

Land-use legacy and forest origin determine the climate sensitivity and resilience of Scots pine stands

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Abstract

Tree growth sensitivity to climate is influenced by multiple interacting factors, including forest origin and land-use history. To assess their effects on the sensitivity, resistance, and resilience of Scots pine (*Pinus sylvestris*), we compared four regional tree-ring chronologies representing different combinations of forest origin and land-use history: naturally regenerated forest on former forest land (NatFor), planted forest on former forest land (PIFor), naturally regenerated forest on former agricultural land (NatAgr), and planted forest on former agricultural land (PIAgr). Each chronology comprised more than 60 trees from three forest stands in western Belarus. All 12 stands were approximately 80 years old, grew on sandy soils, belonged to the same forest type, and had similar stand structures.

All stands showed similar positive tree-ring index responses to June–July precipitation and winter and spring temperatures, particularly in February and March. However, trees on former agricultural land, especially in planted stands, were more sensitive to environmental stress. During pointer years, these stands also showed lower resistance than stands on former forest land. In PIAgr, climatic sensitivity declined to levels comparable to NatFor by 70–80 years of age, whereas NatAgr reached similar levels of sensitivity and resilience as early as 40–50 years. These findings indicate that forests planted on former agricultural lands require site-specific afforestation practices to enhance their long-term stability under projected climate change.

Introduction

In recent decades, against the backdrop of climate warming, forest mortality has increased across many regions of Europe (Allen et al. 2010, 2015; Knutzen et al. 2025). Although climate change is an important underlying driver, the immediate causes of forest mortality are often multiple and interacting, including drought (Anderegg et al. 2016), wildfires (El Garroussi et al. 2024), diseases (George et al. 2022), and bark beetle outbreaks (Hlásny et al. 2021). Climate change has become sufficiently severe to cause widespread dieback of Scots pine, a species with a broad Eurasian distribution, wide ecological amplitude, and generally high resilience to diverse environmental stresses (Bose et al. 2024).

Belarus, located at the transition between the boreal and continental biogeographic zones, is no exception. Over the past three decades, the country has experienced four episodes of widespread forest mortality, exhibiting a pronounced approximately 7-year cycle: 1996–1998, 2002–2004, 2009–2012, and 2016–2019 (Baychorov et al. 2020).

The area of forest loss in Belarus is largely determined, first, by droughts, followed by the activation of bark beetles and diseases, as well as the impact of storm wind on forests (Fedorov and Sarnatskiy 2001; Sazonov et al. 2014; Puhacheuski and Barsukova 2015; Sazonov and Zviagintsev 2016). The frequency, intensity, and duration of droughts have increased in recent decades, exacerbating forest damage (Loginov et al. 2020). Until 2016, Norway spruce stands were the most severely affected, with outbreaks of *Ips typographus* occurring during drought periods. The first unusual episode of pine dieback was recorded in southeastern Belarus in 2010. By 2016, the dieback had spread across the entire country,

reaching its peak in 2018, when nearly 40,000 ha of pine forests were lost. Although *Ips acuminatus* was the proximate cause of tree mortality, drought was the primary factor that reduced forest resilience (Sazonov et al. 2019).

The current forest structure in Belarus reflects not only recent climate change but also a long history of forest management. By the late 1940s, forest cover had declined to approximately 20% of the country's total area (Baginski and Esimchik, 1996). Since then, extensive reforestation and afforestation efforts have increased forest cover to 40% by the 2010s (State Forest Cadaster 2016). Planted forests, predominantly composed of Scots pine, account for 24% of the total forested area, and approximately 40 000 ha of new forests continue to be established annually on sites of clear-cut forests or former agricultural land (State Forest Cadaster 2016).

Research conducted in 2020–2021 across three forestry enterprises located in different regions of Belarus demonstrated that the resilience of Scots pine stands and their susceptibility to dieback are primarily determined by two factors: (1) previous land use (former forest land vs. former agricultural land) and (2) stand origin (natural regeneration vs. planting). Pine stands planted on former agricultural land exhibited the highest proportion of dieback, regardless of stand composition. In monospecific stands, the proportion of dieback reached up to 25%, approximately 20 times higher than that observed in naturally regenerated stands growing on former forest land (Yermokhin et al. 2023).

In this study, we investigated the effects of stand origin and previous land use on tree-ring width variability and the influence of climatic factors on stand stability. To this end, we compared four groups of Scots pine stands of similar age and composition but differing in origin and land-use history. Specifically, we addressed the following questions: (1) To what extent are stands established on former agricultural land more sensitive to climate variability than those growing on former forest land? (2) At what stand age are these differences most pronounced, and do they diminish over time?

Material and methods

The study area

The study was conducted in western Belarus within the territory of the Baranovichi Forestry Enterprise (Fig. 1). The terrain is predominantly flat and lies within the Shchara River basin, with elevations ranging from 140 to 200 m above sea level. The region is characterized by nutrient-poor sandy and sandy loam soils; consequently, natural and planted Scots pine stands account for approximately 90% of the forested area. According to forest inventory data, Norway spruce, English oak, black alder, and silver and downy birch occur in small, isolated stands, mainly in river valleys.

Climate

The climate is temperate continental with no dry season and warm summer and corresponds to Dfb region according to Köppen-Geiger climate classification (Beck et al. 2018). The average January temperature in the last decades is -4.0°C, while the average July temperature is 17.6°C. The mean annual sum of precipitation is 640 mm, with 70% falling between April and October. The prevailing winds are from the west and southwest (National atlas of Belarus 2002).

Tree-ring data

The study was conducted in 12 monodominant Scots pine (*Pinus sylvestris* L.) stands united in four groups (three stands in each group): 1 – natural forest on former forest land (NatFor), 2 – planted forest on former forest land (PIFor), 3 – natural forest on former agricultural land (NatAgr), and 4 –planted forest on former agricultural land (PIAgr) (Fig. 1, Table 1). Historical topographic maps at a scale of 1:50000 from the 1920–1930s were used to determine the previous land category (forest or agricultural land). Additionally, shallow soil excavations were taken during the study to confirm the presence of a former arable horizon. All stands are 80 years old according to the forest inventory database. However, dendrochronology analysis shows that mean age of main tree generation in separate stands varies from 70 to 87 years (Table 1). All stands grow on sandy soil and belong to the *Pinetum pleuroziosum* forest type (Yurkevich 1980).

