Climate, *Picea abies* stand state, and *Ips typographus* in the Czech Republic from a viewpoint of long-term dynamics

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Abstract

For description of changing climate in the Czech Republic, 38 meteorological stations with complete data on basic weather variables since 1961 were selected. Development of air temperature with increase of 0.37 °C per 10 years, relative air humidity and precipitations was described. Precipitations were evaluated on the base of wetness index, which identify periods of drought. Norway spruce (*Picea abies* L.) is the most important commercial tree species in the Czech Republic. Spruce bark beetle (*Ips typographus* L.), is the most important species of bark beetles associated with coniferous forests in this region and is known as a driver of development of Norway spruce forests. A basic question is how are spruce and bark beetle influenced by changing climate during the period of precise instrumental weather measurement. Yearly *I. typographus* dynamics was evaluated using the PHENIPS model. Earlier onset of *I. typographus* infestation (by 1.9 days per 10 years, which value is greater at higher altitudes) and acceleration of *I. typographus* development (*G* index increasing by 0.07 per 10 years) are documented. Climatic stress was modelled using daily air temperature and relative humidity data. It developed nonlinearly: until 1990 fluctuating around the mean, then increasing significantly, when we see a decrease in modelled mean radial increase by about 20%. The basic factor for accelerating the *I. typographus* gradation is the occurrence of climatically extreme conditions creating strong climatic stress for Norway spruce.

Keywords: air temperature, air relative humidity, climatic stress, sanitation felling, growth index, PHENIPS model, wetness

Introduction

Climate, consisting in the long-term state of the atmosphere, or weather as its immediate condition, is one of the most important environmental factors. It is important both for describing the current ecosystems, their geographical distribution, and species composition (e.g., FRANKLIN 2009) and for understanding the dynamics of ecosystems and their parts. Climate has always changed and never has been a stable element (consider, for example, the alternation of glacial and interglacial periods), but, due to the short period that is modern human history, it might seem that climate was more or less constant until now. After it became clear that the global climate has been changing relatively faster in recent decades, the term *climate change* was introduced to underscore the fact of accelerated climate dynamics and the problems resulting from it. A detailed analysis of the issue with regard to forests in the Czech Republic was provided by MATĚJKA (2019).

Based on the measured temperatures in the Czech Republic between 1961 and 1990, temperature norms were published (KVĚTOŇ 2001). The development of a set of weather characteristics between 1961 and 1998 was evaluated in HUTH ET POKORNÁ (2004). Since 1998, however, a number of extreme situations have occurred and several episodes of temperature and precipitation extremes (mainly maximum temperatures) have appeared. NEKOVÁŘ ET POKORNÝ (2012), for example, dealt with temperature change within similar periods but limited regions. Rainfall, again for a single region, was analysed in the work of DOLEŽELOVÁ (2012). MATĚJKA (2021a) presented graphs summarizing the development of "territorial temperatures" (average temperatures in a given territory, which are related to the mean altitude of the given territory) and "territorial precipitation" (similarly mean precipitation totals for the territory) within the Czech Republic based upon data published by the Czech Hydrometeorological Institute in Prague (www.chmi.cz, section historical data). PRETEL (2012) provided a brief overview of changes in these territorial weather characteristics. In the paper MATĚJKA (2021a), trends in the development of data for individual months or for whole years are evaluated using linear regression analysis in the period from 1961. The basic conclusions of the analysis of changes in territorial parameters over the last 60 years can be summarized as follows (see Supplementary material 1): The average annual temperature for the entire monitored period was 7.9 °C. Cold years were concentrated at the beginning of the observed period, these were the years 1962, 1980 and 1996 (6.3 °C), 1995 (6.4 °C) and 1963 (6.5 °C). On the contrary, the warmest years were 2018 (9.6 °C), 2019 (9.5 °C), 2015 and 2014 (9.4 °C) and the three years 2000 - 2007 - 2020 (with the same temperature of 9.1 °C).

Overall, the average annual temperature increased significantly by 0.0344 °C/year ($p <$ 0.01%). In the winter months from December to February, the mean temperature increase was 0.0420 °C/year. In the months of the growing season (May to August), the increase was similar, 0.0411 °C/year. The most temperature-stable period of the year is early autumn (September and October).

Temperatures were stable until 1982, and increasing temperatures are visible from 1983. Since 1995, the mean annual increase in temperature has been 0.0602 °C/year. Until 1994, a significant increase was observed in January and August, but in following years the temperature increase occurred mainly in November and December.

A different picture can be seen in the period of intense vegetation growth during the months of May to August (vegetation season, which period can be defined variously): In this period, the average temperature was 15.8 °C and the years with the warmest vegetation season were 2018 (18.5 °C), 2003 (18.4 °C), 1992 (17.7 °C), 2002 (17.6 °C), and 2015 (17.5 °C). The temperature-extreme year 2003, often mentioned in ecology studies (e.g., REBETEZ ET AL. 2006), although not exceptionally warm as a whole (with an average of 7.6 °C), was very warm at the beginning of summer (May and June, respectively, at 15.1 ° C and 15.5 °C).

For the monitored period as a whole, the average annual rainfall was 673 mm. The mean annual increase in precipitation totals calculated for the entire period 1961–2020 was only 0.329 mm/year.

A winter increase in precipitation totals was observed in January. In February and March, we see little to no change in precipitation sums. Precipitations in March 1961–1980 were very even. There is a clear decrease in precipitation during April. That decrease continues in May and June, but less pronouncedly so. An increase in totals can then be seen in July. August is invariable in terms of precipitation. September and October show an overall increase in precipitation totals, but this change appears variously in the different subperiods.

We should take notice of any events of extremely high precipitation totals and flooding. Winter extremes were recorded in December 1974 (104 mm, 225% of the 1961–2016 average), January 1976 (104 mm, 246%), and February 1970 (87 mm, 237%). The spring period does not have higher rainfall totals, but there were extremes in March 2000 (117 mm, 273%) and in April 1965 (80 mm, 187%). Extreme totals during the growing season were as follow: May in 1965 (141 mm, 196%) and 2010 (133 mm, 185%), June in 2020 (152 mm, 181%) and 2013 (146 mm, 178%), July in 1997 (204 mm, 240%), August in 2002 (177 mm, 227%), September in 2007 (117 mm, 214%), and October in 1998 (113 mm, 256%). Only insignificant extremes have been recorded in November. Overall, the winter (December to February) extremes occurred in the 1970s. Spring–summer (March to August) extremely high precipitation totals have been observed since 1997. The 1980s to the mid-1990s were characterized by even or lower precipitation totals. The occurrence of floods should also be related to the occurrence of extreme precipitation. It is interesting that the frequency of floods on the Vltava and Elbe rivers was minimal in the 1960s (KYSELÝ ET AL. 2008) and, at the same time, the occurrence of extremely high summer precipitation totals is not mentioned above from this period. At the same time, however, flood activity has been increasing since the 1970s, with a peak at the turn of the 1970s and 1980s. Further attenuation is apparently related also to the functioning of the constructed dam cascade.

Similar to high precipitation totals, the occurrence of dry periods, which were described in TREML (2011) for the period since 1875, is also essential for the analysis. Although the three driest years occurred toward the end of the observed period (516 mm in 2003, 521 mm in 2018, and 532 mm in 2015), even in the first part of the period from 1961 dry years were occurring more frequently (539 mm in 1982, 542 mm in 1973, 567 mm in 1969).

From the precipitation point of view, July appears to be the least stable. In that month, a slight decrease in precipitation totals was seen in the period 1983–1994 and a contrasting increase in these totals is visible in the following period. This last period also includes the two years 2002 and 2010, with the highest annual rainfall totals, as well as the two years 2003 and 2015 with the lowest totals. During the growing season (May–August), the driest years were 1990 (201 mm), 2015 (210 mm), 1992 (214 mm), and 2018 (215 mm). The highest rainfall totals in this period of the year were recorded in 2010 (475 mm), 1966 (447 mm), 2002 (409 mm), and 1965 (407 mm).

In evaluating long-term weather changes, a comparison with the period of the so-called climate normal, which was established for the period 1961–1990 (KVĚTOŇ 2001), is often used. This comparison period ("normal") is unfortunately purposefully shifted in some studies (for example, to 1971–2000 or 1981–2010). One of the latest works (BRÁZDIL ET AL. 2022a) is based on a comparison of the two periods 1961–1990 and 1991–2020 and is in accordance with the analysis MATĚJKA (2021a). This work also shows that linear regression of the monitored variables has different parameters in the two periods, but it does not ask whether the change occurs between 1990 and 1991 or at some other time. According to previous analyses, the period of this change could be the years 1994/1995 (MATĚJKA 2014).

Direct damage to forest stands is caused by strong winds that appear irregularly in different parts of the year. In recent decades, strong winds have been associated mostly with named storms: 18 January 2007 (Kyrill; see HOSTÝNEK, NOVÁK, ŽÁK 2008), 1 March 2008 (Emma; see HOSTÝNEK, NOVÁK, ŽÁK 2008), 31 March 2015 (Niklas), 29 October 2017 (Herwart; see TOLASZ ET AL. 2018), 24 August 2018, 10 February 2020 (Sabine), and many others. Such disintegration of forest stands is often associated with the initialization of bark beetle gradations on Norway spruce (*Picea abies*).

