

## Climate Change Induced Tree Mortality in a Relict Scots Pine (*Pinus sylvestris* L.) Forest

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**Abstract** – Mortality appeared in a relict Scots pine (*Pinus sylvestris* L.) forest where the sandy pine forest association (*Pinetum-Festuco vaginatae sylvestris*) is unique in the Carpathian Basin. To identify the complex causes of tree mortality, we analysed the climatic and soil conditions completed with bryological and biotical (pests) surveys. Altogether the results show that unfavourable soil conditions (coarse sand) and increasing aridity have led to a decline in tree vitality. Bark beetles have a high population density in the stand, and they have colonised both the felled trap trees and the standing trees, where the beetles contributed to tree mortality. New spreading invasive moss species have appeared in the recently formed gaps, where crone projection is low. The disappearance of this relict forest stresses the urgent need for Hungarian forest management to prepare strategies for adaptive tree species selection.

**climate extremes / damage chain / climate adaptation / relict forest association / water holdig capacity**

**Kivonat – Klímaváltozás okozta fapusztulás egy reliktum erdeifenyves (*Pinus sylvestris* L.) erdőben.** A mortalitás jeleit tapasztaltuk egy reliktum erdeifenyvesben (*Pinus sylvestris* L.), mely társulás (*Pinetum-Festuco vaginatae sylvestris*) egyedülálló a Kárpát-medencében. A fapusztulás összetett okainak feltárása érdekében az éghajlati és talajviszonyokat elemeztük, kiegészítve bryológiai és biotikus (kártévő) felmérésekkel. Az eredmények azt mutatták, hogy a kedvezőtlen talajviszonyok (durva homok) és a gyakoribbá váló aszályperiódusok vezettek az erdőállomány legyengüléséhez, majd pusztulásához. A szűbogarak populációsűrűsége nagy volt az állományban, és nem csak a kivágott fogófákat, hanem az álló fákat is megtámadták hozzájárulva ezzel pusztulásukhoz. Új, terjedő invazív mohafajok is megjelentek a felnyíló állományban ott, ahol alacsony volt a záródás. A reliktum erdő eltűnése még sürgetőbbé teszi, hogy a hazai erdőgazdálkodás mielőbb klímaadaptációs stratégiai lépéseket tegyen.

**éghajlati szélsőségek / kárlánc / klímaváltozáshoz való alkalmazkodás / reliktum erdőtársulás / talaj víztartóképesség**

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## 1 INTRODUCTION

Threats to the vitality of forest ecosystems depend more on the frequency and expected tendency of extremely hot and dry events than on the changes in the climatic means (Mátyás 2009). Recurrent and increasingly severe droughts have been observed in southern Europe in recent decades, while northern Europe has experienced an opposite tendency (Spinoni et al. 2005, Gudmundson et al. 2016). Forest ecosystems have already responded to prolonged droughts and heat stress with defoliation, crown dieback, reduced growth and production, and widespread mortality (Bréda et al. 2006, Allen et al. 2010, Lindner et al. 2014). Projected climate conditions (Jacob et al. 2014, IPCC 2021) pose an increasing risk to the forests (Allen et al. 2010). Mortality can occur rapidly under hotter droughts, associated biotic damages, and other disturbances (Hlásny et al. 2014, Allen et al. 2015). The Carpathian Basin is considered highly sensitive and vulnerable to climate change and the increased probability and severity of extreme events (Spinoni et al. 2013, Gálos et al. 2015). The xeric limit of Scots pine is located mainly at the foot of the Alps (Marqués et al. 2018). To the south-east and south-west of the latitude of the Alps, the xeric limit tends to occur only in patches in the high-mountainous landscapes at an altitude of 1000–2000 meters in southern Europe. From the Iberian Peninsula, studies have already reported that climate change has influenced forest stand structure and increased the competition between species in the case of Scots pine (Primicia et al. 2016, Marqués et al. 2018). The area already experiences drought-induced mortality (Camarero et al. 2015) and competition-induced mortality (Ruiz-Benito et al. 2013). Moreover, negative impacts are observed in drier areas (Marqués et al. 2021, González de Andrés et al. 2018). The xeric conditions in Central Europe suggest the remaining stands of the middle mountains will disappear within two decades.

Vitality decline induced by abiotic damages leading to tree mortality is a serious problem in Hungarian forests (Berki et al. 2009). The large amount of these damages in recent decades suggests severe difficulties for forest management in the future (Mátyás et al. 2018). Forest sites with detectable drought-induced damages are increasing in Hungary (e.g. Rasztoivits et al. 2013, Móricz et al. 2018). The investigated old-growth Scots pine (*Pinus sylvestris* L.) forest is located in a protected area. Climate, soil, and local hydrological conditions highly influence the health conditions of this relict forest stand. However, complex analyses assessing the observed tendency of all of these site factors are still missing. Examining each factor separately could encompass wide spatial and temporal scales. Nevertheless, the lack of information on other factors potentially creates biased assessments of conclusions about the inducing causes. Site conditions always affect vegetation. Conversely, vegetation always affects site conditions. Therefore, the relationship between forest stand vitality and stand growth becomes more complicated in the case of damage chain appearance in an elder, resistant forest stand. Our research aimed to answer the following questions:

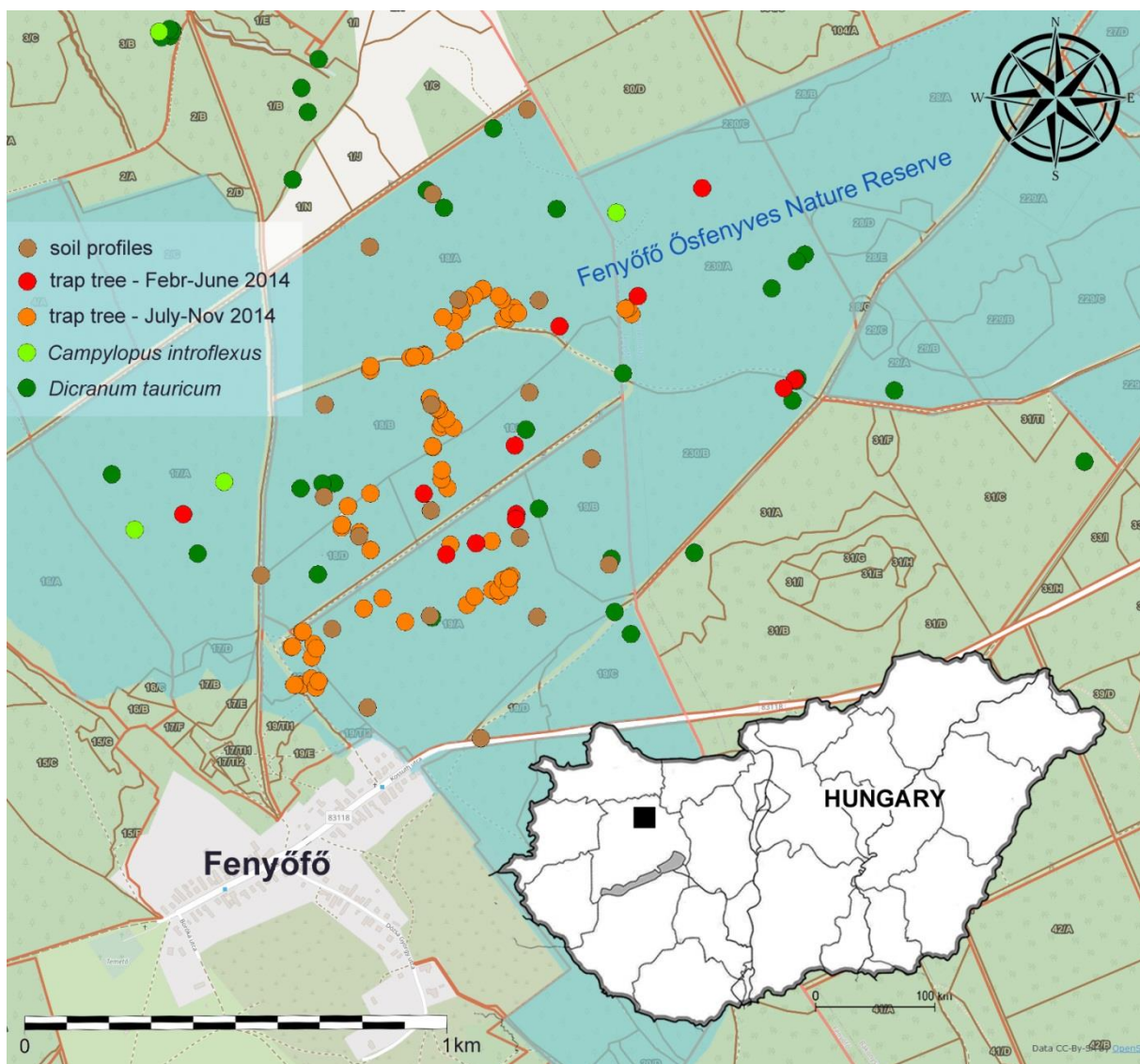
1. How have site conditions and especially climate changed in the research area in recent decades?
2. Which key factors and mechanisms determine tree mortality in this pre-boreal forest?
3. Which are the most important site-limiting factors in this case?
4. What kind of biotic damage chain do the changing climate conditions induce?
5. Can a relict and protected ecosystem adapt to the changed conditions?

## 2 MATERIALS AND METHODS

### 2.1 Study area

The research site is located in the Transdanubian region. The area of the protected relict forest (called Fenyőfő) is approximately 578 ha, of which the investigated area is ca. 200 ha. *Figure 1* shows the sampling plots at the research site.

The age of the original community can be estimated at ~10 000 years (established 8000–7000 B.C.). Settlers who came to the area completed the community with special Scots pine seedlings in the middle of the 18th century (Babos et al. 1966). Therefore, the vegetation types in the study area are *Festuco vaginatae–Pinetum sylvestris*, *Festuco rupicolae – Pinetum sylvestris*, and *Quercetum petraeae – Cerris pannonicum*, while the vegetation near creeks is classified as *Aegopodio – Alnetum* (Dövényi 2010). Majer confirmed the relict origin (a remnant of a formerly widespread species in an isolated area) of the forest at the end of the 19th century (Majer 1988).



The water streams of the area are periodic. The groundwater level is between 4–6 m, and is likely inaccessible to vegetation (Dövényi 2010); therefore, precipitation is the only water uptake option for vegetation. The precipitation sum in the vegetation period is 380 mm, which indicates a sufficient water supply in the area. The fluctuation of annual temperature is 21.8°C, which provides balanced climate conditions. Annual sunlight duration is above 1,980 hours; thus, the actual evaporation is high (Halász 2006). Soil texture shows that 56% of soils are sand, and 42% are loam. Soil texture and hydrological factors allow for versatile soil types in the area. We rarely detected perigon sand caused by sedimentation, while along streams, we found meadow soils (Babos et al. 1966). Climate and forest vegetation have leached out the carbonated quicksand, which led to the formation of humic sands, slightly acidic rusty brown, and lessivated brown forest soils.