Table 1
Forest stands characteristics

Code	Latitude	Longitude	Composition*	DBH, cm	H, m	Volume, m3 ha-1	Age, years
Natural forest located on former forest land (NatFor)							
BRN001	52.97512	25.78236	10Ps	30.0	25.4	281	83
BRN007	52.95625	25.50598	10Ps, s. Qr	28.8	26.6	322	82
BRN012	52.86189	25.60678	10Ps	27.3	25.0	326	84
Planted forest located on former forest land (PIFor)							
BRN002	52.97722	25.78481	10Ps, s. Qr	22.2	20.3	264	82
BRN006	52.96484	25.50704	10Ps	30.4	21.7	343	72
BRN010	52.86388	25.61161	10Ps, s. Pa	25.8	23.5	260	85
Natural forest located on former agricultural land (NatAgr)							
BRN003	52.97754	25.75426	10Ps, s. Qr	23.5	24.0	288	70
BRN005	52.95682	25.5384	10Ps + Bp, s. Pa. Qr	28.2	24.9	294	81
BRN008	52.843	25.57837	9Ps1Bp + Qr	23.6	20.2	253	87
Planted forest located on former agricultural land (PIAgr)							
BRN004	52.94661	25.54926	10Ps, s. Qr. Bp	23.7	21.3	257	71
BRN009	52.84312	25.57591	10Ps, s. Bp	29.9	24.8	394	70
BRN011	52.98186	25.74264	10Ps, s. Qr	25.9	24.3	379	85
* Bp – <i>Betula pendula</i> , Pa – <i>Picea abies</i> , Ps – <i>Pinus sylvestris</i> , Qr – <i>Quercus robur</i> , s. – single trees, + – less than 5%							

At each site, two cores per tree were collected at breast height from 20–25 dominant or co-dominant trees without visible wounds. Tree ring width (TRW) was measured either from a scanned image or using a LINTAB tree-ring measuring table with a precision of 0.01 mm under binocular microscopes. The quality of measurements was verified using TSAP-Win software (Rinntech-Metriwerk GmbH & Co) and COFECHA (Holmes 1983), following a visual inspection of the tree-ring series.

The ARSTAN program (Holmes 1984) was used to build four tree-ring chronologies (TRC), one for each stand-origin group (NatFor, PIFor, NatAgr, PIAgr). A cubic smoothing spline, that preserves 50% of the variance at a wavelength of 20 years, was applied to remove the age-related growth trend from each individual tree-ring series (Cook and Peters 1981). Tree-ring indices (TRIs) were calculated by dividing the observed ring widths by the corresponding values of the fitted curve. Standard dendrochronological

statistics, including 'Gleichläufigkeit' (GLK) (Eckstein and Bauch 1969) and *tBP*-value (Baillie and Pilcher 1973), were used to assess the degree of agreement among the group chronologies.

To assess the sensitivity of the standardized tree-ring chronologies to external factors, we calculated the sensitivity coefficient (Fritts 1969). A 20-year moving sensitivity coefficient was used to assess the change in chronology sensitivity over time.

Negative pointer years were identified using the moving-window method introduced by Cropper (1979), as implemented in the R package *pointRes* (van der Maaten-Theunissen et al. 2015). A 7-year moving window, a threshold value of 0.75 for identifying event years in individual series, and a minimum of 60% of series exhibiting an event year were used to identify pointer years.

To assess the differences in growth responses between stands of different origin during pointer years, the resistance (*R_t*) and resilience (*R_s*) indices were calculated (Lloret et al. 2011). These indices were calculated using four-year pre- and post-disturbance periods and the *pointRes* package in R (van der Maaten-Theunissen et al. 2015). Differences among groups were assessed using the Mann–Whitney U test (Mann and Whitney 1947).

Monthly precipitation sums and means monthly air temperatures for the period 1945–2021, averaged for the Baranavichy and Ivatsevichy meteorological stations, were used to analyze climate–growth relationships. The analysis was performed using the RESPO program (Holmes 1984). To assess drought intensity during June–July in pointer years, we used the Standardized Precipitation Evapotranspiration Index (SPEI) (Vicente-Serrano et al. 2010), obtained from the Global SPEI database (https://spei.csic.es/spei_database), and the Selyaninov Hydrothermal Coefficient (HTC) (Selyaninov 1928), calculated from data obtained from the meteorological stations. The latter index is widely used in agrometeorological studies in post-Soviet countries and expresses the ratio of precipitation to accumulated air temperature over a specified period. HTC values below 1.0 indicate dry conditions; values of 0.6–0.7 indicate moderately dry conditions, 0.4–0.5 indicate very dry conditions, and values below 0.4 indicate extremely dry conditions. SPEI and HTC are generally well correlated, although they may occasionally identify different years as experiencing summer drought (Khlebnikova et al. 2012; Cherenkova and Zolotokrylin 2016).

Results

Tree-ring chronologies

The four master Scots pine tree-ring chronologies (NatFor, PIFor, NatAgr, PIAgr) range from 79 to 87 years in length (Table 2). Each TRC includes a similar number of trees (60–64), and since 1947, all of them have been based on at least 20 trees (Fig. 2b). TRCs were developed from stands of the same forest type located no more than 21 km apart, therefore they have statistically significant ($p < 0.05$) very high correlation (t -value > 10) and exhibit a high coefficient of synchronicity (> 80) with one another.

However, the synchronicity between the PIAgr and NatFor are slightly weaker than those observed among the other chronologies (Fig. 2, Table 3).

All TRC are characterized by high $rBar$ values (0.321–0.386), which support good correlations between trees from different stands of the same origin and land-use history. The lowest mean sensitivity (MS) and standard deviation (SD) were observed in NatFor group (0.123 and 0.133, respectively) and in NatAgr group (both 0.134). In contrast, the highest MS and SD values were recorded in PIAgr group (0.154 and 0.203, respectively) (Table 2). This suggests that PIAgr should be more influenced by climate than stands from other groups of origin and land-use history.