Traditionally, the relationship between the growth of tree species and weather is considered, and on that basis the methodology of tree ring analyses has been developed. Seen less frequently is detailed analysis endeavouring to define the parts of the year when a certain factor (temperature, precipitation, etc.) has the most significant positive or negative effect on the growth of a tree species. For *P. abies* in the Czech Republic, Vejpustková (2022) tried to do something similar while considering average monthly values. A more sophisticated procedure was chosen in the work of Mondek et al. (2021), when the authors forewent arbitrarily predetermined periods (months) and generally looked for some interval of days within the year when growth of the tree species is most strongly affected (correlated with a selected climate parameter).

Spruce bark beetle, *Ips typographus* (Linnaeus, 1758), is the most important bark beetle species associated with coniferous forests in the conditions of the entire Palaearctic region (Christiansen et Bakke 1988), especially for its ability to multiply exponentially. It is the species of natural occurring in the whole Norway spruce area. During the period of its latency, the beetle is found in low population densities that do not allow it to attack healthy living trees. Violation of the equilibrium state occurs either by an increase in the beetle's population density or by a decrease in the trees' resistance (Kausrud et al. 2012). Usually, there is an increase in the population density of the beetle following a wind disturbance, after which the clearings are easily occupied due to their weaker defence (Schroeder 2001). Higher reproductive success on felled wood (Komonen et al. 2011) then enables the beetle's population density to increase above the threshold necessary to attack standing trees (Berryman et Kindlmann 2008). Spruce vitality is most often reduced due to periods of drought, which limit the trees' ability to effectively defend themselves against attack of the beetle (Netherer et al. 2015) and enable a lower local population density to be sufficient for successful colonization of standing trees (Lieutier 2004). Uprooting of trees by wind has been considered one of the main triggers of large beetle gradations (Økland et Berryman 2004), and this has been confirmed also by analyses of salvage logging from the Czech Republic for the period 1964–1991 (Modlinger et Novotný 2015). In the past 30 years, however, we have observed a higher frequency and intensity of drought periods (Brázdil et al. 2022a), after which significant waves of *I. typographus* gradation occurred, for example in the Šumava Mts. (Bohemian Forest) after 1994 and 2003 (Kindlmann et al. 2012) or gradually after 2015 across most territory of the Czech Republic (Hlásny et al. 2021). It is apparent that in recent years changing conditions have been leading to decrease in forests' resistance (Forzieri et al. 2021) and probably also to a fundamental transition to drought-driven bark beetle dynamics (Hlásny et al. 2021). The increase in mean temperatures that has been observed in the past 30 years (Brázdil et al. 2022a) not only reduces the resistance of trees but also fundamentally affects the speed of bark beetle offspring's development (Wermelinger et Seifert 1999) and the number of generations that insect can develop within a year (Wermelinger 2004, Marini et al. 2016).

Increase in the number of bark beetle generations in connection with global climate change has been predicted on a continental (Jönsson et al. 2011) and regional scale (Hlásny et al. 2011). In both studies Jönsson et al. (2011) and Hlásny et al. (2011), various climate scenarios were used and development in the period 2010–2022 was predicted.

The aim of this study was to evaluate data from weather stations of the Czech Hydrometeorological Institute in such a way as to describe also changes in the vitality of spruce stands and spread of the bark beetle after 1961, when the first such data became available (CHMI 2021), up to 2020. Based on these data, climatic stress on Norway spruce was modelled. A further aim was to verify change in the number of generations of spruce bark beetle modelled on the basis of meteorological variable measurements using the PHENIPS model (Baier et al. 2007) as it has been validated for conditions of the Czech Republic (Berec et al. 2013).

Methods

Daily data from individual meteorological stations (CHMI 2021) was imported into the MS SQL server database. The CHMI stations were classified according to their location in the terrain (Matějka 2021; LANDTYP parameter):

F = station in formerly forested landscape,
A = station in formerly agricultural landscape, and
C = station surrounded by constructions.

A set of 38 basic stations (Table 1) was selected so that measurements were carried out at them in the period from 1961 to 2020 for all the main parameters, which are air temperature and humidity at 2 m above the ground, amount of precipitation, and length of the sunshine period (data gaps in shorter periods are possible). Only two stations are located in positions that can be assumed influenced by a nearby river's water level (C2VBRO01 and P1PKLE01).

Moving average of the monitored variables were calculated for the stated characteristics and selected stations with windows of 30, 90, and 365 days. Averages of air temperature, relative humidity, and yearly precipitation sum were calculated for each decade.

Table 1. Selected meteorological stations of the CHMI and their locations

Indicative	Station name	Longitude (°)	Latitude (°)	Altitude (m)	LANDTYP[a]
B1HOLE01	Holešov	17.570000	49.320556	222	A
B1PROT01	Protivanov	16.831050	49.477820	675	A
B1STRZ01	Strážnice	17.338100	48.899200	176	A
B2BTUR01	Brno, Tuřany	16.688889	49.153056	241	A
B2KMYS01	Kostelní Myslová	15.439167	49.159167	569	A
B2KUCH01	Kuchařovice	16.085278	48.881111	334	A
B2LEDN01	Lednice	16.798895	48.792616	177	A
B2NEDV01	Nedvězí	16.309700	49.634400	722	A
B2VMEZ01	Velké Meziříčí	16.008600	49.352800	452	C
C1CHUR01	Churáňov	13.615278	49.068333	1118	F
C1VRAZ01	Vráž	14.128900	49.384400	433	A
C2JHRA01	Jindřichův Hradec, Děbolín	14.957500	49.155600	524	A
C2TABO01	Tábor, Měšice	14.703240	49.405270	467	C
C2VBRO01	Vyšší Brod	14.314400	48.617500	559	C
H3HRAD01	Hradec Králové, Nový Hradec Králové	15.838452	50.177649	278	A
H3SVRA01	Svratouch	16.034167	49.735000	734	A
L1KLAT01	Klatovy	13.303016	49.390420	421	C
L2KRAL01	Kralovice	13.494007	49.981823	449	C
L2PRIM01	Přimda	12.678056	49.669444	743	F
L3CHEB01	Cheb	12.391389	50.068333	483	A
O1CERV01	Červená	17.541944	49.777222	748	F
O1LYSA01	Lysá hora	18.447500	49.546111	1322	F
O1MOSN01	Mošnov	18.112778	49.691944	253	A
O1OPAV01	Opava, Otice	17.876100	49.919700	270	A
O2OLOM01	Olomouc, Holice	17.284400	49.575800	210	C
O2PASE01	Paseka	17.234500	49.777600	271	A
O3PRER01	Přerov	17.458889	49.464444	210	A
O3VALM01	Valašské Meziříčí	17.974200	49.463600	334	C
P1NEUM01	Neumětely	14.037500	49.854200	322	A
P1PKAR01	Praha, Karlov	14.427778	50.069167	261	C
P1PKLE01	Praha, Klementinum	14.416923	50.086634	191	C
P1PRUZ01	Praha, Ruzyně	14.255556	50.100278	364	A
P2BRAN01	Brandýs nad Labem-Stará Boleslav	14.660600	50.189700	179	C
P2SEMC01	Semčice	15.003600	50.367100	234	A
P3PRIB01	Přibyslav, Hřiště	15.762500	49.582778	533	A
U1DOKS01	Doksany	14.170000	50.458890	158	A
U1ZATE01	Žatec	13.543190	50.341470	210	C
U2LIBC01	Liberec	15.023890	50.769720	398	A

[a] A = station in formerly agricultural landscape, C = station surrounded by constructions, F = station in formerly forested landscape.

Wetness index

For each day of the year, the wetness index (W) was calculated according to MATĚJKA (2014). This calculation was based on rainfall data for the 150 days preceding the given date. Furthermore, the standardized value of this index was calculated according to the equation

$$W_{rel} = (W - W_{avg}[d])/W_{std}[d] \tag{1}$$

relative to the average $W_{avg}[d]$ and standard deviation $W_{std}[d]$ for the relevant day d of the year, where the average and standard deviation were calculated for the period 1961–1990. For the indices W (which have significant periodicity within the year according to the annual course of precipitation) and W_{rel} (which is independent of the day of year and for which a normal distribution can be assumed, and so we can easily derive the limit values), we assume their connection with stress of the spruce caused by the lack of precipitation and thus also with the trees' predisposition to be attacked by bark beetle.

