(c)** cumulative monthly anomalies of temperature, precipitation, and scPDSI in 1992–1995 (1961–1990 reference period). Abbreviations of districts: BI – Brno-venkov; BR – Bruntál; OP – Opava; KT – Klatovy; TR – Třebíč.

temperature, precipitation, scPDSI-3 and scPDSI-12 anomalies of 5 years (from $n-5$ until $n-1$) before the first year of an outbreak (n) and 5 years afterwards (from $n+1$ until $n+5$) were analysed. The years 1834, 1870, 1949, 1982, 1992, 2007, and 2015 were taken as the starting years of seven selected outbreaks. The analysis was performed separately for annual and summer series expressed as anomalies from the 1961–1990 reference period (Fig. 11). The highest and significant ($p < 0.05$) annual and summer temperatures in the starting year of the bark beetle outbreak are followed

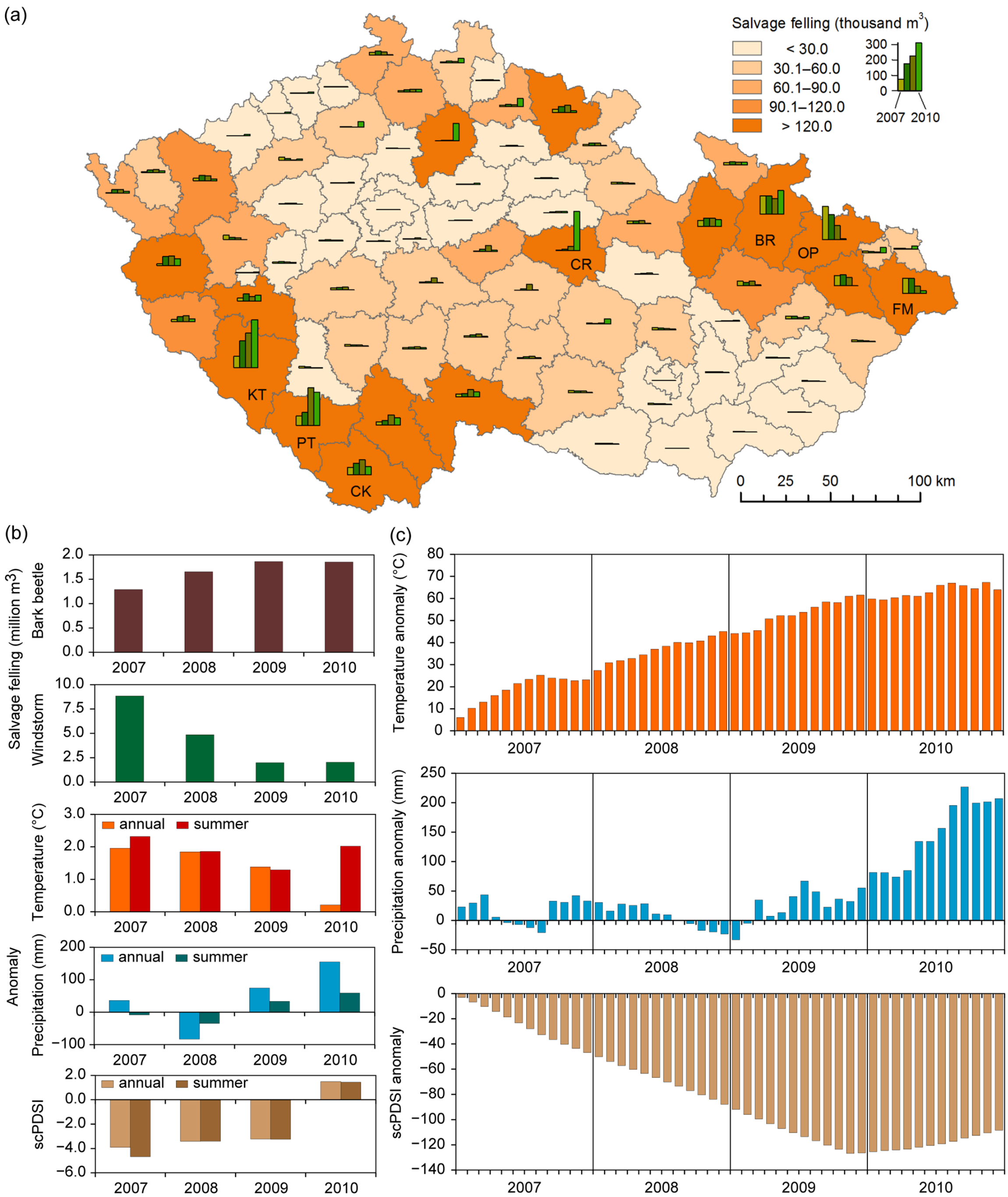

Figure 9. Bark beetle outbreak of the 2000s on the territory of the Czech Republic: **(a)** the volume of bark beetle salvage felling in 2007–2010 in individual districts; **(b)** annual bark beetle and windstorm salvage felling, annual and summer anomalies of temperature, precipitation, scPDSI-12, and scPDSI-3 in 2007–2010; **(c)** cumulative monthly anomalies of temperature, precipitation, and scPDSI in 2007–2010 (1961–1990 reference period). Abbreviations of districts: BR – Bruntál; CK – Český Krumlov; CR – Chrudim; FM – Frýdek-Místek; OP – Opava; KT – Klatovy; PT – Prachatice.

by especially warmer summers in the following years (significant in summers $n+1$ and $n+3$), but positive temperature anomalies compared to the reference period also appeared in the years $n-1$ to $n-4$ (Fig. 11a).