Table 2

Characteristics of the standardized tree-ring chronologies (TRC). $rBar$ (average of all pairwise correlations between all samples), SD (standard deviation), MS (mean sensitivity), AC1 (first order autocorrelation).

TRC	Number of trees	Length, years	Time span	$rBar$	SD	MS	AC1	Total variance explained by response function, %
NatFor	63	85	1937–2021	0.386	0.133	0.123	0.304	37.5
PIFor	64	87	1935–2021	0.368	0.173	0.150	0.395	36.7
NatAgr	62	84	1938–2021	0.321	0.134	0.134	0.314	41.6
PIAgr	60	79	1943–2021	0.367	0.203	0.154	0.552	41.6

Table 3

Coefficients of synchronicity (light grey color) and t-value (dark grey color) between tree-ring chronologies (TRC)

TRC	NatFor	PIFor	NatAgr	PIAgr
NatFor	–	93	82	80
PIFor	19.2	–	80	80
NatAgr	11.1	12.1	–	83
PIAgr	10.5	11.0	13.1	–

Climate-growth relationship

The climate–growth response functions explained 36.7–41.6% of the variability in tree-ring indices (TRIs) of the standardized TRC and are 4–5% higher for stands growing on former agricultural land, both NatAgr and PIAgr (Table 2). These values are lower than those reported for the regional Scots pine

master chronology (Yermokhin 2020) but are comparable to those obtained for local tree-ring chronologies from the same forest types in Belarus (Yermokhin and Saveliev 2011).

The climate–growth responses of stands growing on former forest lands (NatFor and PIFor) were very similar (Fig. 3). The strongest and statistically significant ($p < 0.05$) positive correlations were observed with mean air temperature in December (0.25–0.26), February (0.41–0.43), and March (0.42–0.46), as well as with precipitation in June (0.31–0.36) and July (0.30–0.32).

A similar pattern was observed for stands growing on former agricultural lands. However, in natural stands (NatAgr), an additional statistically significant positive correlation with January temperature (0.28) was detected. In contrast, for forest planted on former agricultural lands (PIAgr), the effects of December and January temperatures were not statistically significant. Instead, this chronology shows the strongest positive correlation with June precipitation (0.42) among all TRC, indicating greater sensitivity to summer drought (Fig. 3).

Pointer years analysis

The TRCs reflect eight negative pointer years that are characteristic of at least two of them: 1954, 1964, 1979, 1986, 1996, 2005, 2006, and 2018. Of these, only two years (1954 and 2018) are common to all TRCs, while four years (1979, 1986, 1996, and 2006) occur in three TRCs (Fig. 4).

Comparison of the pointer years with extreme climatic conditions – low temperatures in February–March and droughts in June–July – shows generally good agreement (Fig. 4). However, the pointer years of the last two decades (2005, 2006, and 2018) are associated exclusively with drought events indicated by both HTC and SPEI (Figs. 4c and 4d). All shared pointer years before the mid-1990s correspond well either to extremely low mean February–March temperatures (below -6.0°C) (1954, 1979, and 1996) or to the combined effects of low temperatures in these months and summer drought (1964). One pointer year (1986) cannot be explained by either of these climatic factors; however, the reduction in growth that year was relatively small (up to 20%), although it occurred synchronously across TRCs (Fig. 2a).

In contrast, several years characterized by exceptionally unfavorable climatic conditions – including a cold beginning of spring (1963, 1969, and 1970) and severe summer droughts recorded simultaneously by both the HTC and the SPEI (1951, 1992, 1994) – did not produce pointer years in the tree-ring chronologies.

Resistance and resilience in pointer years

The resistance and resilience of stands of different origins changed over time, and the differences among groups diminished with stand age (Fig. 5). In the pointer year 1954, the greatest variation in resistance coefficients was observed. Only the PIFor group exhibited a statistically significant ($p < 0.05$) decrease in resistance compared with the NatFor and PIAgr groups (Fig. 5a). In contrast, the resilience

coefficient was significantly higher in the PIAgr group than in the other groups, with the TRI becoming nearly twice as high as during the pre-depression period (Fig. 5b).

In 1964, which was characterized by an exceptionally cold spring followed by summer drought, the greatest declines in TRIs were recorded in the NatFor and PIAgr groups, and these declines were significant compared with PIFor and NatAgr groups (Fig. 5a). Recovery of tree-ring width in this year was slowest in the PIAgr group. The resilience coefficient was close to 1.0 in the NatFor and NatAgr groups and exceeded 1.0 in the PIFor group, whereas it reached only 0.9 in the PIAgr group, significantly lower than in the other groups (Fig. 5b). Recovery of TRIs in the PIAgr group to pre-depression levels required for three years (Fig. 2a).

In 1979, characterized by a cold early spring, the lowest resistance was observed in the PIAgr group, where the reduction in TRI differed significantly from all three other groups (Fig. 5a). Reduced resistance was also observed in the NatAgr group, which was significantly lower than that of stands on former forest lands (NatFor and PIFor). However, no statistically significant differences in coefficients resilience were detected among the groups (Fig. 5b).

In 1986, no differences in either resistance or resilience were observed among stands of different origins, but dropdown of TRI in this year was smallest.

In 1996, as in 1979, the lowest resistance coefficients were recorded in stands on former agricultural lands (PIAgr and NatAgr). The decline in TRI was significantly greater than that in stands on former forest lands (NatFor and PIFor) (Fig. 5a). In contrast, recovery from growth depression was strongest in the PIAgr group, where the resilience coefficient reached 1.2, significantly higher than in the remaining groups (Fig. 5b).

No differences in stand resistance and resilience among the different groups were observed in the subsequent pointer years of 2005, 2006, and 2018, when stands age exceeded 60 years.

Sensitivity of TRCs

In general, standardized TRCs are characterized by low sensitivity coefficients, although these vary depending on stands origin and land-use history (Table 2). These differences become more evident when 20-year moving sensitivity coefficients were analyzed (Fig. 6). The high year-to-year variability in tree-ring width observed in young trees is reflected in elevated sensitivity coefficients, which gradually decline by the age of 40–50 years. During this period, the highest sensitivity was found in the PIAgr, followed by NatAgr, PIFor, and NatFor.