Weather (climate) stress in *Picea abies*

Spruce stress as a result of weather parameters' development in individual years was calculated based on an analysis of annual radial increments as determined by tree ring analysis. Tree ring index data from the work of MONDEK ET AL. (2021) were used. This analysis was performed for 121 *P. abies* individuals from research plots near Písek in South Bohemia, using tree-ring indices from 1962 to 2019 and meteorological data from the CHMI Vráž station (indicative C1VRAZ01). It shows that radial growth of Norway spruce is mostly influenced by average air temperature $T_{avg}(225;30)$, average maximum air temperature $T_{max}(20;345)$, average minimum air temperature $T_{min}(20;335)$, and average relative air humidity $H_{avg}(230;60)$. Each of these variables $Var(D,P)$ was calculated for an interval P days in length ending on the D-th day of the year. Correlations between tree ring indices and these variables are significant. Therefore, a multiple regression was calculated in the form

$$\begin{aligned} GI = a + b_{\text{t-avg}}\, T_{avg}(225;30) + b_{\text{t-max}}\, T_{max}(20;345) + \\ b_{\text{t-min}}\, T_{min}(20;335) + b_{\text{h-avg}}\, H_{avg}(230;60) \end{aligned} \tag{2}$$

This regression is highly significant. The calculated regression coefficients a, $b_{t\text{-}avg}$, $b_{t\text{-}max}$, $b_{t\text{-}min}$, and $b_{h\text{-}avg}$ were used to calculate the spruce growth index GI at each of the CHMI stations for which measurement data of basic meteorological elements (air temperature and humidity, total rainfall, and duration of sunshine) for the period 1961–2020 are available. There were 38 stations from the Czech Republic (Table 1). Because the conditions at the stations (especially their altitude) vary substantially, there is considerable interstation variability. Therefore, a standardized growth index was calculated for each year Y as follows

$$gi_{\text{Y}} = GI_{\text{Y}} - avg(GI_{1962\text{–}1990}), \tag{3}$$

where $avg(GI_{1962\text{–}1990})$ is the arithmetic mean of GI within the period 1962 to 1990.

PHENIPS model

The PHENIPS model (BAIER ET AL. 2007) needs as one input parameter the daily value of global radiation, which is not available for use from the stations. For CHMI stations, the sunshine duration is used, which is recalculated by the program to estimate global radiation according to MATĚJKA (2021b):

$$E = \alpha\, e_T^{\varepsilon}(s_0 + s^{\sigma}), \qquad (4)$$

where e_T is the theoretical radiation at the atmospheric boundary ($\mathrm{MJ.m^{-2}.d^{-1}}$), s is the sunshine time ($\mathrm{h.d^{-1}}$), and E is the global radiation ($\mathrm{MJ.\ m^{-2}.d^{-1}}$). Based on nonlinear regression analysis, parameters α, ε, and s_0 were estimated for Mrzky station ($r^2 = 0.938$).

Realization of the PHENIPS model (Matějka 2021c) calculates infestation date as term when the temperature sum according to equation A.8 in Baier et al. (2007) exceeds the limit. For each day after infestation, sums of effective bark temperatures according to equations A.10 – A.12 (Baier et al. 2007) are divided by the sum temperature constant which is necessary for total development of parental generation. This ration is labelled as G value. Final dimensionless G value in the year corresponds to number of finalized bark beetle generations (integer part of G) and stage of development of the last incomplete generation. The following parameters were used for the PHENIPS model, which was applied as the new software (Matějka 2021c):

Start day = 80 (day of the year for calculation begin)
K = 557 (sum temperature limit)
Day length = 14.5 (day length conditioning the transition to diapause)
Glag = 0 (coefficient for delaying the begin of infestation)

Compared to the original proposal of the model (Start day = 92; Baier et al. 2007), the first value was adjusted for the reason that the growing season starts significantly earlier, and especially in recent years, and thus the spring *I. typographus* infestation was several times observed earlier. Moreover, if there is a cold onset of spring, the values of the additive model increase only slowly, if at all, in the first few days, and the final modelling results are only slightly affected.

The PHENIPS model was calculated for each CHMI meteorological station for which data on daily average temperatures, daily maximum temperatures, and daily hours of sunshine are available for a given year. The I_{DoY} values, representing the day of the year when infestation probably occurs, and G values at the time of the end of *I. typographus* development in autumn were stored in the database. The G values were plotted in maps for selected years. Stations where the PHENIPS model was calculated for at least 50 years within the period 1961–2020 were selected for further calculation. There are 53 such stations.

A linear correlation analysis was performed between the year of measurement y and the respective values $I_{DOY}(y)$ and $G(y)$ in the form:

$$I_{DOY}(y) = a_I + b_I\, y \qquad (5)$$

$$G(y) = a_G + b_G\, y \qquad (6)$$

The regression coefficients b_I and b_G describe the shift rate of the infestation and the rate of change of the index G. Next, the potential dependence of the calculated coefficients b_I and b_G on the landscape category (using one-way analysis of variance) and altitude (using linear regression analysis) was analysed. The values of these coefficients were displayed in point maps.

Bark beetle sanitation felling data in the Czech Republic

Data on volume of bark beetle felling in the years 1964–1991 were taken from Modlinger et Novotný (2015). This data comes from records of the Forests of Czech Republic state enterprise provided on standardized forms (Form L116). After 1991, there were restitutions of forest property and the share of state-owned forests decreased by more than 40%. The follow-up record of harmful agents has only been consolidated since 1998, covers approximately 70% of the Czech Republic, and is provided on a voluntary basis. In order to maintain continuity with previous records, we decided to use data collected by the Czech Statistical Office (CSO) since 1992. These data are based on the reports of economically active entities (both state and nonstate owners). Bark beetle fellings are included into the CSO's records within the volume of wood harvested as a result of all insect pests, but the share of damage caused by other types of insects has been negligible since 1992.

Results

Table 2 summarizes the development of basic climate characteristics in the set of 38 evaluated stations according to individual decades, and running averages are plotted in figures S3-1–S3-4 of Supplementary material 3. For completeness, the values of the last two years were also added, when the trends from the previous periods are not preserved. Trends for all basic variables at each station are enumerated in Supplementary material 2.

Table 2. Average climate characteristics in the set of selected meteorological stations by decades: T = average air temperature, H = average relative air humidity, R = average annual sum of precipitation.

From	To	T [°C]	H [%]	R [mm]
1961	1970	7.3	78.5	653.2
1971	1980	7.6	77.7	621.4
1981	1990	7.8	76.8	622.4
1991	2000	8.2	76.7	624.5
2001	2010	8.5	77.6	665.2
2011	2020	9.3	74.7	612.6
2021	2022	9.0	74.2	619.9

The annual average air temperature across all 38 evaluated stations increased over the 60 years by a statistically significantly 0.37 °C per 10 years ($r = 0.3636$; $p > 0.999$; Figures 1, S3-1–S3-2). The temperature averages of the warmest and coldest quarters increased even more according to the extremes of the 90-day moving average (both by 0.46 °C per 10 years). The growth of average temperatures differed at individual stations within the range from 0.23 °C per 10 years (at Žatec) to 0.47 °C per 10 years (at Praha-Klementinum). The greatest dispersion is seen at the stations at the lowest altitudes, where the character of their surroundings is significantly variable. On the contrary, at higher altitudes, where stations are more often located in forest landscapes, the variability is minimal (ranging between 0.34 °C per 10 years at Lysá hora and 0.37 °C per 10 years at Červená).

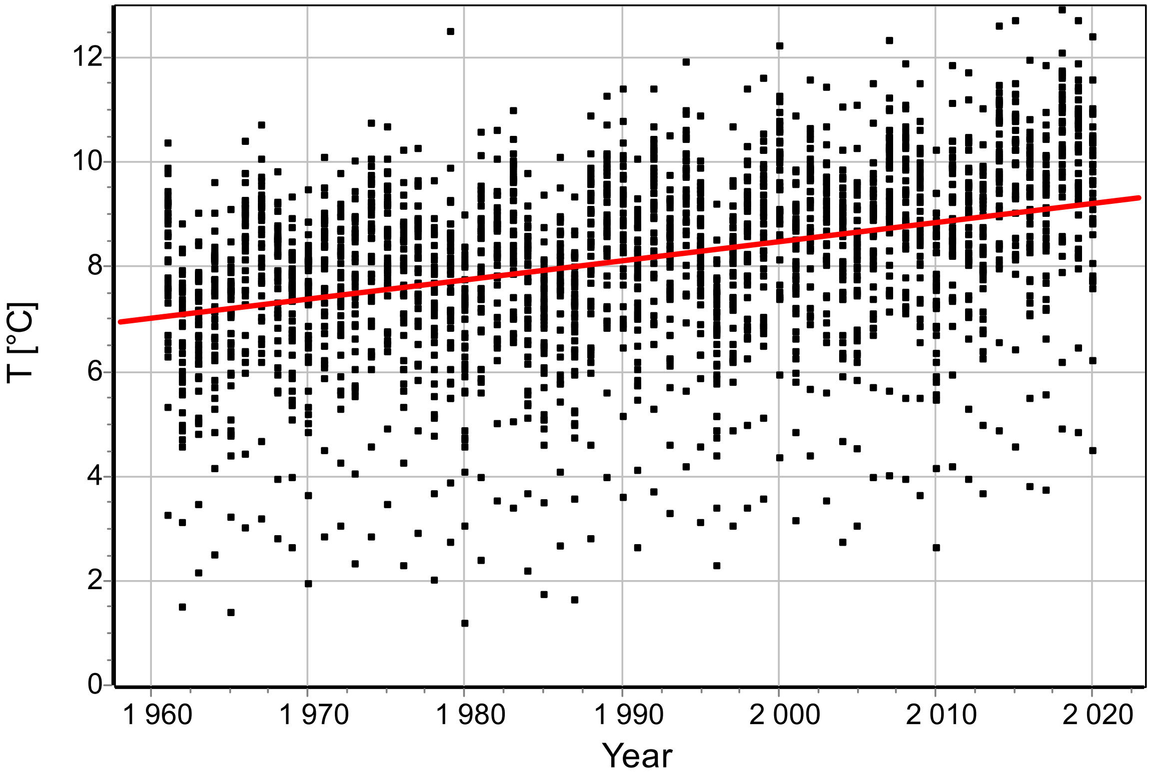

Figure 1. Average annual air temperature according to 38 selected meteorological stations between 1961 and 2020. Regression T = −64.616 + 0. 03654 Y (r = 0. 3636; p > 0.999).