Based on previous investigations, the Scots pine has existed since the dry and cold pine-birch age (Babos et al. 1966). The deciduous tree species could not displace the Scots pine from the sandy mounds, even during favourable climatic periods. The Scots pine mixed with different oak (*Quercus* spp.) and other deciduous tree species. Forests began to disappear due to land-use changes in the area in recent decades. Only a few individual trees survived this period; the saplings were used for a tree-planting program on sandy sites (Borhidi 2006). Scots pine forests (*Festuco vaginatae-Pinetum sylvestris*) are currently located on sandy mounds (Bartha 1995) and produce low crown closure stands. At the lower canopy level, Turkey oak (*Quercus cerris*), sessile oak (*Quercus robur*), and flowering ash (*Fraxinus ornus*) are present; Juniper (*Juniperus communis*) also occurs in the gaps. The mortality of Scots pine causes shrub species to gain ground, while the number of deciduous tree species is also increasing.

## 2.2 Methodology

The climate analyses are based on the nearest weather station datasets of the Hungarian Meteorological Service (OMSZ). There is no OMSZ station in the area of Fenyőfő; therefore, the data of Tés (47.26°E 18.03°K; 460 m a.s.l., 19 km distance from the study area) and Bakonybél (47.26°E 17.73°K; 286 m a.s.l., 10 km distance from study area) station were interpolated. Furthermore, the interpolated data were compared and corrected with local forestry measurements. Monthly temperature and precipitation time series, the total number of summer days ( $T_{\max} \geq 25$  °C), and hot days ( $T_{\max} \geq 30$  °C) per year were investigated for the period 1961–2021 (Table 1). Two climate parameters were calculated. PET (potential evapotranspiration (mm/month)) was determined based on Thornthwaite's formula (1948) (1).

$$PET = 16 \times \left(\frac{L}{12}\right) \times \left(\frac{N}{30}\right) \times \left(\frac{107d}{I}\right)^{\alpha} \quad (1)$$

Where:

L:	the average day length (hours) of the month being calculated
N:	the number of days in the month being calculated
Td:	the average daily temperature of the month being calculated
$\alpha$ :	$(6.75 \times 10^{-7}) I^3 - (7.71 \times 10^{-5}) I^2 + (1.792 \times 10^{-2}) I + 0.49239$
I:	$\sum_{i=1}^{12} \left(\frac{T_{\text{mean}}}{5}\right)^{1.514}$

Aridity index was determined as the quotient of precipitation (P) and potential evapotranspiration (PET). We used a modified Thornthwaite-type monthly water-balance model (Thornthwaite – Mather 1955) based on mean monthly temperature and precipitation, soil texture, rooting depth, and the maximum amount of available water in the soil. We assumed water stress when the relative extractable water (REW) decreases below 40%

(Granier et al. 1999). In addition, the REW calculated by monthly temperature and precipitation data, soil physical diversity, root depth, available water volume (EW), and maximum water uptake (EW<sub>m</sub>) (2). Monthly precipitation was reduced by an interception to determine the annual drought stress index (Is) (3). With SWD, the water deficit stored in the soil could be calculated (4).

$$\text{REW} = \text{EW} / \text{EW}_m \quad (2)$$

$$\text{Is} = \sum \text{SWD} / \text{EW}_m \quad (3)$$

$$\text{SWD} = \text{EW}_m * 0.4 - \text{EW} \quad (4)$$

Where:

REW:	the relative extractable water content
EW:	the available water volume
EW <sub>m</sub> :	the maximum of water absorption
Is:	the annual drought stress index
SWD:	the water deficit stored in the soil.

We collected 119 samples from 20 soil profiles and identified the following soil properties:

- soil pH (potentiometrically in water and KCl suspension),
- texture (particle size distribution based on the Hungarian Standard (MSZ-08-0206)),
- CaCO<sub>3</sub> (Scheibler-type calcimeter),
- soil organic matter content (FAO 1990),
- ammonium lactate/acetic acid extractable (AL) potassium and phosphorus content (MSZ 20135:1999).

We evaluated the soil samples according to Van Reeuwijk (Van Reeuwijk 2002), and Stefanovits and colleagues (Stefanovits et al. 1999). We used C2 software to represent the data of selected soil profiles (Juggins 2007). Based on Stojanovic (Stojanović et al. 2015), we investigated the climatic response through tree ring widths as follows:

- 12 Scots pine trees with different health conditions were felled,
- two discs were taken from each pine tree:
  - one at breast height (1.3 m) (Group I),
  - one from root welling (0.1 m) (Group II),
- dry samples were sanded with progressively finer sandpaper until they acquired a highly polished surface (Stoke – Smiley 1968),
- after preparing the discs, we elaborated high-resolution pictures and measured the tree ring widths (TRW).

Several studies have described the bryophyte flora of the study area. Purger (Purger 1992) studied the bryophyte flora about 30 years ago, while a second bryofloristical study was performed in the spring of 2014 (Szűcs 2014, Szűcs – Patocskai 2014). In these two papers, the authors compared the main elements that influence changes in the bryophyte flora. During the field collections, the typical habitat and substrate, the time of collection, as well as the GPS coordinates and the altitude of the site points were recorded. The nomenclature of mosses and liverworts follows the classification of Hodgetts et al. (2020).