By the age of 40–50 years, the differences among the NatAgr, PIFor, and NatFor chronologies disappear, and their sensitivity coefficients stabilize at approximately 0.10. In the PIAgr chronology, the sensitivity coefficient also declines markedly by this age but stabilizes at approximately 0.13 and remains at this level until the trees reach 70–80 years of age. During this period, the sensitivity coefficient of the PIAgr

chronology is significantly higher ($p < 0.05$) than those of the other chronologies. At 70–80 years, it declines sharply to approximately 0.10, matching the values observed in stands of the other origins (Fig. 6).

Discussion

The results of this study demonstrate that Scots pine stands growing on former agricultural lands, particularly planted forests, are more sensitive to external factors than stands growing on former forest lands, regardless of whether they are natural or planted (Table 2). Correlations between TRIs and climatic variables indicate that forest stands of different origin and land-use history exhibit a similar pattern of positive responses to June–July precipitation and winter air temperatures, particularly in February and March. This pattern is also characteristic of the surrounding regions (Vitas 2022; Yermokhin 2020; Koprowski et al. 2010; Zunde et al. 2008). However, climate-growth response functions explain a greater proportion of TRI variability in stands growing on former agricultural lands.

These relationships are also reflected in the pointer years, all of which are associated either with droughts during the growing season or with extremely cold conditions in late winter and early spring (Fig. 4). Moreover, climate warming since the early 1990s, which has been most pronounced during the winter months and in March (Loginov et al. 2020), has altered the overall pattern. Before the mid-1990s, all pointer years were associated with exceptionally cold conditions in February and March (1954, 1979, and 1996), sometimes compounded by drought during the same growing season, as in 1964. Moreover, climatic conditions during 1963–1964 greatly affected the PIAgr stands (Fig. 2a) – the tree-ring index (TRI) declined to its minimum values in both years and remained low for two additional years after 1964.

Since the 1990s, however, all pointer years have been associated exclusively with June–July droughts.

During pointer years, differences between stands growing on former forest and former agricultural lands are particularly pronounced up to an age of 70–80 years. In 1964, 1979, and 1996, the decline in TRIs was significantly greater in PIAgr than in stands of other categories. Similarly, in 1979 and 1996, NatAgr stands exhibited significantly greater growth reductions than stands on former forest lands. The apparent higher resilience of trees in PIAgr group in 1996 may reflect the mortality of the most severely affected trees or the removal of damaged individuals, resulting in improved growth of the surviving trees due to reduced competition. The floating sensitivity coefficient stabilizes after approximately 40–50 years but remains significantly higher in PIAgr group (0.13 compared with 0.10) until stands reach 70–80 years of age (Fig. 6). Notably, the highest levels of damage to Scots pine caused by *Ips acuminatus* have also been reported in stands aged 40–60 years, after which damage intensity declines (Sazonov and Zviagintsev 2016).

Earlier analyses of forest stability in the same region during the peak of mass Scots pine dieback in 2017–2019 revealed a similar pattern. The condition of Scots pine stands was significantly poorer in planted forests on former agricultural lands, and the probability of dieback in planted monodominant

pine stands on former agricultural lands was 25 times higher than in natural forests growing on former forest lands (Yermokhin et al. 2023).

The lower stability of forests on former agricultural lands is likely related to the long-lasting legacy effects of former agricultural management on soil properties (Foster et al. 2003). Studies conducted in neighboring regions have demonstrated substantial differences between soils on abandoned agricultural lands and long-established forest soils. At a depth of 0–20 cm, forest soils have a less compact structure and water permeability that is approximately three times higher than that of former agricultural soils. In addition, soils withdrawn from agricultural use are approximately 15 times more susceptible to siltation (Rakhmatullozoda 2000). According to several studies, differentiation of former arable soils into two horizons with bulk densities comparable to those of forest soils becomes statistically evident only after 20–40 years (Fomina 2005; Chalaya 2012), whereas the balance and intensity of elementary soil-forming processes recover only gradually and may require approximately 100 years after cultivation has ceased (Fomina 2005). Traces of the former plough layer can persist beneath forest stands for up to 180 years (Rakhmatullozoda 2000). Likewise, the chemical composition of soils under planted forests on former agricultural lands may remain similar to that of agricultural soils for several decades (Smal and Olszewska 2008; Falkengren et al. 2006), while differences from continuously forested soils may persist for centuries (Koerner et al. 1997; Dupouey et al. 2002; Zajícová and Chuman 2019). These long-term changes are closely linked to the development of the soil microbiome, which plays a critical role in forest ecosystem functioning and can strongly influence forest productivity and resilience (Allsup et al. 2023).

Conclusions

Current and projected climate change is expected to reduce forest resistance and resilience to environmental stressors, necessitating the adaptation of forest management to emerging challenges. In this context, improving reforestation and afforestation practices is one of the highest priorities. Our results clearly demonstrate that Scots pine trees planted on former agricultural lands are more sensitive and less resistant to external factors during the first decades of stand development than naturally regenerated trees on former forest and even agricultural lands. These differences disappear only after approximately 70–80 years, likely when soil properties and microbial communities have developed characteristics comparable to those of long-established forest soils.

However, recent episodes of widespread Scots pine dieback indicate that many planted Scots pine stands may not survive long enough to reach this stage of increased stability. Our finding suggests that forests established on former agricultural lands require site-specific afforestation practices to ensure the long-term stability of the resulting stands. Because the ecological legacy of former agricultural land cannot be eliminated rapidly, promoting natural forest succession on abandoned agricultural lands may represent a more effective strategy. Under natural succession, forest stands established on former agricultural lands can attain levels of resistance and resilience comparable to those of naturally regenerated stands on former forest lands within 40–50 years. Consequently, encouraging natural

succession could enhance forest state and resilience while simultaneously increasing biodiversity and the long-term capacity of forests to sequester atmospheric CO₂.

Declarations

Competing interests.

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

Ethics approval.

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Author Contribution

Conceptualization: M.Y., A.P.; Methodology: M.Y.; Investigations: M.Y., V.L., Ya.I., N.K.; Formal analysis: M.Y.; Writing – original draft: M.Y.; Writing – review and editing: V.L., Ya.I., N.K., A.P.; Resources: M.Y., A.P.; Supervision: M.Y., A.P.