As for precipitation anomalies, they do not show such consistent patterns as temperatures do: the driest starting year of the outbreak was accompanied by those precipitation anomalies in $n+1$ and $n-2$ (significantly lower for both annual and summer values), while especially wet patterns occurred

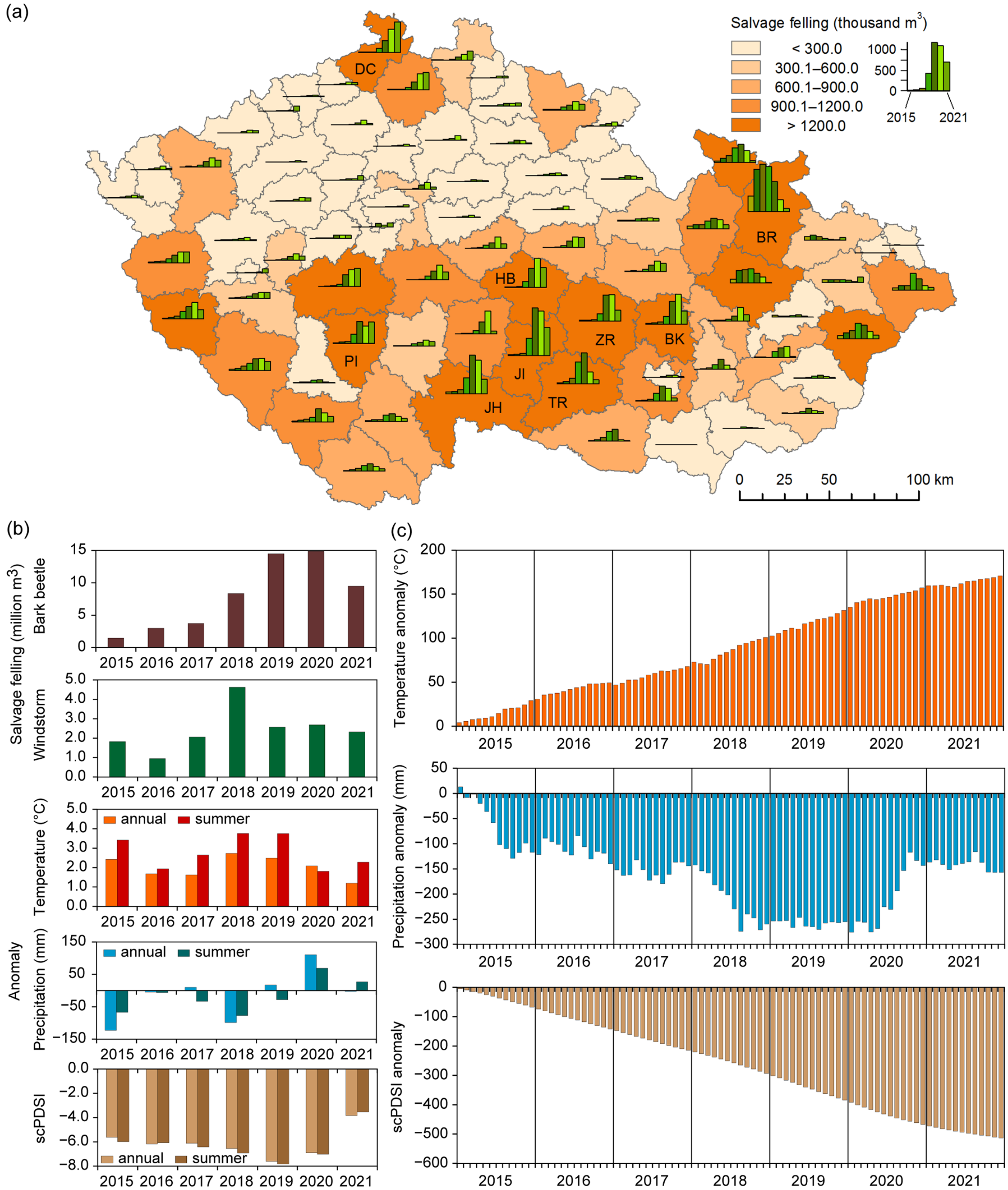

Figure 10. Bark beetle outbreak of the 2010s–2020s on the territory of the Czech Republic: **(a)** the volume of bark beetle salvage felling in 2015–2021 in individual districts; **(b)** annual bark beetle and windstorm salvage felling, annual and summer anomalies of temperature, precipitation, scPDSI-12, and scPDSI-3 in 2015–2021; **(c)** monthly cumulative anomalies of temperature, precipitation, and scPDSI in 2015–2021 (1961–1990 reference period). Abbreviations of districts: BK – Blansko; BR – Bruntál; DC – Děčín; HB – Havlíčkův Brod; JH – Jindřichův Hradec; JI – Jihlava; PI – Písek; TR – Třebíč; ZR – Žďár nad Sázavou.