This study uses a broad spectrum of various methods to focus on a complex examination of the temporal change of the limiting site factors. Through an initial “rough” estimation of the new ongoing tendencies, we could detect the impact of dry years by applying relatively simple

empirical methods (e.g., the tendency of narrowing *TRW*). More precise but expensive procedures are not required to fulfil the aim of our study. More accurate measurements are planned later to obtain more detailed information about specific drought events and their impacts.

*Table 1. Analysed climate variables and indices*

Selected climate parameters	Abbreviations	Time period
Mean air temperature	T	monthly, seasonal, annual
Maximum air temperature	T <sub>max</sub>	monthly, seasonal, annual
Minimum air temperature	T <sub>min</sub>	monthly, seasonal, annual
Precipitation sum	P	monthly, seasonal, annual
Summer days	T <sub>max</sub> ≥ 25°C	daily
Hot days	T <sub>max</sub> ≥ 30°C	daily
Extremely hot days	T <sub>max</sub> ≥ 35°C	daily
Ice days	T <sub>max</sub> < 0°C	daily
Frost days	T <sub>min</sub> < 0°C	daily
Cold days	T <sub>min</sub> < -10°C	daily
Potential evapotranspiration	PET	monthly, annual
Aridity index	P/PET	monthly, annual
Dry days	DD; P <sub>day</sub> < 0.1	daily

Pearson's correlation tests were used for the two groups of ring widths and temperature, potential evapotranspiration (*PET*), and aridity index (*P/PET*) as climate variables. The tree ring widths (*TRW*) were measured with AutoCAD 2015 software (released by Autodesk). For statistical analyses, SPSS vers. 20.0 and R 3.2.2 programs (IBM Corp. 2011, R Core Team 2018) were used.

### 3 RESULTS

Temperatures have exhibited a significant increase in the investigated region in the last 60 years, with the most intense increases occurring in summer. The temperature means and temperature extremes both indicate a robust warming tendency. The total number of summer days and hot days per year have been higher in 1991–2020 than in 1961–1990. In the early 1990s, 2000s, 2010s, and consecutive periods were extremely dry compared to the long-term mean (*Figure 2*). In these 3 to 4 long periods, low summer precipitation occurred together with high temperatures that enhanced the severity of the drought condition.

We used both extreme low and high high-temperature indices in our investigation. The average total number of cold days from 1961 to 1990 is 9 days/year and decreases to 7 days/year from 1981 to 2010. Similarly, the number of ice days declined (from 21 days/year to 20 days/year), and frost days also fell (from 89 days/year to 85 days/year). The total number of extremely hot days was 0 days/year during the 1961–1990 period and 1 day/year between 1981 and 2010. The total number of hot days increased from 12 days/year to 19 days/year; summer days increased from 63 days/year to 75 days/year (*Figure 3* and *Table 2*).



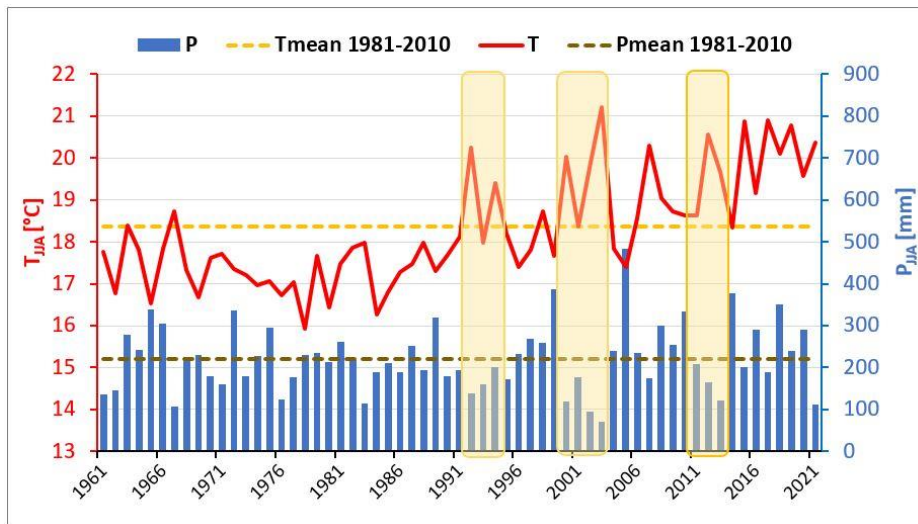


Figure 2. Mean summer temperature and precipitation sum for the period 1961–2021. Shaded areas indicate the consecutive drought periods.