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Data availability.

Data will be made available on valuable request.

Code availability.

Not applicable.

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Figures

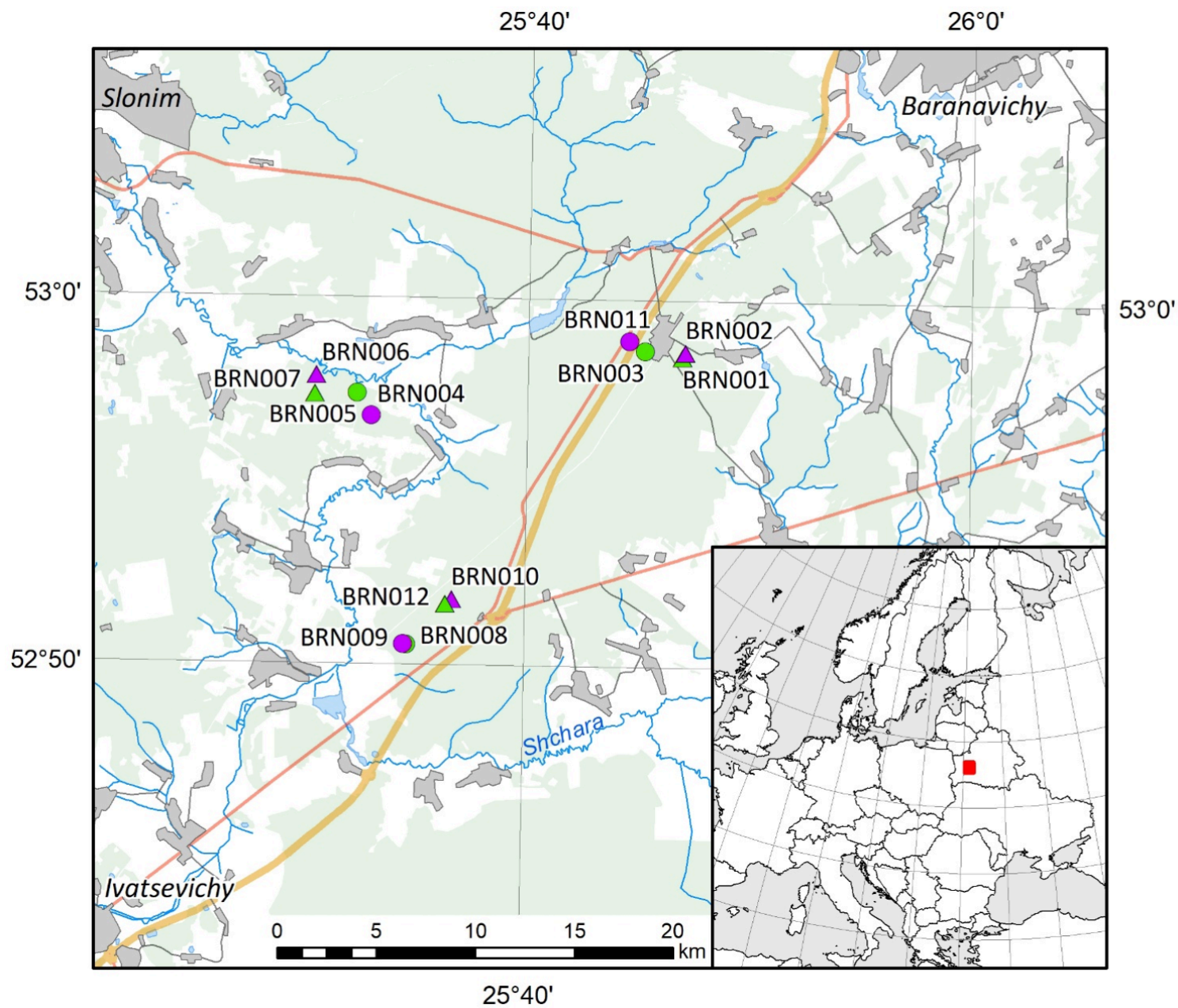


Figure 1

Location of the sample plots. Triangles indicate natural forests, and circles indicate planted forests. Green denotes former forest land, and purple denotes former agricultural land.