The relative air humidity was highly variable, decrease -0.549 % per 10 years is statistically significant (r = −0.5072; Figures S3-3–S3-4). Precipitation sums were highly variable without any trend (Figures S3-5–S3-6).

Wetness conditions (average of W_{rel} values at all evaluated stations; Figures 2, S3-7–S3-8) were highly variable in individual years without any trend (r = 0.002, W_{rel} average = 0.036). The lowest values corresponding to the deepest drought were found in 1973, 1991, 2003, 2015, and 2018. If we only observe the period of intensive growth in the growing season (April to August; r = −0.147, W_{rel} average = −0.002), we find the lowest values in 1976, 1993, 2003, 2015, and 2018, with insignificant decrease (p = 0.133).

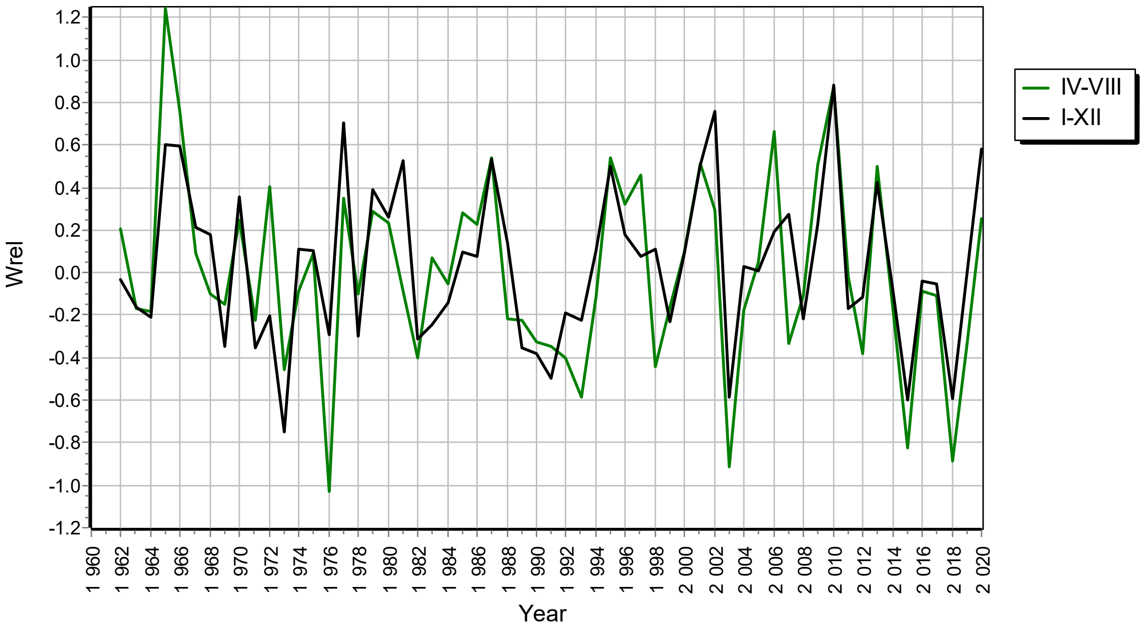

Figure 2. Wetness index (W_{rel}) according to 38 selected meteorological stations from 1962 to 2020. Displayed are average values for whole years (months I–XII) and for growing seasons (months IV–VIII).

PHENIPS model

Stations' classification according to their locations was insignificant both for the change in start of infestation (b_I; $n = 38$, F-test ANOVA $p = 0.13$) and change in the generation number and achieved stage of *I. typographus* development (b_G; $n = 38$, F-test ANOVA $p = 0.97$).

Across the entire Czech Republic in the period from 1961, the earliest infestation start was day 91 of the year and the latest was day 165th of the year. Depending on the shortening of the day length in the given locality, the end of the *I. typographus* development occurred on day 224 to 229 day of the year.

According to the all-monitored-station data, during the 60 years, the beginning of the *I. typographus* infestation has shifted to an earlier time ($n = 3039$; $r = -0.2810$; $p < 0.001$; Figure 3), its beginning shifting by a mean 11.4 days during that time. Altitude has an effect on shifting the infestation start to an earlier time ($n = 38$; $r = -0.4945$; $p = 0.002$; $b_I = -0.1366\text{-}9.5485\ 10^{-5}\ A$, where A is altitude in m). The infestation date accelerates more significantly at higher altitude. A similar relationship for the value of b_G is insignificant.

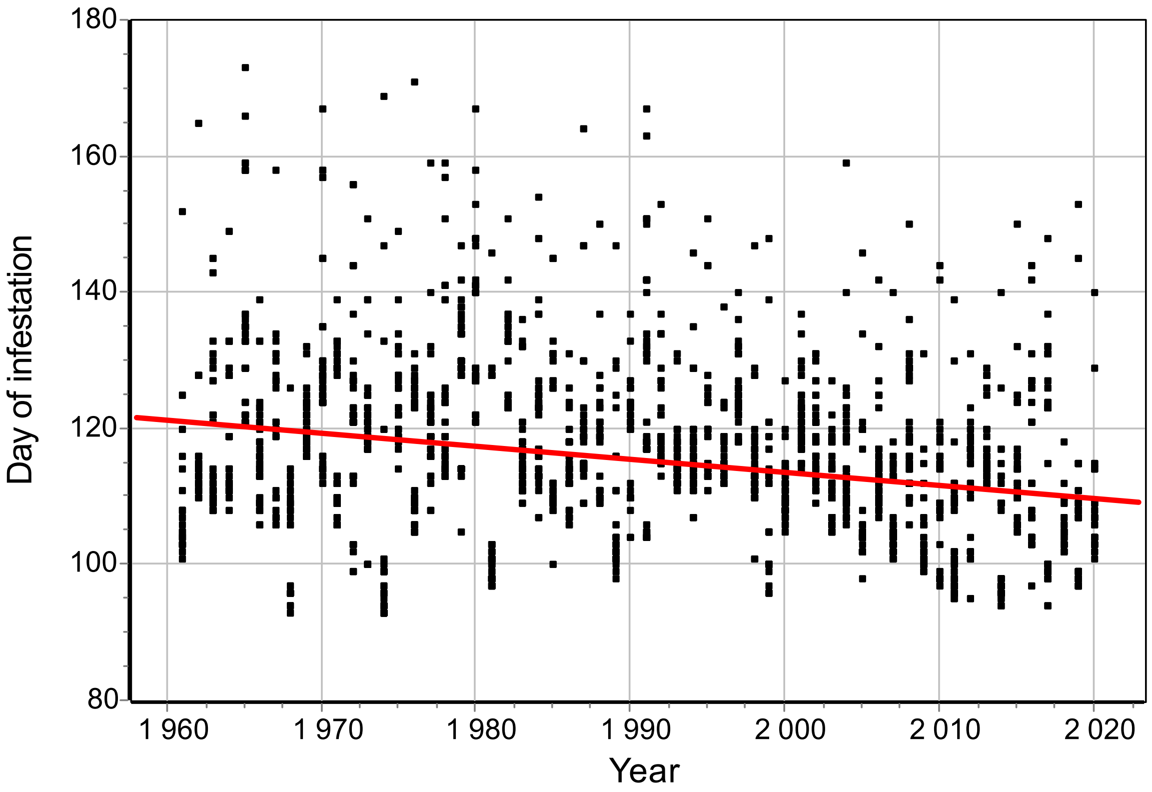

Figure 3. Day of *Ips typographus* first infestation modelled according to 38 selected meteorological stations between 1961 and 2020. Regression $Day = 493.04\text{-}0.\ 18978\ Y$ ($r = -0.\ 2810$; $p < 0.001$).