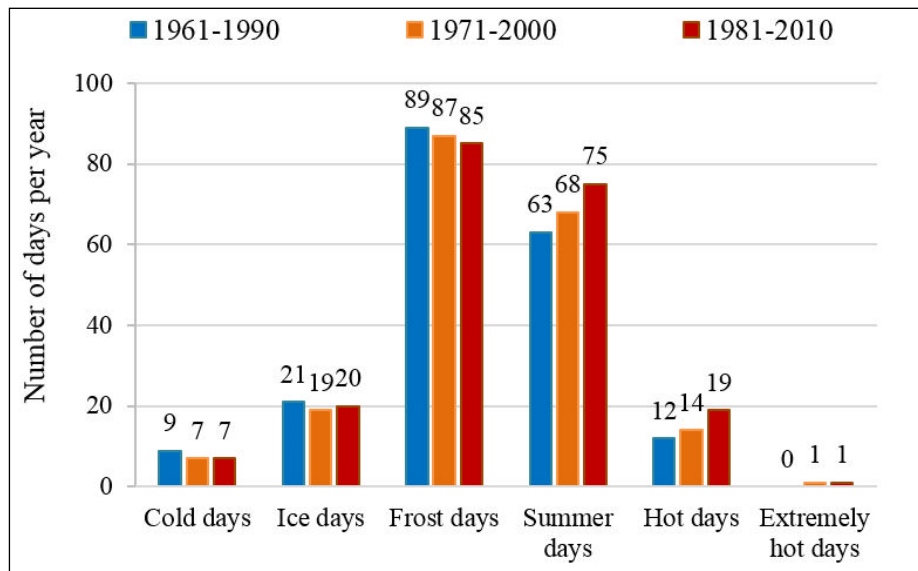


Figure 3. Total number of extreme low and high temperature in three different time periods (1961–1990; 1971–2000; 1981–2010)

Table 2. Differences between 1961–1990, 1971–2000 and 1981–2010 for temperature means (T) and dry days (DD). dT (°C) means the temperature differences and dDD (%) mean the dry day differences between 1981–2010 and 1961–1990 time periods. The bold red values are significant changes.

T (°C)	I.	II.	III.	IV.	V.	VI.	VII.	VIII.	IX.	X.	XI.	XII.
1961–1990	-	0.9	5.3	10.2	14.8	18.0	19.7	19.4	16.0	10.6	5.5	0.4
1971–2000	-	1.2	5.8	10.2	15.1	18.2	20.1	20.0	16.0	10.6	5.2	0.9
1981–2010	-	1.1	5.8	10.9	15.7	18.7	20.8	20.5	16.2	11.0	5.8	0.7
dT (°C)	1	0.2	0.5	0.7	0.9	0.7	1.1	1.1	0.2	0.4	0.3	0.3
DD (days)	I.	II.	III.	IV.	V.	VI.	VII.	VIII.	IX.	X.	XI.	XII.
1961–1990	1	13	15	15	14	13	17	17	19	19	13	13
1971–2000	1	14	15	15	15	14	16	18	18	19	13	13
1981–2010	1	15	16	16	16	16	18	18	18	20	13	13
dDD (pcs)	0	2	1	1	2	3	1	1	-1	1	0	0

The recurring hot and dry periods caused decreasing relative extractable water in the soil for *Pinus*. Figure 4 shows that relative water capacity was below the water stress limit several times and decreased during the period 1990–2021. Water balance diagrams were prepared using the properties of the soils (e.g. texture, humus content), root depth, and the climatic conditions of the area. It is important to note that below a certain limit, plants cannot absorb enough water, and water stress develops.

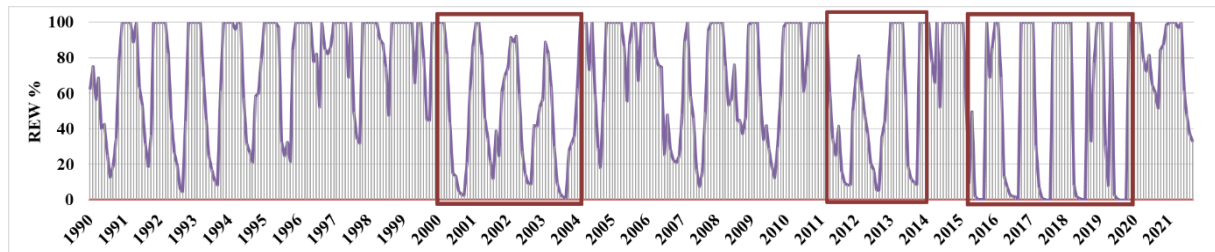


Figure 4. Relative water capacity based on Thornthwaite water balance model 1961–2021 (red frames highlighted the drought periods)

Soil types are very similar over the entire area. Soil pH ( $\text{pH}_{\text{H}_2\text{O}}$ ) was between 4.2 and 8.5. Soil pH in the upper layers varies from the most acidic to the weakly alkaline categories (Figure 6), but most of the soil samples were acidic. The soil pH of lower layers was frequently alkaline. Leaching is characteristic in the soil profiles; this seems to be the leading cause of the acidic values in the upper layers. The results of ( $\text{pH}_{\text{KCl}}$ ) were followed by the values of ( $\text{pH}_{\text{H}_2\text{O}}$ ). Soil pH ( $\text{pH}_{\text{KCl}}$ ) was between 3.5 and 8.3.

The  $\text{CaCO}_3$  content of the soils was between 2% and 19% below 20 cm of depth, which is unfavourable to all of the present tree species. We also found very little saline ( $<0.5\%$ ) in the lower layers during the conductometric analysis. The sum of clay% ( $<0.002$  mm) and silt% ( $0.05\text{--}0.002$  mm) fractions was low (between 3%–11% in the samples; thus, we classified them as coarse sand. Due to the low ratio of sedimentable soil particles, the water holding capacity of the investigated soils is unfavourable for the vegetation. The humus contents of the soils were between 0.01% and 8.8%. High values were found close to the surface, but they also occurred in lower layers ( $>40$  cm depth), where buried humus layers were found in a few cases. The total nitrogen supply was between 0.01% and 0.25% of nitrogen; however, these levels are considered to be low rather than medium. AL extractable phosphorus content was low ( $3.4\text{--}15.9 \text{ P}_2\text{O}_5$  mg/100g soil), and AL extractable potassium ranged between  $1.5\text{--}9.1 \text{ K}_2\text{O}$  mg/100g soil (Figure 5).