in the years $n-5$ and $n+5$ (Fig. 11b). Most consistent patterns appear in a composite of annual and summer scPDSI anomalies, indicating growing dryness from the year $n-3$ to its maximum in the $n+1$ year, and after slightly smaller scPDSI in the following year $n+2$, they indicate an important weakening of dryness afterwards, i.e. from $n+3$. Both summer and annual values show significant negative deviations for 5 years centred around the starting outbreak year, that is, from $n-2$ to $n+2$ (Fig. 11c). This clearly demonstrates the importance of temperature and precipitation patterns (and

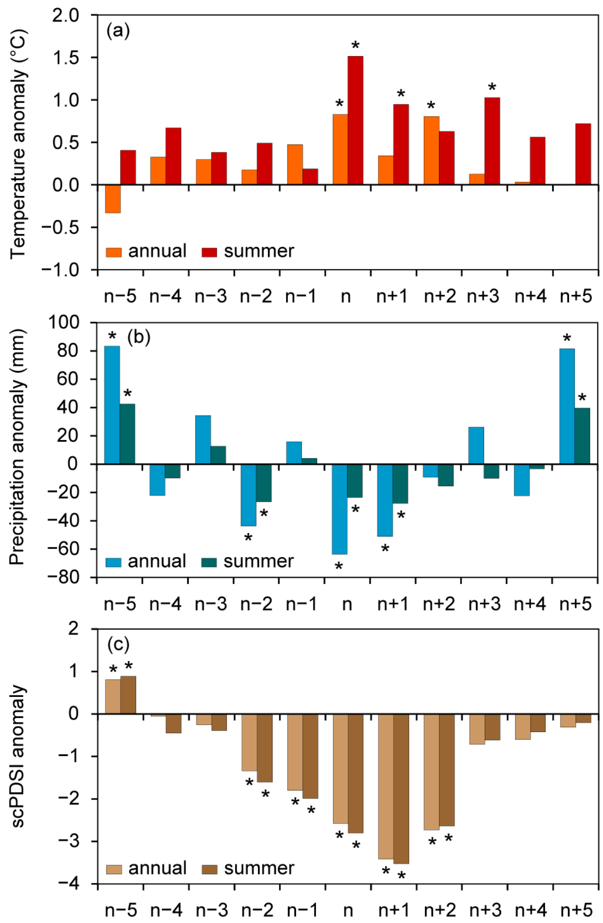

Figure 11. Composite of annual and summer temperatures **(a)**, precipitation **(b)**, and scPDSI-12 and scPDSI-3 **(c)** in the 5 years before (from $n-5$ until $n-1$) and 5 years after (from $n+1$ until $n+5$) the starting year (n) of bark beetle outbreak for the seven outstanding outbreaks of the 19th–21st centuries on the territory of the Czech Republic. Values are anomalies with respect to 1961–1990. Significant anomalies ($p < 0.05$) are indicated with asterisks, and they were defined as values exceeding 95 percentiles derived from 500 random samples using the bootstrapping method.

scPDSI as their combined effect) at the start of and 2 years following bark beetle outbreaks. But the triggering role of large windstorm calamities cannot be omitted here.

In order to analyse circulation patterns in the above key years of bark beetle outbreaks, we used an objective classification of circulation types (see Sect. 3) for the years $n-1$ to $n+2$ to compare composite relative frequencies of circulation types with their means in 1961–1990. Positive differences between them indicate higher relative frequencies of types in composite sets compared to those in the 1961–1990 reference period and vice versa. Because of the availability of objective classifications from 1961, we did composite analysis only for four selected outbreaks in the 1980s, 1990s, 2000s, and 2010s.

A composite of summers in the years $n-1$ to $n+2$ (Fig. 12) indicates statistically significant positive differences for the group of anticyclonic types (14.6 % in $n+1$ and 13.5 % in $n+2$), compensated for by significant negative differences for directional types in the summers n to $n+2$ as well as cyclonic types for $n+1$ and $n+2$ summers. As for individual circulation types, the type central anticyclone A shows significant positive differences (maximum 5.4 % in $n+2$) as well as other anticyclonic types with westerly airflow (maxima: anticyclonic southwestern ASW 4.9 % in $n+1$, anticyclonic western AW 4.9 % in $n+2$, anticyclonic northwestern ANW 3.9 % in $n+1$) (for schemes of these types see Fig. S2). These types are favourable for warm and dry weather in summer. For statistically significant differences in individual cyclonic circulation types there are characteristic rather negative deviations, achieving values primarily between −1 % and −2 %, despite the fact that during the first summer of bark beetle outbreaks the types CE (cyclonic eastern), CSE (cyclonic southeastern), and CNW (cyclonic northwestern) experienced positive differences. Among directional circulation types with significant differences, those with colder airflow from the north or east directions especially appear like the eastern type E with −2.6 % in $n+2$ summer (as significant also in $n-1$ and $n+1$) or the northern type N with −4.0 % in the summer n and −2.6 % in $n+2$. A similar dominance of anticyclonic types A, ASW, AW, and ANW, as in the summer, appears also in the annual composite, when cyclonic and directional types again show rather negative differences; but the number of circulation types with statistically significant differences is considerably smaller (not shown).