The distribution of localities according to the stage of the *I. typographus* development changes significantly across the entire monitored interval. For the first period, the comparison year 1975 (Figure 4) was chosen and shows small deviation from the mean values of temperature and precipitation. The calculated values of the *G* index were around 1.6 at most stations. After 20 years (Figure 5), the situation has changed only slightly, the values of the *G* index have increased to approximately 1.8 to 2.2. The year 1995 is at the same time a year when the nature of the weather changes, in particular the annual distribution of precipitation changes and droughts occur more frequently. The year 2014 (Figure 6) is the first year in the final series of significantly warm and dry years when there was a significant *I. typographus* gradation. Especially in southern and central Moravia and in the Elbe region, the *G* index mostly rose to values of around 2.2. The year 2018 (Figure 7) was the most extreme, with high summer temperatures and severe drought. This is reflected also in the calculated *G* index, which often exceeds 2.4, not only in the warmest areas but also at medium altitudes.

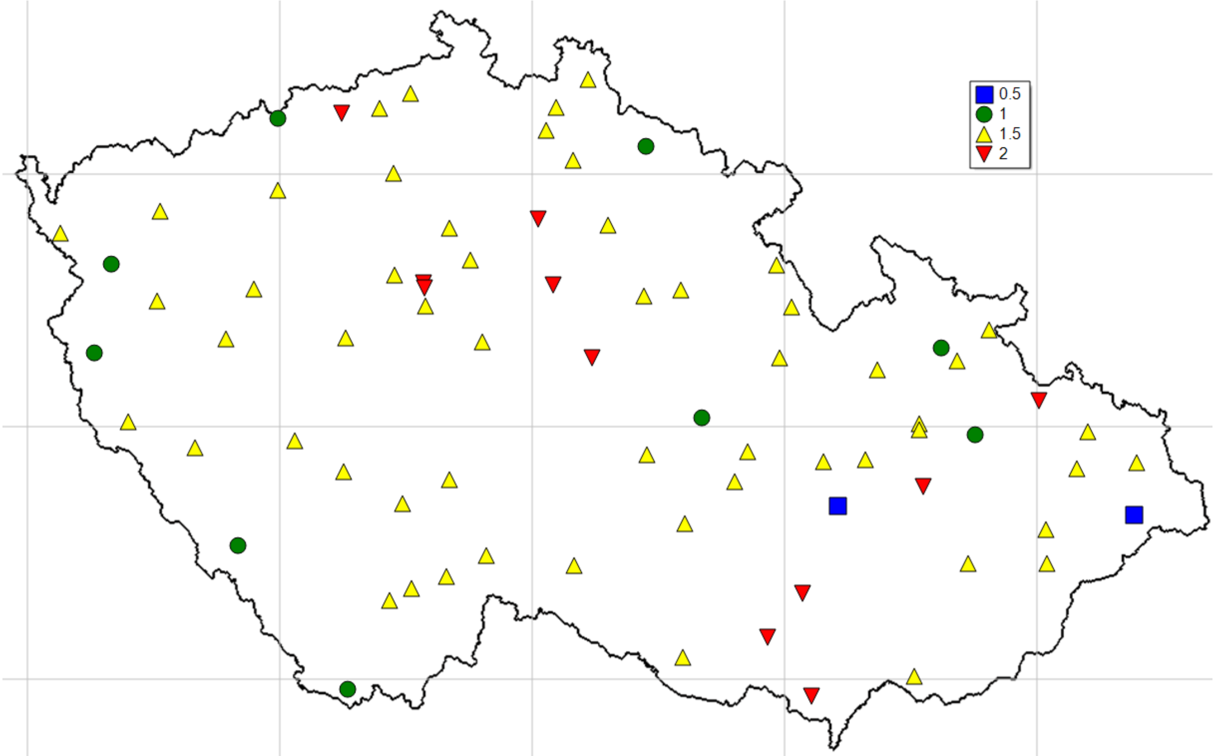

Figure 4. Maximum value of the *G* index - degree of development of *Ips typographus* in the Czech Republic in 1975.

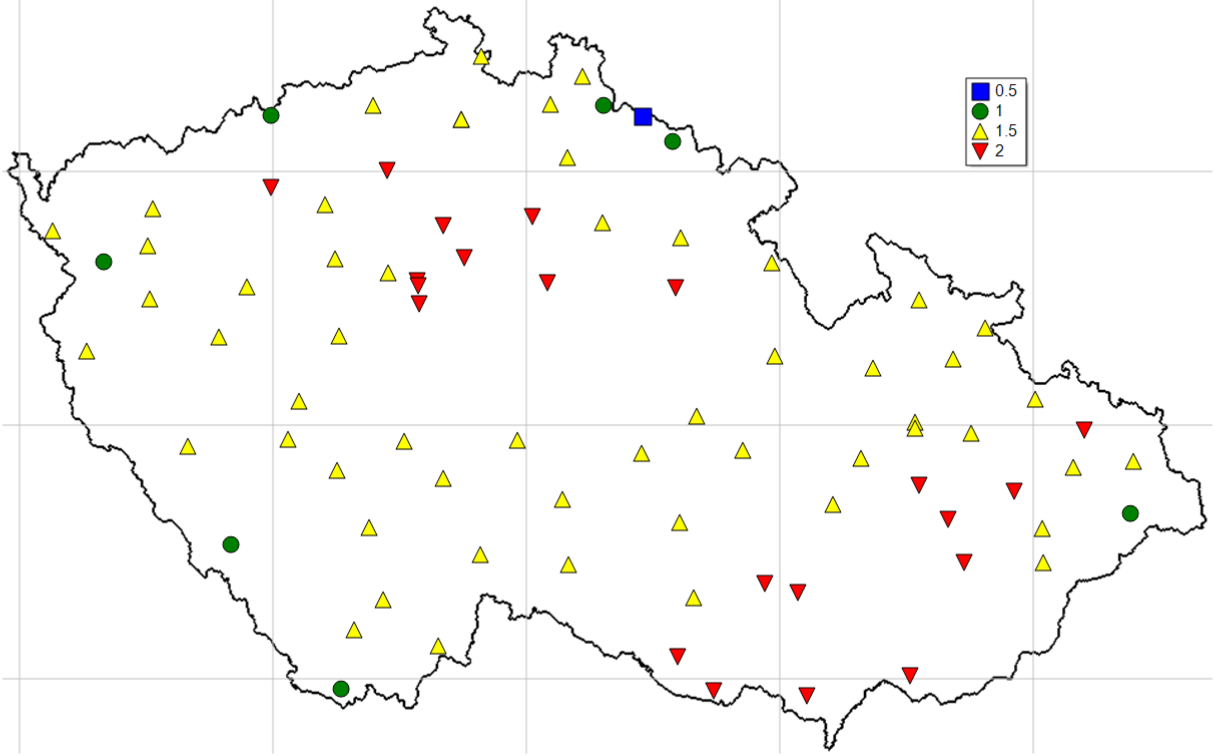

Figure 5. Maximum value of the *G* index - degree of development of *Ips typographus* in the Czech Republic in 1995.

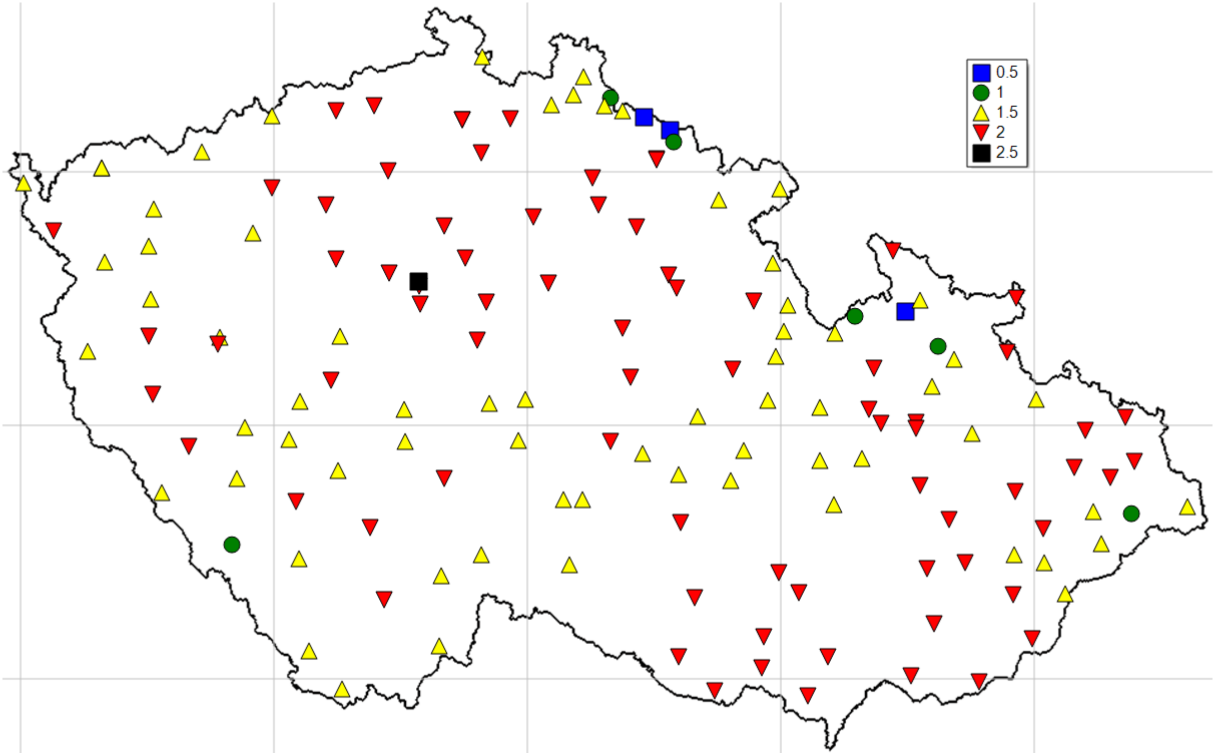

Figure 6. Maximum value of the *G* index - degree of development of *Ips typographus* in the Czech Republic in 2014.