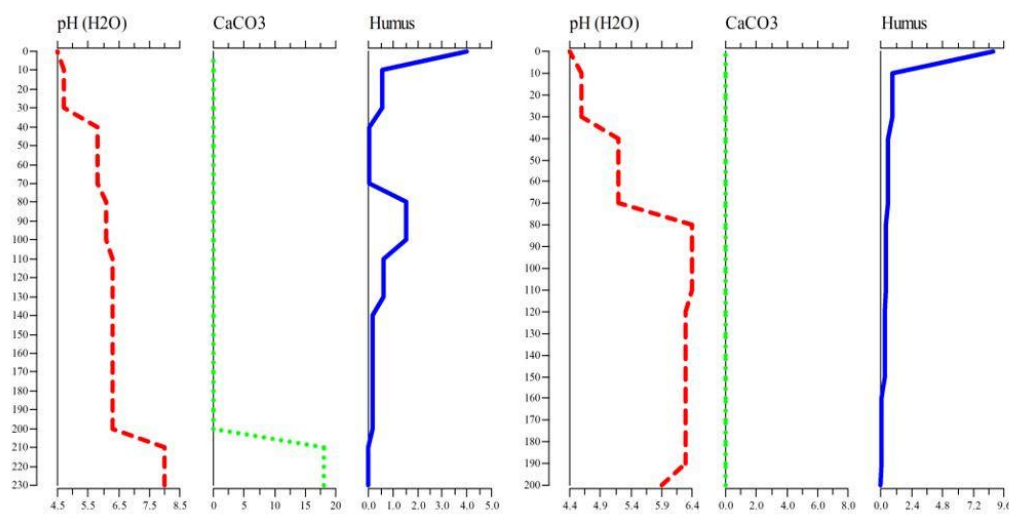


Figure 5. Distribution of soil  $\text{pH}_{\text{H}_2\text{O}}$ ,  $\text{CaCO}_3$  content and Humus% in profile 5 (left) and in profile 15 (right).



Three bark beetle species – *Tomicus piniperda*, *Ips sexdentatus*, and *Ips acuminatus* – were the most frequent in both trap tree cohorts. In some of the trees, *Tomicus minor* was also found in high numbers. While all trees of the first cohort were colonised, 5 out of 70 trees remained intact in the second cohort (Table 3). *T. piniperda* and *T. minor* colonised the trees first; they were followed by *I. sexdentatus* and *I. acuminatus*. We noted that there were some overlaps between the colonised tree parts. *I. sexdentatus* dominated the lower part of the trunk, *I. acuminatus* dominated the upper part of the trunk and the crown, including thicker branches. *T. piniperda* and *T. minor* excavated mother galleries in the trunk and in the crown, respectively.

Table 3. Bark beetle colonisation of the trap trees

Tree part	Bark beetle species	1 <sup>st</sup> cohort (n=25)	2 <sup>nd</sup> cohort (n=70)
Top (from crown base to the top)	<i>I. acuminatus</i>	6	56
	<i>I. sexdentatus</i>	3	10
	<i>T. piniperda</i>	–	3
	<i>T. minor</i>	14	–
Middle (crown base)	<i>I. acuminatus</i>	–	8
	<i>I. sexdentatus</i>	18	29
	<i>T. piniperda</i>	11	2
	<i>T. minor</i>	6	–
Trunk	<i>I. acuminatus</i>	–	–
	<i>I. sexdentatus</i>	21	42
	<i>T. piniperda</i>	23	–
	<i>T. minor</i>	–	–

Concerning bryological investigations, the largest population of *Campylopus introflexus* (5 dm<sup>2</sup>) was found in a decayed *Pinus sylvestris* trunk in an open site. *Dicranum tauricum* is a new floral element in the *Pinus* study stand, and their populations have spread considerably in the last 30 years. We found all the 34 individual occurrences of these mosses, which live predominantly on decayed *Pinus sylvestris* trunks and logs. Some other new species were also collected on dead pine woods in the study area. These new species included *Nowellia curvifolia*, *Dicranum montanum*, and *Leucobryum juniperoideum*. In total, 102 bryophytes are known to live in the study area, of which 49 taxa were identified during the last decade, 32 species were confirmed, and 21 species of mosses were not found again (Table 4).

Table 4. Species richness of bryophytes, liverworts and mosses of the study area. “old”: old records based on an early study (Purger 1992), and later not found; “old-new”: species recorded by both bryological studies; “new”: species recorded in latest fieldwork (Szűcs – Patocskai 2014), missing from earlier reference (Purger 1992).

Bark beetle species	old	old-new	new	total
Liverworts	0	1	5	6
Mosses	21	31	44	96
Total species number	21	32	49	102

The decreasing tendency of available water has a negative effect on tree ring widths (TRW). The TRW decreased in recent decades (since ~1990). Thus, we compared the climate datasets with the growth of tree ring widths. Figure 6 shows the relative water capacity based on the Thornthwaite water balance model between 1961 and 2021. The connection between the previous year and the year of growth is represented with a 95 % confidence limit for the

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calculated parameters. The most intriguing fact in *Figure 6* is that despite the differences in age and soil characteristics, the physiological mechanisms in trees that are responding to environmental factors are basically the same. Generally, the available precipitation from June to August strongly influenced radial growth in the largest part of the observed period. June–August temperatures show a high negative effect on TRW. High summer temperature and intensive potential evapotranspiration influence significant negative effects on TRW values. Moreover, when the groundwater level started to decrease in the last 30 years, the correlation between the water level and radial growth began to decay, while at the same time, precipitation in May became more important. The correlation between the aridity index and TRW is not significant; this may explain that a high correlation between precipitation and TRW has not been observed. In Group I, the influences of the three selected parameters are stronger than in Group II.