5 Discussion

5.1 The database and data uncertainty

Data concerning past and recent bark beetle outbreaks are biased by different types of uncertainties. As is typical of data collected from different documentary sources (e.g. Brázdil et al., 2005), they can only go into certain detail (e.g. forest stands belonging to any estate in the past without detailed specification into individual forest districts) and suffer by incompleteness; i.e. they represent rather lower estimates of spatiotemporal occurrences. Many reports of past bark beetle outbreaks suffer from missing quantitative data about the volume of damaged wood. Such data appear rather randomly in some reports without the possibility of obtaining total volumes for the whole country. If such country estimates do exist, they can differ from author to author or only repeat earlier presented data. Concerning older reports, in some cases not only could *Ips typographus* have been named as a primary pest damaging spruce trees, but information could be included on other pests or conifers (fir, pine), depending also on the related development of knowledge about forest pests (see Sect. 5.2). For example, the order of the Prague *Gubernium* from 1784 "points out a mass withering of spruce

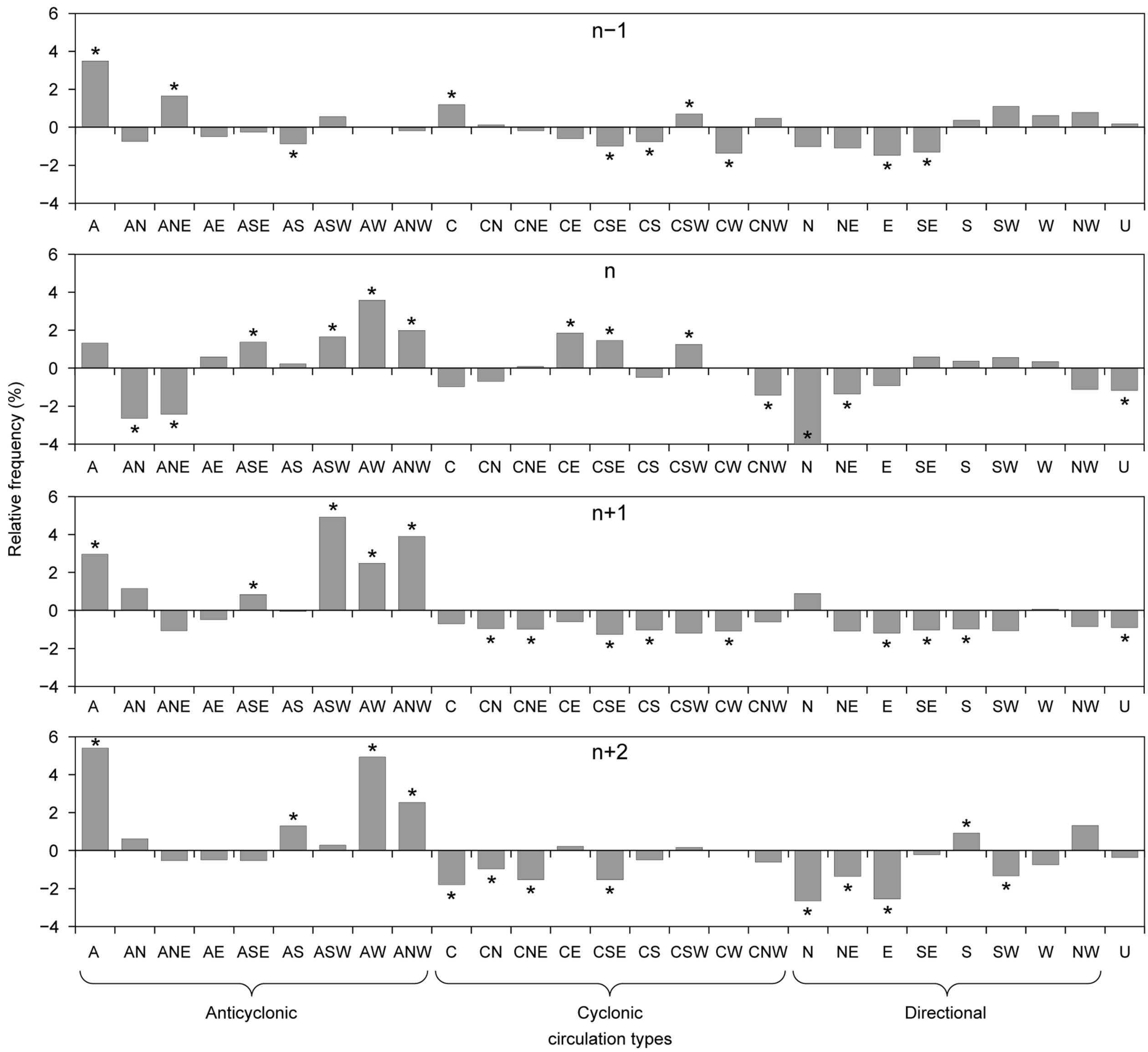

Figure 12. Differences in mean relative frequencies of individual circulation types of the objective classification in a composite of summers related to four bark beetle outbreaks from the 1980s (1982–1987, 1992–1995, 2007–2010, 2015–2021) and mean relative frequencies of the 1961–1990 reference period in the Czech Republic: $n-1$ – a year before the first year of a bark beetle outbreak (n) and 2 years $n+1$ and $n+2$ after the first year n. Symbol * indicates statistically significant differences.

and fir caused by worms between wood and bark, which cannot be killed ... " (Nechleba, 1929) and also reported them as "flying worms" (Lubojacký, 2012).