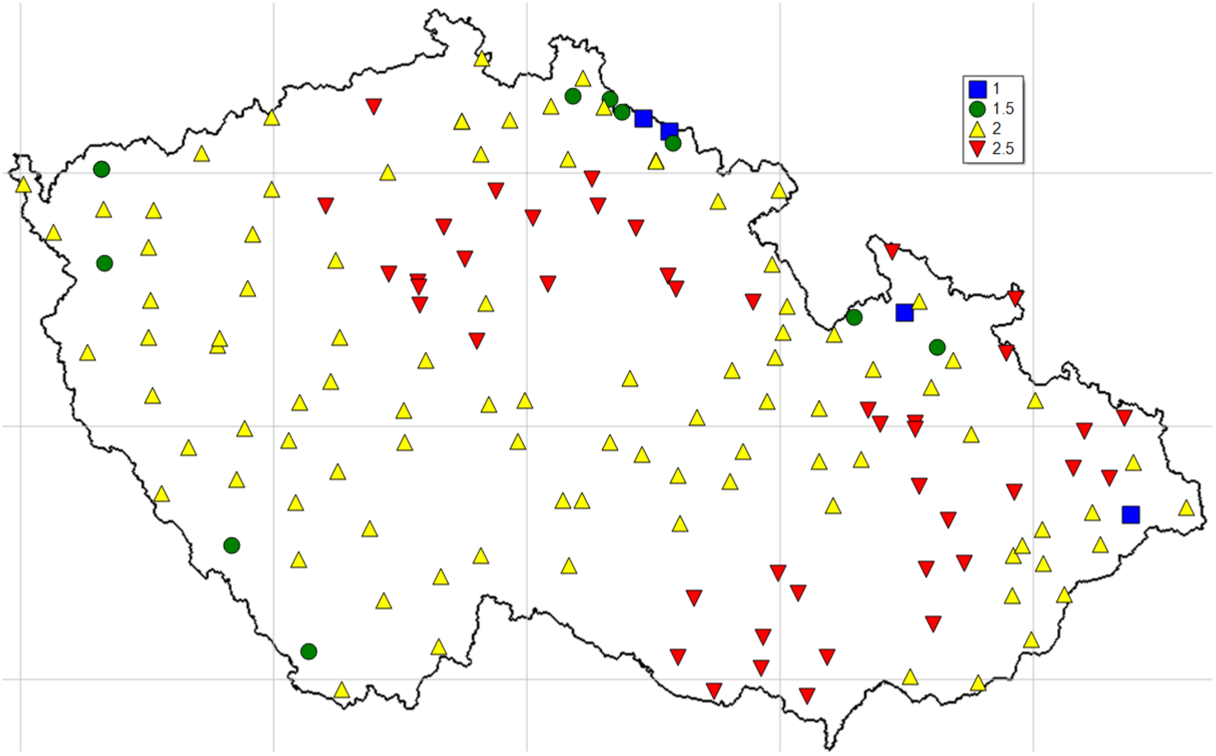

Figure 7. Maximum value of the *G* index - degree of development of *Ips typographus* in the Czech Republic in 2018.

The *I. typographus* development stage as evaluated by the *G* index was strongly influenced by increasing mean temperatures so that the values of *G* also increased significantly by 0.42 during the 60 years ($n = 3038$; $r = 0.3593$; $p > 0.999$), i.e., by almost half a generation (Figure 8). This change corresponds fully to the mean increase in air temperatures (Figure 9). It can be seen from the graph that for the first 20 years the values of the *G* index were rather steady and the lowest value was recorded in 1980. This was followed by a period of accelerated rise in the index, which peaked in the climatically extreme year 2003. Thereafter, this development slowed. The highest values of G were then recorded in 2018, which was a year with extremely high temperatures during the growing season for the Czech Republic.

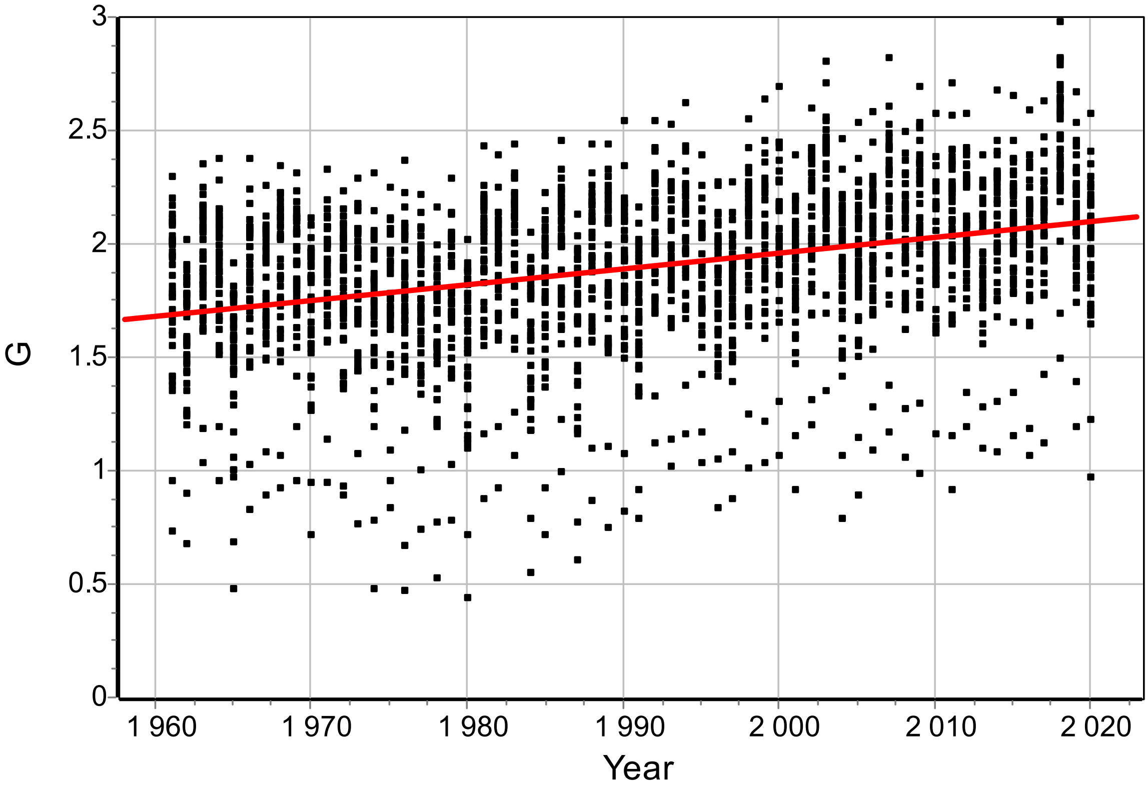

Figure 8. Final *Ips typographus* state of development modelled according to 38 selected meteorological stations between 1961 and 2020. Regression $G = -12.090+0.00702\ Y$ ($r = 0.3593$; $p > 0.999$).

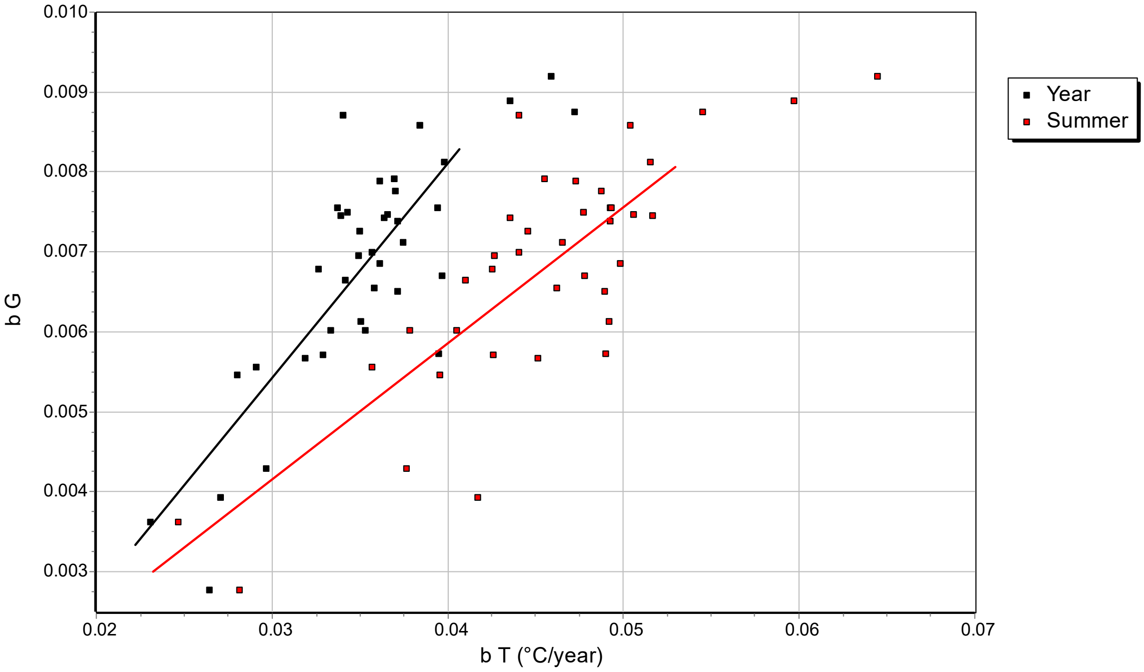

Figure 9. Dependence of change in final degree of *Ips typographus* development state (b_G) on average air temperature change (b_T) in the year and during the warmest 90-day period (summer). The three stations with the highest temperature increase were not included into the regression.