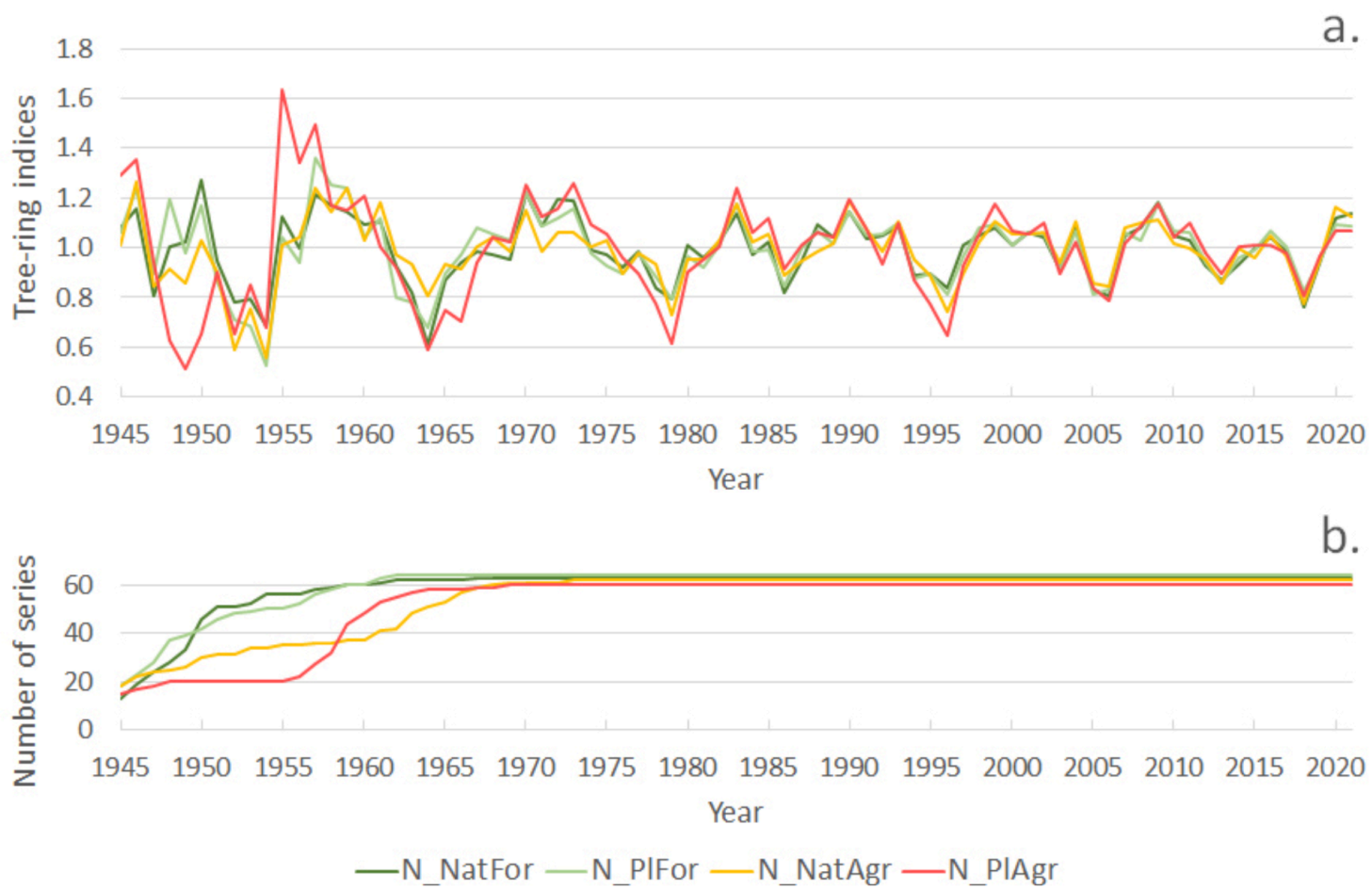


Figure 2

Standardized tree-ring chronologies (a) and sample depth (b) for the four stand groups (NatFor, PIFor, NatAgr, PIAgr) for the period 1945–2021.

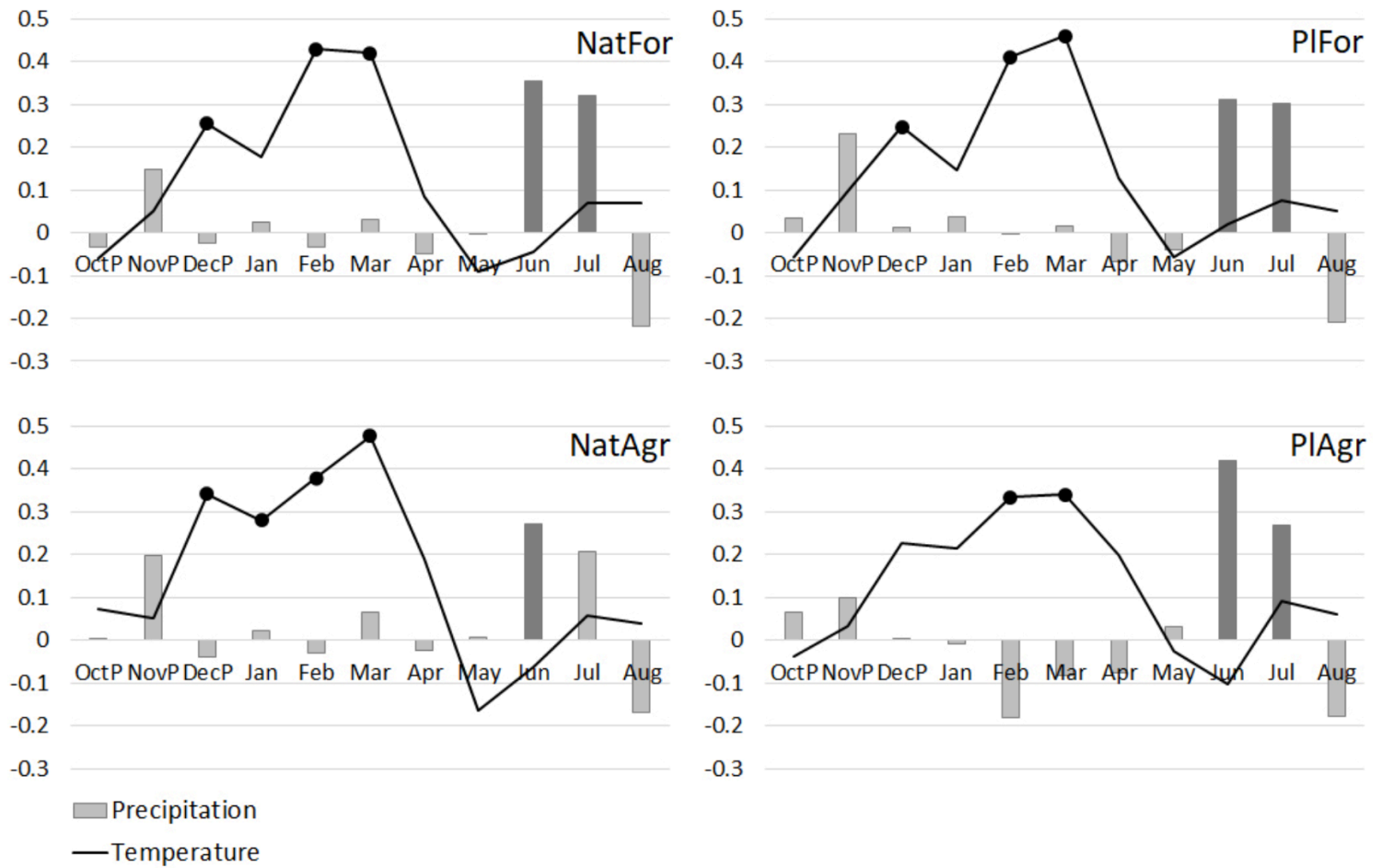


Figure 3

Correlation coefficients between the group chronologies and monthly temperature (lines) and precipitation (bars) from the previous October to the current August for the period 1945–2021. Dark bars and markers indicate statistically significant correlations ($p < 0.05$).