Concerning data about bark beetle salvage felling from 1964, some uncertainties may also appear there, like problems with a clear distinction between the volumes of salvage felling attributed to drought, air pollution, and bark beetle infestation, as reported by individual foresters. Concerning the homogeneity of the whole 1964–2021 series, political change in former Czechoslovakia after the Velvet Revolution in 1989 led to a change in the ownership of forest stands. The privatization of some forests (from former state ownership to private owners) after 1990 led to a lower number of reporting districts, i.e. data concern approximately three-quarters of the forest stands in the CR.

Despite the above uncertainties, the created database, covering the last 240 years, represents a unique source of information not only for the CR but also as an important contribution to the knowledge of past (historical) and present bark beetle outbreaks in Europe, complementing similar data from some other studies (see, e.g., Fig. 8 in Schelhaas et al., 2003). For example, Schafstall et al. (2022) found only three main bark beetle outbreaks between 1400 BP and the present in the High Tatras (Slovakia) (the last one post-2004 after the disastrous windstorm Elizabeth of 19 November 2004), in which *Ips typographus* was rather low in numbers. Moreover, bark beetles remain rather neglected in palaeoecology with only a few dozen reported sites in Europe for the whole of the Holocene (Schafstall et al., 2020).

5.2 Human responses to past bark beetle outbreaks

Studies on bark beetles were published as early as the 18th century, especially by foresters from Saxony, which was hit by a severe bark beetle outbreak in the 1780s (Jäger, 1798; Dallinger, 1798), similar to the Czech Lands (see Sect. 4.1.1). These works also mention that beetles had been destroying spruce stands for centuries, for example, in the Harz mountains in north-central Germany. Similarly, in the Czech Lands, Trzebitzky (1798) published a practical handbook on the drying out of needle-leaved forests, in which he discussed bark beetles as well. Bark beetles also remained a much discussed topic in the first half of the 19th century (e.g. Krutzsch, 1825), but, according to Pfeifer (1875), in the 1820s there was still a general lack of knowledge among local foresters concerning bark beetles. Such early studies mainly focused on the natural history of bark beetles in order to come up with a device for forestry managers to prevent outbreaks. The 1830s outbreak led to the publication of management guidelines by the Czech *Gubernium* on the handling of beetle-infected forest stands (Nožička, 1957).

The outbreak following the 1868 and 1870 windstorms led to intense interest in the topic. First, the logistics of removing huge numbers of infected trunks posed considerable challenges. For example, in the Šumava Mts, the processing of damaged trees required the construction of new roads and tracks. To obtain access to the forests, 33 000 trunks in the Vimperk area had to be processed in November 1870 (Záloha, 1970). Moreover, seven water sawmills were newly created and 850 workers from Bohemia and Bavaria were hired, of whom 670 worked throughout the summer of 1871. However, it was clear that infected trees could not be removed quickly enough. This created societal tensions as well. An attempt to save money with the hiring of foreign workers after the 1870 windstorm was reported on the Prášily estate. The local forester hired only 50 foreign workers to process the windstorm-damaged trees, and, together with local workers, they were unable to debark all trunks in time, and a subsequent bark beetle outbreak threatened the forests of the surrounding estates, including those in neighbouring Bavaria (US8, pp. 217–218). The owner of the Chodová Planá estate warned his forest employees in 1875 that they were not allowed to speak publicly about the calamity and that all the data about the felling were an official secret. This was a reaction to newspaper articles criticizing the estate for its insufficient measures against bark beetles (US9, pp. 117–118).

The catastrophe also shook the foundations of the forestry profession. The Society of Bohemian Foresters (Böhmischer Forstverein) – the main forum for exchanging knowledge on forestry in the country – kept the topic on its agenda. Lively discussions on bark beetles took place at the plenary meetings of the society every year from 1870 to 1875. In the beginning, most contributions focused on technical solutions, such as the use of "trap trees" (to attract bark beetles) or the swift removal and burning of infected tree bark. Only occasional references were made to alternative methods; for example, the protection of birds, being as they are the natural enemies of bark beetles (Vereinsschrift für Forst-, Jagd- und Naturkunde, 1872, p. 64). In 1874, however, *Forstmeister* Alois Nedobitý argued that the outbreak could to a large extent be blamed on the foresters themselves. The forced removal of dead trees was counterproductive because it prevented those useful insects from developing that could slow down the procreation of bark beetles (Vereinsschrift für Forst-, Jagd- und Naturkunde, 1874, p. 66). A year later, *Forstmeister* Soucha made an appeal to the entire nation (and, by implication, to all Czech foresters) to reconsider clear-cuts and tree planting as their preferred way of forest regeneration. What the bark beetle outbreak taught foresters, he argued, was that natural regeneration was plentiful under the damaged trees if only foresters did not destroy it through tree removal (Vereinsschrift für Forst-, Jagd- und Naturkunde, 1875, pp. 150–157). However, reactions to such contributions were not favourable and cutting remained the main method to combat bark beetle outbreaks.