If we compare the regression coefficient b of the linear regression for the temperature change (b_T) and the change in the index G (b_G) over time, we see their dependence up to a certain limit: for the increase in the mean annual temperature, it is a value of 0.41 °C / 10 years and for the increase in the mean temperature in summer (the warmest 90-day period) the value is 0.53 °C / 10 years (Figure 9). These limit values were exceeded at three extreme stations in lowlands: Brno-Tuřany, Paseka, and Praha-Klementinum. The linear regression of the b_T and b_G is statistically significant in both cases (with the exceptions of the three mentioned stations): for the change in average annual temperature, $r = 0.776$ and for the change in average summer temperature, $r = 0.766$ (in both cases $p > 0.999$).

Weather (climate) stress of *Picea abies*

The relative growth index for *P. abies* (*GI*) has been decreasing for localities in the Czech Republic since approximately 1990, with the lowest value (equal to the greatest stress) having been reached in 2018. The value of this index fluctuated around 1.0 prior to 1990, but by the end of the next 30 years it had decreased to approximately 0.8 (i.e., by 20%). It is also necessary to draw attention to the decreases of the curve in the years 1976, 1983, 1990, 1994, 2003–2004, 2015, and 2018–2019. The persistent decrease since 2012 is especially noticeable. All the named years represented significant physiological stress manifest in Norway spruce growth and at the same time correspond to individual bark beetle gradations during 1983–1984, 1992–1996, 2003–2004 (continuing at less level until 2010), and 2015–present (Figure 10). By comparing to the occurrence of drought (Figure 2), it is clear that the droughts in 1973 and 1991 did not increase the climatic stress on spruce. In the past two decades, by contrast, droughts in combination with high mean air temperatures have significantly affected that stress.

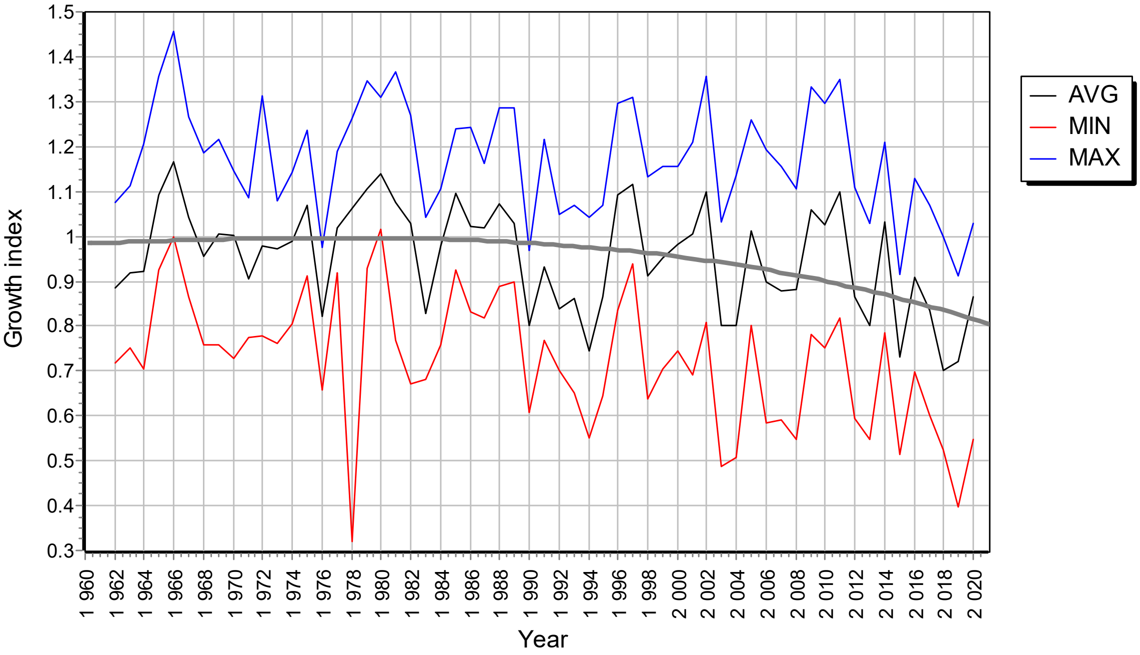

Figure 10. Average, minimum, and maximum of the relative growth index for *Picea abies* (*gi*) at 38 selected meteorological stations in the years 1962 to 2020. Values are smoothed by regression with polynomial of 3rd degree.

Influence of temperature anomalies on volume of bark beetle felling

Data for bark beetle felling in the Czech Republic have been collected since 1964 (Figure 11). Although reported volumes were minimal in the 1960s and 1970s, several waves of bark beetle gradation have been recorded since the 1980s.

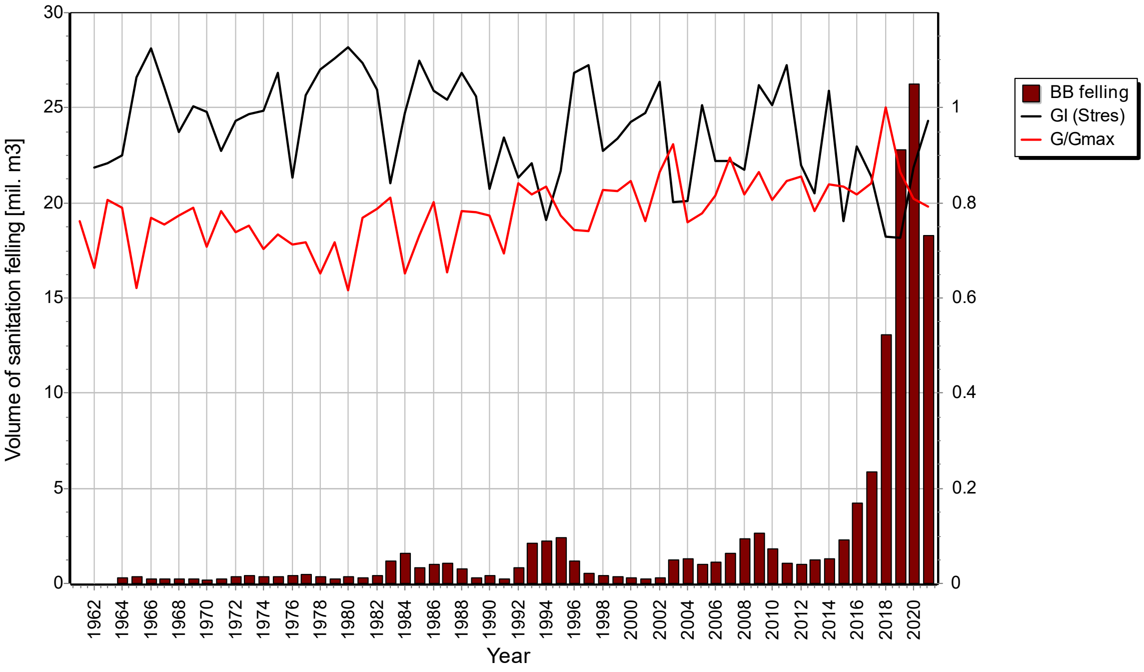

Figure 11. Development of reported bark beetle felling in the Czech Republic compared to the relative growth index for *Picea abies* (*gi*) indicating degree of climate stress and to the *G* index of the PHENIPS model relatively to the maximum value in 2018 (G/G_{max}).

The first wave of bark beetle harvesting, occurring around 1984, is associated with an increase in the *G* index in 1981, which lasted until 1983. Additionally, in 1983, spruce growth conditions were extremely unfavourable, as shown by a reduced value of the *GI* index indicating high stress.

The second wave, culminating in the years 1993–1995, is again associated with more intensive bark beetle development (i.e., with an increase in the value of *G* already in 1992). This increase lasted until 1994. The growth stress on Norway spruce increased until 1994 (i.e., *GI* values decreased).