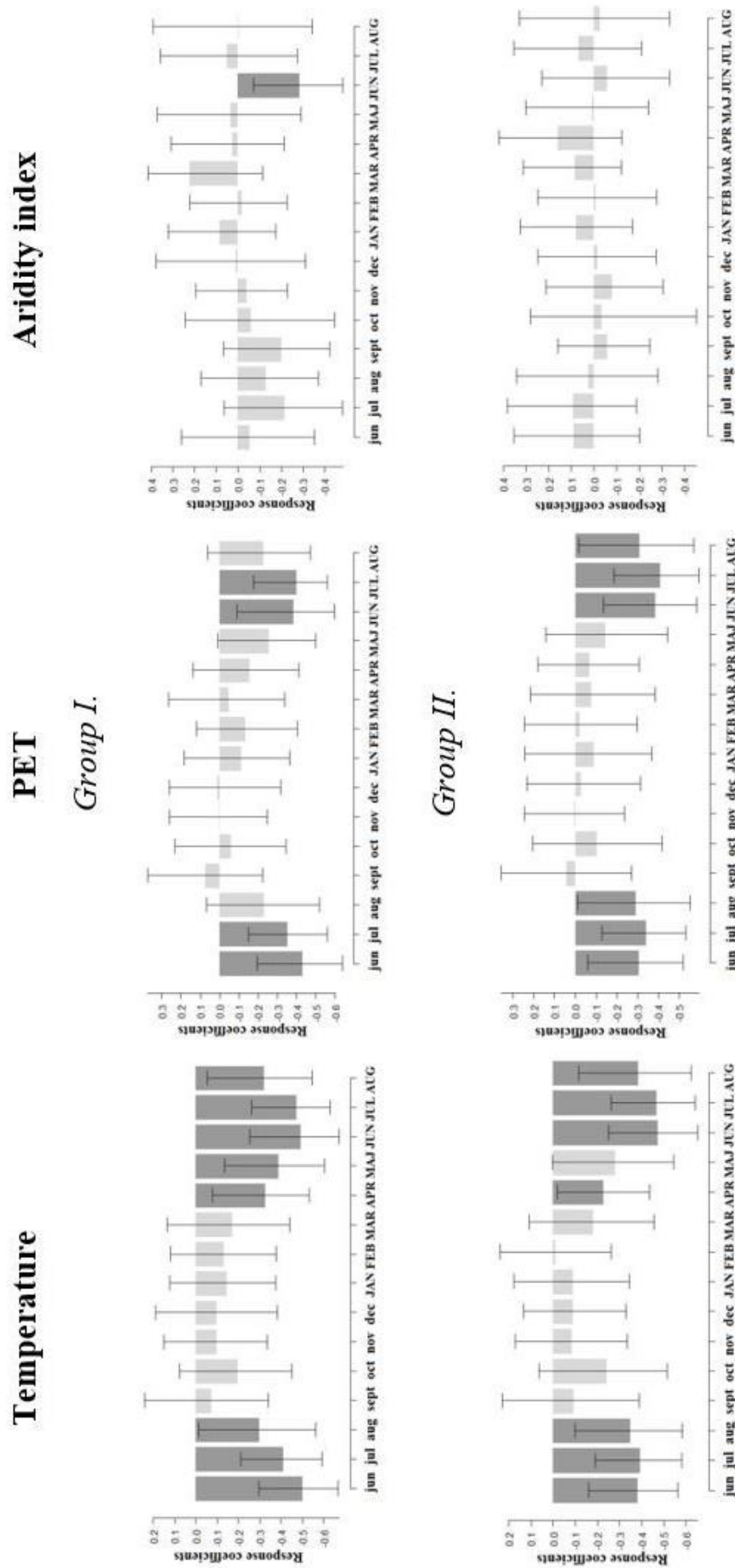


Figure 6. Results of Thornthwaite water balance model 1961–2021 was correlated with different climate parameters. Small letters representing the previous year and capital letters the year of growth. Light grey is the correlation values, where dark colour represents bootstrapped correlations significant at  $p < 0.05$ , lower and upper lines represent 95% confidence limit for the calculated parameters. Group I: discs from breast height, Group II: discs from root welling

## 4 DISCUSSION

Climate analysis shows that the increasing temperature, frequency of warm extremes, and recurring consecutive drought periods in the research area resulted in the poor health status of Scots pine.

Hardly any water is available for the species due to the shallow root zone and the scarce soil water storage. Water storage is poor even during extreme precipitation events. The frequency of drought periods and unfavourable soil conditions have reduced the relative water capacity of the soil. A Thornthwaite-type monthly water-balance model (Thornthwaite – Mather 1955) indicated that the water stress has increased significantly. We found decreasing TRW values caused by water stress in both old and young trees. The combination of temperature increases, precipitation decreases, and unfavourable sandy soils have likely caused the decrease in radial growth. The humic sand soils of the area absorb water relatively quickly, but it releases it just as quickly due to the physical variety of the soil. The maximum amount of water that can be stored in the soil is 100 mm. During drought periods (1990–1993; 2000–2003; 2011–2013), this soil type could not store enough water for vegetation. Moreover, the figure clearly shows the difference during very wet years (e.g., the year 2010), which could relieve plants from water stress. The measured TRW-s followed the monthly water balance model. Nevertheless, based on the TRW measurements, the TRW of older trees (> ~50 years) cannot increase their widths in wet years after the third drought period.