In the following decades, the focus of foresters shifted from bark beetles to other insects, mainly the nun moth, which caused much more damage in this period (Syrovátka, 1922). However, the catastrophes of the latter were used as opportunities to carry out comparative studies on bark beetles in the 1920s (e.g. Komárek, 1925). Some attention reverted to bark beetles as a result of the outbreak in 1944–1947. New perspectives were also included: for example, Pfeffer (1952) wrote that this outbreak was the first that was not directly connected to a previous windstorm. Rather, the proximate cause was the excessive harvesting of spruces during World War II that were often left lying in forests.

As the state gradually took over the management of forests from estates, regulations concerning bark beetles started to be included in national legislation. The first and second forest laws of Czechoslovakia (1960 and 1977) both included passages on bark beetles, mainly on the obligations of forest owners to find and remove infected trees. Following the outbreak of the 1980s, special instructions for fighting bark beetles were issued by the Ministry for Forestry and Water Management (Lubojacký, 2012). Mutatis mutandis, all these instructions followed the general principles established in the 19th century without questioning their general validity or effectiveness.

5.3 Environment, climate, and bark beetle outbreaks

Bark beetle outbreaks in the 19th century appear to have occurred mostly at higher altitudes, where the presence of extensive spruce stands can be expected. Even though conifer plantations started in the Czech Lands after 1800 (Nožička, 1968), discussions after the bark beetle outbreak in the 1870s suggest that many, if not most, stands affected were not yet spruce monocultures. More detailed studies would be needed to confirm this, but the prevailing method of dealing with outbreaks (removing all infected trees) and artificial forest regeneration – as observed by foresters in the 19th century – may have contributed to creating forests that were increasingly susceptible to windstorms (Brázdil et al., 2018b) and also to bark beetle outbreaks. In addition, in the 20th century, spruce was extensively planted in even-aged monocultures in lower-lying regions. While such regions were not hit by bark beetle in the 1940s–1950s (Fig. 6), they suffered considerable damage from the 1980s onwards (Figs. 7–10). The planting of extensive conifer monocultures reduced the biodiversity of Czech forests, exhausted the soil, and increased the susceptibility of forests to natural disasters (e.g. through even-aged structure, mutual competition for essential nutrients, lack of space for the root system and treetop) (Daniel et al., 2013). Without the existence of conifers monocultures in the lowlands and at middle altitudes, forests would be composed especially of oak, beech, and fir (Neuhäuslová et al., 1997). However, in the last few years, the area covered by spruce monoculture plantations in the CR declined from 54.1 % in 2000 to about 48.8 % in 2020, which should contribute to the attenuation of the above-mentioned negative phenomena (Ministerstvo zemědělství, 2021).

The analysis of past and recent large bark beetle outbreaks in the CR demonstrates the importance of meteorological (windstorms) and climatological (temperature and precipitation, resulting in droughts) factors as the main triggers of such outbreaks (cf. Fig. 11), appearing as a manifestation of long-term climate variability, enhanced by recent climate change (cf. Fig. 3). These results are confirmed by many other European studies, demonstrating the importance of temperatures for the development and voltinism of bark beetles (e.g. Annila, 1969; Wermelinger and Seifert, 1998, 1999; Jönsson et al., 2009), heavy windstorms as drivers of subsequent bark beetle outbreaks (e.g. Temperli et al., 2013; Thom et al., 2013; Stadelmann et al., 2014; Seidl and Rammer, 2017; Brázdil et al., 2018a), and droughts accompanied by high temperatures as other key factors in producing disastrous outbreaks (e.g. Marini et al., 2017; Matthews et al., 2018; Netherer et al., 2019; Hlásny et al., 2021b; Jaime et al., 2022).

Unsurprisingly, many researchers address the problem of bark beetle outbreaks in the context of future climate change manifest in global warming, the latter of which will contribute to worsening conditions for spruce forests (e.g. Hlásny et al., 2011; Jönsson et al., 2011; Berec et al., 2013; Jakoby et al., 2019; Sommerfeld et al., 2020). Hlásny et al. (2021a) summarized the effects of climate change on bark beetles as being factors facilitating their survival and development, increasing their potential to spread to higher altitudes and latitudes, and contributing to reduced tree resistance due to extreme weather/climatic extremes.

Recent climate developments in the CR are characterized by continuous warming in past decades, enhanced from the 1980s and especially from the 2010s (Zahradníček et al., 2021, 2022), and relatively stable precipitation totals (Brázdil et al., 2021) with increasing soil dryness (Trnka et al., 2015; Řehoř et al., 2021b), and this with the simultaneous effects of windstorms creates suitable conditions for increasing climatic stress on forest stands, resulting in bark beetle outbreaks. The consequences for Norway spruce plantation in the CR from climate change will be further enhanced by the fact that climate projections to 2041–2060 indicate that suitable conditions for spruce only comprise 11.3 % of the area of Czech forests, while in 1961–1990 it was 46.0 % (Čermák et al., 2021).