The third wave started from 2003. The *G* index had climbed further in 2002 from already high values in preceding years. It should be noted that, with some exceptions, the *G* index did not decrease until the end of the evaluated period. During 2003–2004, strong growth stress on spruce was observed, indicated by reduced *GI* values.

The last and most significant wave started in 2015. The highest *G*-index values so far associated with an increase in the bark beetle development state were recorded in 2018. We see extremely high Norway spruce growth stress (reduced *GI* values) in 2015 and 2018–2019.

If we compare the individual waves and the incidence of drought using the calculated wetness index, we can state that the first recorded droughts in 1973 and 1976 did not result in increased bark beetle felling. Droughts in 1991 and 1993 were followed by a 2nd felling wave from 1993. The extreme 2003 drought was associated with a 3rd felling wave. The drought in 2015 started the 4th, extremely high wave of bark beetle felling, and this was accelerated further by the drought in 2018 and 2019.

Discussion

Increasing pressure of disturbance agents in forest ecosystems during recent decades has been observed at regional (Kunca et al. 2019), continental (Patacca et al. 2023), and hemispheric (KAUTZ ET AL. 2017) levels. It is obvious that the cause of this phenomenon must be some globally acting factor, and this undoubtedly is the course of the weather. Different forest ecosystems respond to climate change with different intensity. In Central Europe, we are witnessing an unprecedented bark beetle calamity, the causes of which, in addition to climatic influences, include also inappropriate age structure and species composition of forest stands (HLÁSNY ET AL. 2022). In the conditions of Central Europe, Norway spruce is a mountain tree whose natural representation would be on approximately 11% of the area of the forests of the Czech Republic. In fact, however, it began to be introduced from the beginning of the 19th century at even lower altitudes. It currently is cultivated on about 48% of the area of Czech forests (MINISTRY OF AGRICULTURE OF THE CZECH REPUBLIC 2021). Most spruce stands' resistance to the bark beetle is low, and it is diminished further by a deficit of available water during transpiration (NETHERER ET AL. 2015, Matthews et al. 2018). At least since 1961, we have witnessed a change in most climate variables (BRÁZDIL ET AL. 2022b). The synergistic effect of increasing seasonal temperature and unchanged total precipitation causes drought to occur. To express drought, we used the wetness index (MATĚJKA 2014), the course of which was highly variable in the observed period. The minimum values of the wetness index correspond to periods of significant drought in 1973, 1976, 1991, 1993, 2003, 2015, and 2018. Starting from the 1990s, the lowest values of the wetness index were followed by increase in bark beetle felling (Figure 11). This period corresponds also to changes in the relative growth index of Norway spruce, which has been gradually decreasing through the past 30 years. It is clear that in the conditions of the Czech Republic (Central Europe) growth conditions for Norway spruce have deteriorated and these changes will necessarily be accompanied by increased mortality of spruce stands (HLÁSNÝ ET AL. 2022).

The temperature changes reported here are in accordance with ZAHRADNÍČEK ET AL. (2021), which for the period 1961 to 2019 speaks about average increase in temperatures within the Czech Republic by 0.36 °C per 10 years. They describe the variation of temperatures with altitude differently, however, stating that there is a greater increase at lower locations compared to at higher-altitude stations. In the data we compared, however, it appears that the increase is comparable at all locations. Nevertheless, there is significantly greater variability between individual meteorological stations at lower altitudes, and this may be related to the greater differences among the types of landscape at lower-altitude stations. For example, the heat island effect of the city is more pronounced where these are located. In the meteorological stations we used and that are at altitudes above 560 m, none are located in built-up areas.

The idea of using phenological models for landscape-wide pest risk analysis under climate warming is 20 years old. Approach to the pest modelling in relation to climate warming is highly robust (LOGAN ET AL. 2003). Although it might be debated whether the parameters (in particular start day) for calculation of the PHENIPS model were set correctly, a slight adjustment of these parameters can potentially result only in a shift of the modelled output values in a particular direction (increase or decrease) but always in one direction. The overall trend in the studied period will nevertheless remain the same. This also applies to the parameters of the submodel for calculating global radiation. Another problem is associated with the time when the bark beetle goes into diapause at the end of summer. The model is set on the basis of day length, but temperature is the next important factor (DOLEŽAL ET SEHNAL 2007) and that was omitted here. The start parameter of the model has been verified in MATĚJKA ET MODLINGER (2023).

While at higher altitudes an increase in Norway spruce's growth rate can occur due to an increase in average air temperatures, as has been proven especially for the height increase of young spruce (MATĚJKA ET LEUGNER 2013), climate change more generally has the effects of increasing climatic stress and reducing radial growth rate. The occurrence of climatically extreme years (e.g., 1976, 1984, 1994, 2003–2004, 2015, and 2018) is of particular importance in this sense.

The effect of wind disturbances was not directly evaluated in this text. A relationship between wind disturbances and bark beetle gradation has long been known. In places where stands are damaged by wind, the bark beetle often proliferates (SCHROEDER 2001; ØKLAND ET BERRYMAN 2004), but even after clean-up logging these disturbed stands remain more susceptible to wind damage (MODLINGER ET NOVOTNÝ 2015). After the period we evaluated there is no very detectable influence of wind in bark beetle felling, or perhaps it is better to say there is no increased felling volume that could not be explained by the aforementioned climatic events. It appears that any bark beetle population gradation in this period could have occurred even without wind damage to the forest. A classic example is seen in the impact of windstorm Kyrill in Šumava at the beginning of 2007, which only accelerated the already ongoing gradation (KINDLMANN ET AL. 2012). Given that wind disturbances are mostly local to regional in scope, their analysis on a national scale would be problematic or would require an approach different than that applied in this paper.

Compared to other publications evaluating weather development in the Czech Republic (e.g., BRÁZDIL ET AL. 2022a, ZAHRADNÍČEK ET AL. 2021), this article differs in that the basis for evaluating the development is the processing of moving averages, which are not based on arbitrarily determined periods (e.g., year, month). Nature itself does not know such periods which are only human constructs. A simple humidity index was also newly used, and it is a good indicator of rainfall drought. The entire period since 1961 has been described using data from 38 weather stations for which all necessary data are available, so no data has been extrapolated with the potential thereby to introduce some bias. The data were used to calculate the PHENIPS model for the entire monitored period, which allowed us to estimate the potential for spruce bark beetle development from 1961 to the present. Climatic stress to *P. abies*, which is a significant factor for the possibility of bark beetle attack, was expressed by the growth index *GI* as a linear combination of average values of air temperatures and relative air humidity. These results are consistent with the reported salvage logging, which shows four distinct waves since 1964.

The North American species *Dendroctonus ponderosae* in *Pinus* habitats of western North America and *Ips typographus* in European *Picea* are among the most significant tree mortality agents on each continent (BENTZ ET AL. 2019; LOGAN ET POWELL 2001), thus some parallels can be found between both species. Contemporary very massive bark beetle outbreak in the Czech Republic corresponds to damages in North America (e.g., RAFFA ET AL. 2008). Fire history in forests was identified as important in North America (LOGAN ET POWELL 2001), but not in the Czech Republic, where fires were present only in limited locations.

The model used here for estimating Norway spruce climatic stress is based on the evaluation of tree ring analyses (MONDEK ET AL. 2021) and the inputs to the calculation were average temperatures, average minimum temperatures, average maximum temperatures, and average relative air humidity for the relevant decisive periods of the year. Air humidity turned out to be a better predictor than was total precipitation, which is commonly used for similar purposes (e.g., GIEBINK ET AL. 2022), because a closer correlation was found between air humidity and annual growth than between total precipitation and annual growth (MONDEK ET AL. 2021). Similarly, importance of the variable vapor pressure deficit has been revealed in a Swiss study (FORRESTER ET AL. 2021). Compared to a study by CIENCIALA ET AL. (2018), the data analysed here show a more complex response of *P. abies* in the development of radial growth when climatic stress associated with high temperatures and lack of precipitation has manifested increasingly in recent years.

Summary

In this study, we evaluate the development of weather in the Czech Republic since 1961 in relation to its influence on the growth of forests with *P. abies* and on the dynamics of *I. typographus* (Norway spruce bark beetle) as the main driver determining the development of these ecosystems. In addition to the generally discussed changes in average air temperatures (increase of 0.37 °C per 10 years), also observed were earlier onset of *I. typographus* infestation (by 1.9 days per 10 years, with a greater value at higher altitudes) and accelerating *I. typographus* development (the *G* index increases by 0.07 per 10 years). Climatic stress developed nonlinearly. Until 1990, we observe its fluctuation around the average, but later it increased significantly and we see a decrease in the modelled average radial increase by about 20%. The basic factor in accelerating *I. typographus* gradation is the occurrence of climatically extreme conditions with high climatic stress for Norway spruce.

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Supplementary materials

1. Territorial air temperatures and precipitation sums in the Czech Republic 1961-2020
2. List of the selected meteorological stations and trends of basic variables (MS Excel)
3. Running averages and sums for air temperature, relative air humidity, and precipitation, wetness index in the set of 38 selected meteorological stations.

Available via www.infodatasys.cz/climate/CR1961-2020/CR1961-2020.htm