The acidic pH of topsoil (0–20 cm) is favourable for most tree species. The chemical properties of the soil are suitable for the vegetation, but the high CaCO<sub>3</sub> content of soils decreases soil productivity. Coarse sandy soils have low water storage capacity, and the water drains out from the upper layers rapidly. Therefore, water supply is scarcely available for vegetation (Stefanovits et al. 1999). Buried humus layers, which improve the water and nutrient supply of soils, were found in three soil profiles only (Figure 6). The low amount of total nitrogen, phosphorus, and potassium nutrients means that no part of this soil can store colloids.

Drought-induced mortality has occurred not only in the sandy soils of the study area but also in the entire area of Europe. High mortality of *Pinus sylvestris* has been observed in several places in the Swiss Alps (Rebetez – Dobbertin 2004). Drought was found to be the main limiting factor; however, the soil conditions were also unfavourable (rendzic leptosols, calcic), and in some cases, the calcareous sediment made soils even drier. The effects of a single, severe drought on TRW can be reversible, but a multi-year drought can reduce tree growth for several years and may lead to mortality (Bigler et al. 2006). Bauwe and colleagues (Bauwe et al. 2015) predicted a negative tendency of TRWs in north-eastern Germany towards the end of the 21st century.

A reclaimed area in northeast Estonia, where water deficit also occurs in summer (June–August) due to high temperature, provides another example; this variability is shown by the radial growth of Scots pine (Metslaid et al. 2016). Drought stress has been reported as a major factor in bark beetle attacks on Norway spruce (*Picea abies*) (Ježík et al. 2014). However, similar studies on Scots pine seem to be rare. The present study has shown that various bark beetle species are present in the area and drought stress makes weakened trees ideal candidates for bark beetle colonisation. We can make some notes and observations by comparing recent bryofloristical results (Szűcs – Patocskaï 2014). New bryophyte species occur in the changing forest. The bryophytes do not contribute to the mortality of trees; however, they are indicators of health deterioration of the trees. The expanding (new and already present) species of mosses colonise the rotted wood, which accrued significantly with the increase of drought frequency. Fewer bryophyte species occurred due to the smaller amounts of rotted wood and less light. *Campylopus introflexus* is an invasive moss species in Europe (Hassel – Söderström 2005) that

is expanding toward Eastern and South Europe (Alegro et al. 2018). The first Hungarian occurrence was discovered in NE-Hungary, about 60 kilometers from the study site in an old, declining *Pinus nigra* forest (Blockeel et al. 2007). Although Purger found no moss in 1992, (Purger 1992) the latest research has detected it in four localities. Further Hungarian occurrences have also been described in old pine forest stands where pine wood is available (Szűcs et al. 2014, Szűcs 2018).

The Bakonyerdő Ltd. (local forestry directorate) and the Faculty of Forestry (University of Sopron) jointly examined the climate, soil, and hydrological conditions of the area, as well as the entomological and plant pathological parameters, to uncover the potential direct and indirect causes of mortality. The unique landscape will change significantly despite these efforts because Scots pine will most likely disappear from the area. Based on our results, native deciduous tree species and sandy grassland habitats will develop in the sandy areas for the proposal of professionals and the decision support system.

## 5 CONCLUSIONS

This study aimed to provide a complex analysis to identify tree mortality causes in the only relict Scots pine forest in Hungary. We determined how site conditions have changed in the research area, which key factors were the most important, what kind of damages could occur, and how we could protect this vulnerable forest from decay. The meteorological data shows that the summer mean temperatures increased in the period 1961–2021. The frequency of extremely warm and dry periods and the total number of hot days increased significantly in recent decades. Increasing aridity can lead to higher water utilization and water reduction. These combined processes also had a negative influence on the radial growth of young and old pine trees. We found significant correlations between the decreasing TRW and the summer temperature.

Coarse sand texture is unfavourable to absorbing capacity. Water cannot be stored; thus, it leaches through the soil profile. Therefore, water is barely available to the trees, and the effect of high temperatures leads to increased evaporation. Warm winters help pests to survive. The appearance of bark beetles has started damage chains that lead to eventual mortality. The new invasive moss species displace native species and also damage the herbaceous level of the forest. Climate extremes and unfavourable soil properties affect the stand and induce a damage chain, where abiotic factors can cause secondary (biotic) damage to trees with reduced vitality. The light conditions in gaps within the forest are favourable to new invasive species (e.g., mosses or pests). The already observed impacts in the forest may be more severe in the future when threatening climate conditions are expected to be more frequent (Gálos et al. 2015). Therefore, Hungarian forest management must prepare strategies for the selection of adaptive tree species. This study recommends the following to forest managers:

1. Keep the water in forest areas to increase the groundwater level in ecosystem during prolonged drought periods if possible.
2. Promote mixed forests and close to nature forest management.
3. Take care of soil and consider the soil site properties before plantation.

**Acknowledgements:** This article was made in frame of the “EFOP-3.6.1-16-2016-00018 - Improving the role of research+development+innovation in the higher education through institutional developments assisting intelligent specialization in Sopron and Szombathely”. Borbála Gálos was supported by the János Bolyai Research Scholarship of the Hungarian Academy of Sciences. The authors thank all of the co-workers for their support. Special thanks to the Bakonyerdő Ltd. for the cooperation.

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