In 7 years from 2015 to 2021, the recent bark beetle devastation of forests in the CR destroyed 55.46×10^6 m^3 of wood, which is more than the total for the previous 51 years (34.80×10^6 m^3) for which quantitative bark beetle salvage felling data are available (cf. Fig. 2). The highest annual bark beetle felling in 2020 (14.89×10^6 m^3) was not exceeded by any other biotic factors (other insects, gnawing of trees by wild animals, mushroom pathogens) nor by any abiotic factors (wind, snow, rime, drought, air pollution). As follows from Fig. 13a, bark beetle salvage felling was higher than that caused by windstorms since 1964 only in 1995 and then from 2016 onwards, giving for the last outbreak in 2015–2021 more than 3 times higher volumes than in the case of windstorms (17.03×10^6 m^3). The highest windstorm salvage felling was recorded in 1990 with 8.77×10^6 m^3 of wood (i.e. before the 1992–1995 bark beetle outbreak) and in 2007 with 8.84×10^6 m^3, followed in 2008 by 4.85×10^6 m^3 (i.e. during the 2007–2010 outbreak). Another well-expressed maximum appeared in 1982–1987 outbreak with 5.94×10^6 m^3 in 1984 and 6.50×10^6 m^3 in 1985. There is a clear relationship to extreme windstorms, such as Kyrill in 2007 or Emma in 2008, while the annual frequency of selected severe windstorms across the CR in the months January–March together with October–December (Fig. 13b) does not show any clear relationship to damaged and processed wood. The dominant proportion of windstorms of the winter half year in volumes of salvage felling was disturbed only by the summer windstorm on 12–13 July 1984 (see Brázdil et al., 2018b).

Besides environmental, cultural, and socio-economic consequences, the recent devastation of spruce forest stands and the subsequent formation of forest hollows due to the felling of trees influence fluxes of CO_2 between forests and the atmosphere, when places cleared of trees enhance fluxes of CO_2 from the soil to the atmosphere (Hlásny et al., 2021a). This means that such stands can change from being CO_2

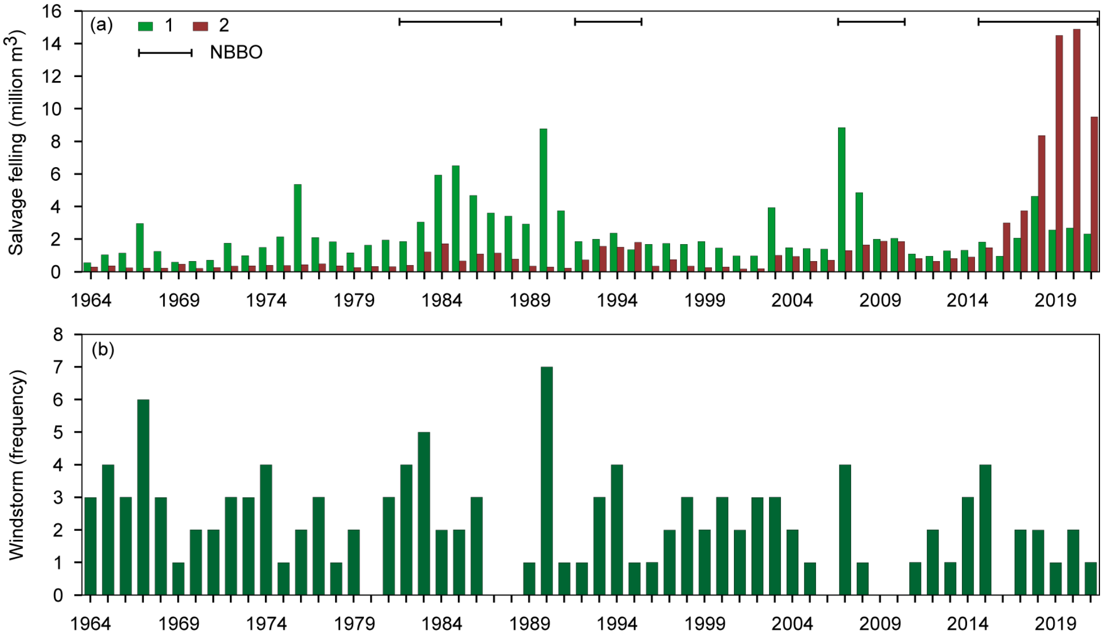

Figure 13. Comparison of bark beetle outbreaks and windstorms in the Czech Republic during the 1964–2021 period (NBBO – notable bark beetle outbreak): **(a)** volumes of annual salvage felling attributed to windstorms (1) and bark beetle infestation (2); **(b)** annual frequency of severe windstorms for January–March and October–December.

sinks to CO_2 sources, as has already occurred since 2018 in the CR (e.g. CENIA, 2021), and in such ways indirectly impact the climate by producing this important greenhouse gas (13.6 Mt CO_2 eq. for 2019 in LULUCF – land use, land-use change, and forestry). As follows from inventorying greenhouse gases produced in the CR, the forests have become sources of increasing CO_2, further promoting the "anthropogenic" footprint of greenhouse gas (GHG) emissions due to the deterioration of the health conditions of forests caused by bark beetle infestation and droughts (e.g. CENIA, 2021).