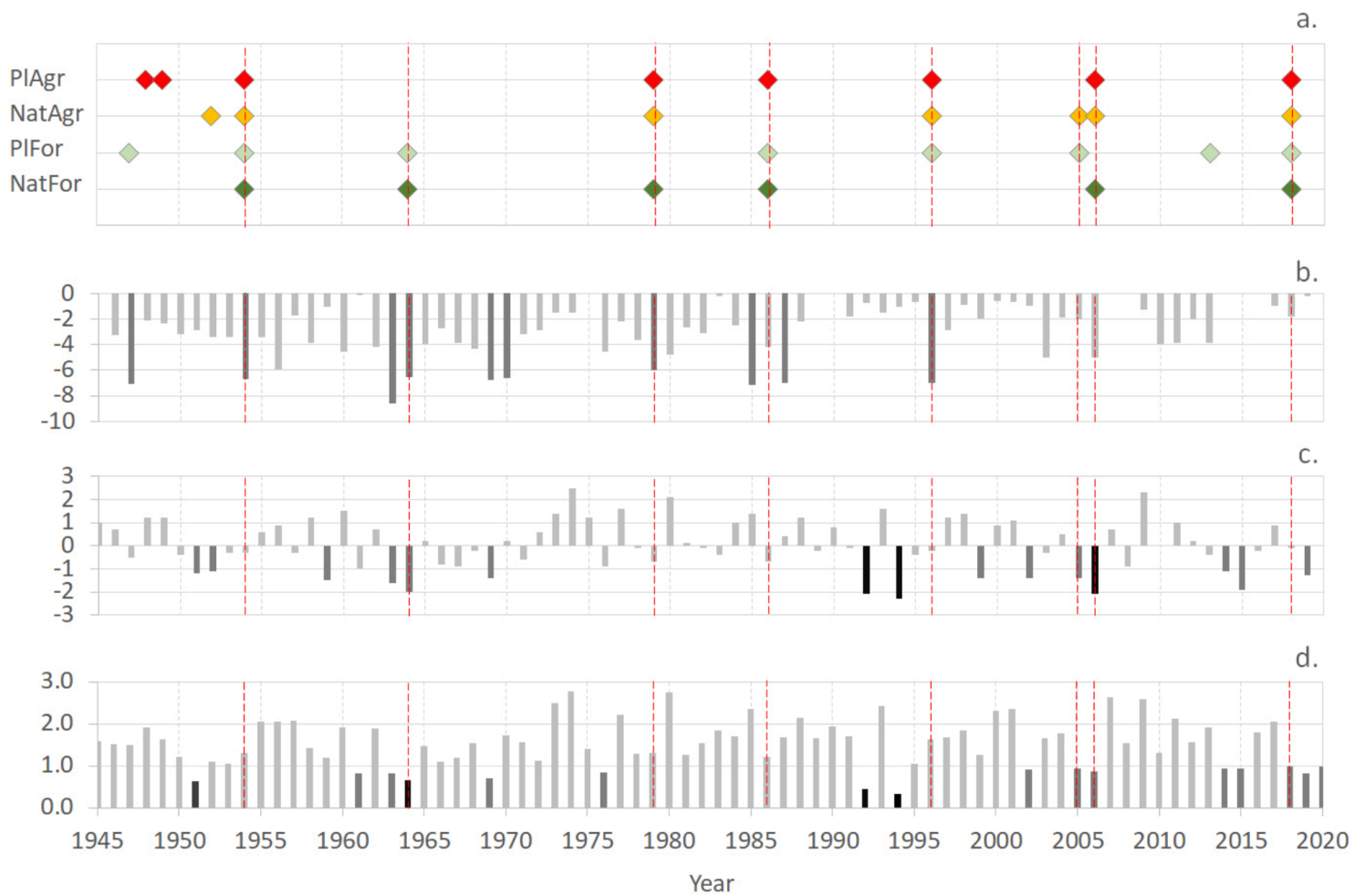


Figure 4

Negative pointer years (a), mean February-March temperature (b), SPEI for June-July (c), and HTC for June-July (d). Dark grey bars indicate very cold February-March (less than -6.0°C) and droughts, black bars indicate extreme droughts. Red vertical lines show pointer years.