6 Conclusion

From a systematic analysis of meteorological and climatological triggers of the notable past and present bark beetle outbreaks in the CR for the 18th–21st centuries, the following conclusions can be summarized:

i. Different types of documentary sources and bark beetle salvage felling were used to create a unique database of the past bark beetle occurrences and their impacts on the territory of the CR from the 18th century to the present. The database allowed us to analyse the spatiotemporal variability in bark beetle outbreaks and select the most notable bark beetle outbreaks from 1781 CE.

ii. Disastrous bark beetle outbreaks of the 19th century in the 1830s and 1870s were triggered by extreme windstorms, when it was not possible to quickly remove a large volume of blowdown wood from forest stands, thus creating good conditions for bark beetle expansions. The drought episodes following windstorm disturbances intensified devastating bark beetle effects.

iii. Disastrous bark beetle outbreaks in the 1980s, 1990s, 2000s, and 2010s are attributed to recent climate change, triggered by the compound effect of windstorms, strongly increasing temperatures, and relatively stable precipitation totals of the past decades, resulting in extreme droughts when many spruce stands now appear to be located in unsuitable environmental conditions, being more susceptible to different disturbances such as those by the bark beetle.

iv. The last bark beetle outbreak in the CR from the mid-2010s forced by high temperatures and drought has no documented historical analogue to its scope and its devastating effects on Czech spruce forests. It has contributed to the fact that Czech forests have become sources of CO_2 since 2018, further increasing the anthropogenic footprint of GHG emissions.

v. Despite great attention devoted to the recent and potential future bark beetle outbreaks forced by recent climate change, there is a great potential to learn more from the past. This study demonstrates a high potential of documentary evidence for the creation of similar databases for other European regions to better understand the natural and socio-economic development that led to the recent situation.

Appendix A: Unpublished sources

Ústav pro hospodářskou úpravu lesů, Brandýs nad Labem: Historický průzkum lesů (Forest History Research).

US1: Málek, J. (1965): Lesní závod Telč (Forest plant Telč).

US2: Tlapák, J. (1960): Lesní závod Červené Poříčí (Forest plant Červené Poříčí).

US3: Ministr, J. (1964): Lesní hospodářský celek Bečov I a II (Forest economic complex Bečov I and II).

US4: Ministr, J. (1963): Jednotný hospodářský celek Kašperské Hory I a II (United economic complex Kašperské Hory I and II).

US5: Ministr, J. (1960): Jednotný hospodářský celek Přísečnice (United economic complex Přísečnice).

US6: Horák, K. (1968): Lesní hospodářský celek Choceň II. Lesní závod Vysoké Chvojno (Forest economic complex Choceň II. Forest plant Vysoké Chvojno).

US7: Hošek, E. (1961): Lesní hospodářský celek Maršov a Trutnov (Forest economic complex Maršov and Trutnov).

US8: Stolařík, R. (1974): Lesní hospodářský celek Modrava (Forest economic complex Modrava).

US9: Ministr, J. (1969): Lesní hospodářský celek Planá I. II. III. Lesní závod Planá u Mar. Lázní (Forest economic complex Planá I, II, III. Forest plant Planá at Mariánské Lázně).

Data availability. The datasets and series used in this article are not publicly available and can be obtained only by personal request.

Supplement. The supplement related to this article is available online at: https://doi.org/10.5194/cp-18-2155-2022-supplement.

Author contributions. RB extended bark beetle chronology and designed and wrote the paper with contributions from all co-authors. PZ provided all data related to bark beetle and abiotic salvage felling and prepared the first version of bark beetle chronology. PS dealt with responses to bark beetle outbreaks. KC worked with the analysis of salvage felling together with climatic conditions and finalized all figures. PD contributed to composite analysis. LD collected digital copies related to bark beetle information from Forest History Research. MT calculated scPDSI series and contributed to relationship of bark beetle forest devastation and CO_2 production. JŘ analysed the relationship of more recent bark beetle outbreaks to circulation types. SS excerpted bark beetle data from *Neue Schriften*. All authors have read and commented on the latest version of the paper.

Competing interests. The contact author has declared that none of the authors has any competing interests.

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Acknowledgements. Rudolf Brázdil, Petr Dobrovolný, Lukáš Dolák, and Miroslav Trnka were supported by the Ministry of Education, Youth and Sports of the Czech Republic for the SustES – Adaptation strategies for sustainable ecosystem services and food security under adverse environmental conditions (project no. CZ.02.1.01/0.0/0.0/16_019/0000797), Petr Zahradník by the Ministry of Agriculture of the Czech Republic, institutional support MZE-RO0118, Péter Szabó and Silvie Suchánková by the long-term research development project no. RVO 67985939, Kateřina Chromá by Global Change Research Institute of the Czech Academy of Sciences, and Jan Řehoř by Masaryk University within MUNI/A/1393/2021. We acknowledge Petr Štěpánek (Brno) for Czech temperature and precipitation series, Laughton Chandler (Charleston, SC) for English style corrections, and particularly critical comments of the anonymous reviewer and the second reviewer, Neil Macdonald (Liverpool), with his important English style corrections.

Financial support. This research has been supported by the Ministry of Education, Youth and Sports of the Czech Republic (grant no. CZ.02.1.01/0.0/0.0/16_019/0000797), the Ministry of Agriculture of the Czech Republic (institutional support MZE-RO0118), the long-term research development (project no. RVO 67985939), the Global Change Research Institute of the Czech Academy of Sciences, and the Masaryk University (grant no. MUNI/A/1393/2021).

Review statement. This paper was edited by Jürg Luterbacher and reviewed by Neil Macdonald and one anonymous referee.

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