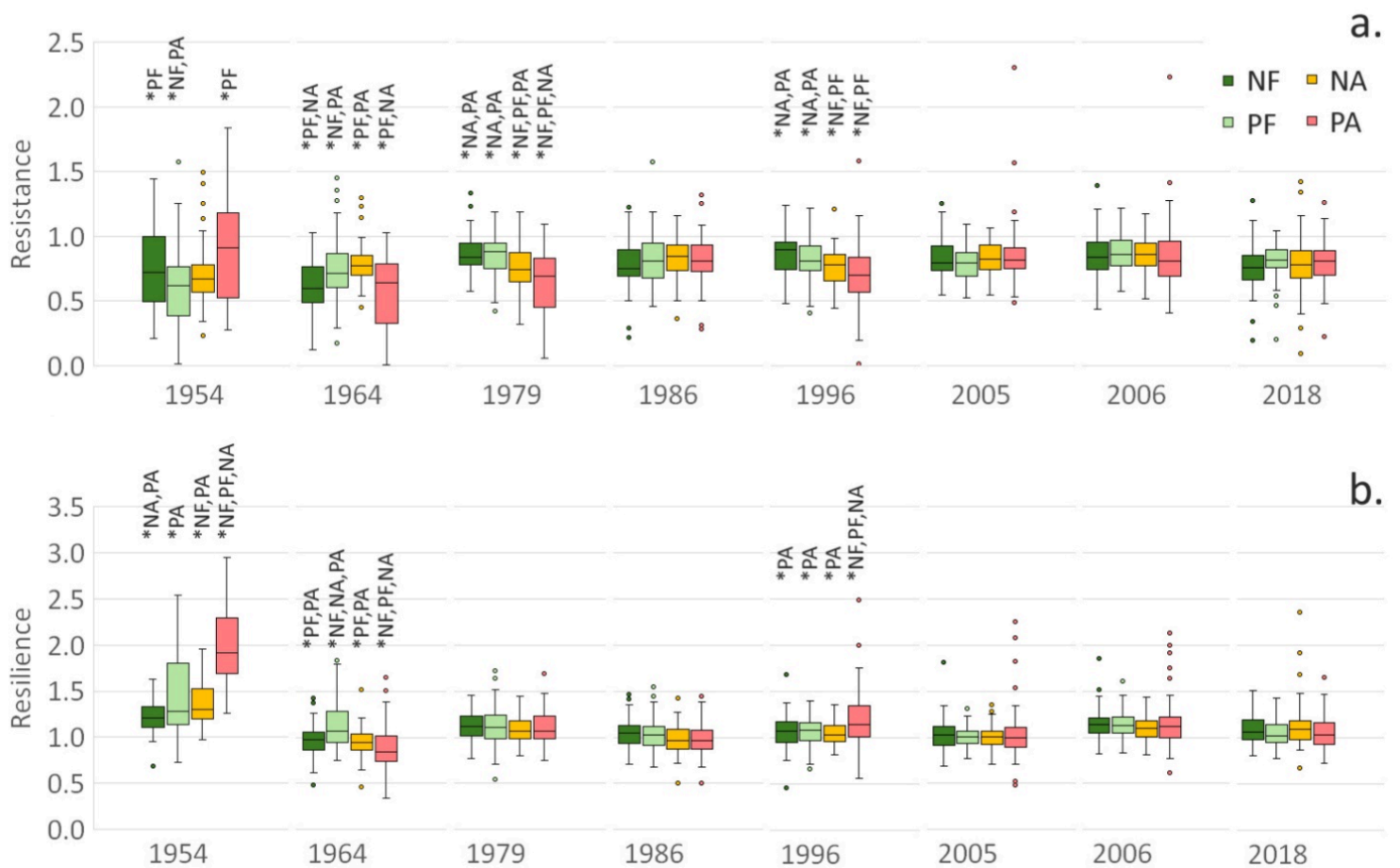


Figure 5

Resistance (a) and resilience (b) coefficients for the four studied stand group in the same negative pointer years. NF is natural forest on former forest land, PF is planted forest on former forest land, NA is natural forest on former agricultural land, and PA is planted forest on former agricultural land. Asterisks accompanying the abbreviations indicate significant differences in resistance and resilience coefficients among the corresponding groups.

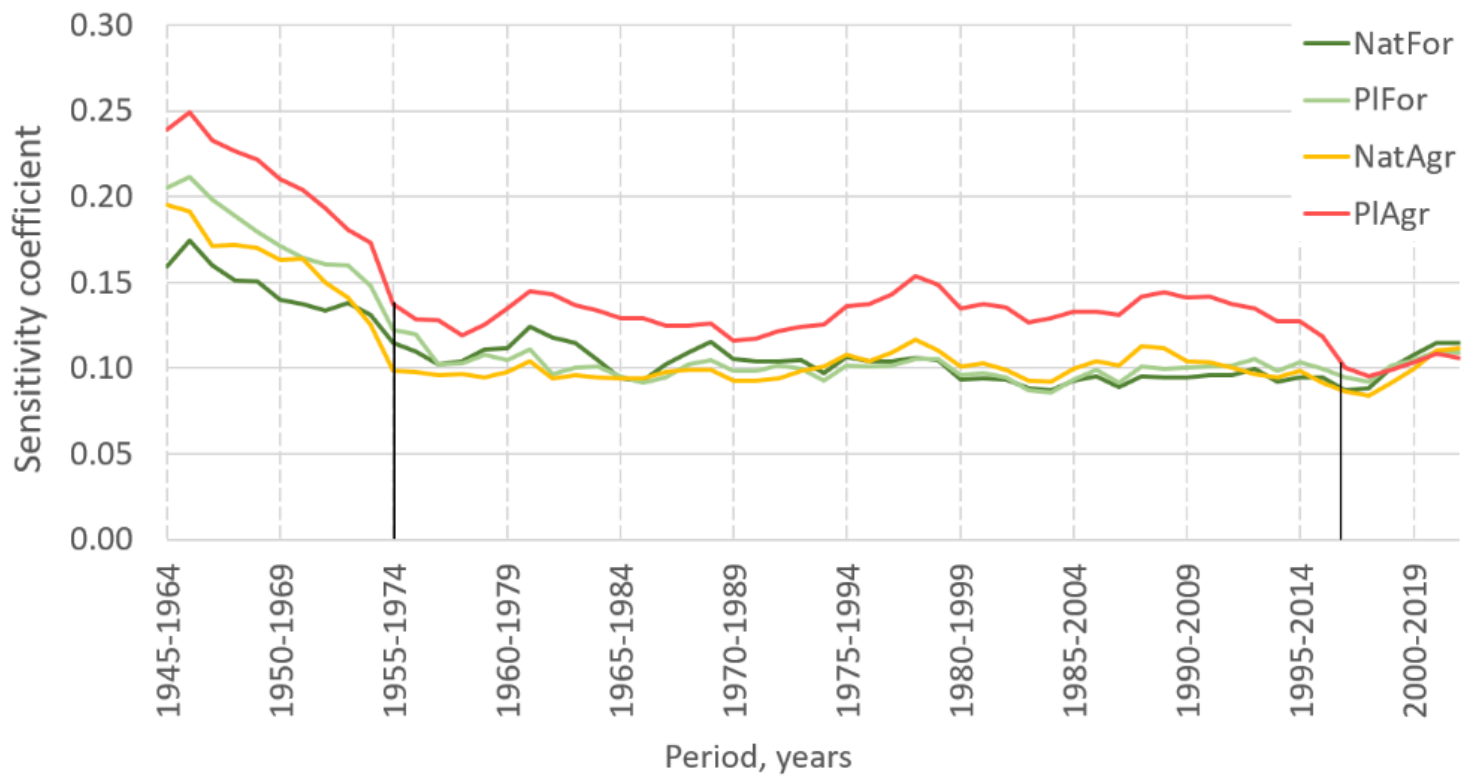


Figure 6

Moving sensitivity coefficient for the four stand groups (NatFor, PIFor, NatAgr, PIAgr) for the period 1945–2021. Black vertical lines indicate two sharp drops of the sensitivity coefficients in the stand' age of 40–50 years and 70–80 years.