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Impact of surface fire on the radial growth of Scots pine in Polissya landscapes

Iryna Koval[1], https://orcid.org/0000-0001-6328-1418, e-mail: koval_iryna@ukr.net

DSc (Agriculture), Senior Researcher at Forest ecology section of Department of Forestry and Forest economics

Nadiya Maksymenko[2], http://orcid.org/0000-0002-7921-9990, e-mail: maksymenko@karazin.ua

DSc (Geography), Professor, Head of the Department of Environmental Monitoring and Protected Areas Management

Ivan Martynchuk[3], https://orcid.org/0000-0002-1370-677X, e-mail: martynchuk.ivan@gmail.com

PhD (Economy), Associate Professor, Vice-Rector for Scientific and pedagogical work, Social and Humanitarian Development, Associate Professor of the Department of Forestry and Horticulture

Olena Andreieva[3], https://orcid.org/0000-0003-0851-800X, e-mail: andreeva-lena15@ukr.net

DSc (Agriculture), Professor of the Department of Forestry and Horticulture

Svitlana Matkovska[3], https://orcid.org/0000-0002-8019-5498, e-mail: matkovcka@ukr.net

PhD (Agriculture), Associate Professor of the Department of Forestry and Horticulture

Andriy Lashchenko[4], https://orcid.org/0000-0002-7638-6400, e-mail: lashchenko@nubip.edu.ua

PhD (Agriculture), Associate Professor of the Department of Forest Assessment and Forest Management

[1] *G. M. Vysotsky Ukrainian Research Institute of Forestry and Forest Melioration, Kharkiv, Ukraine*

[2] *V. N. Karazin Kharkiv National University, Kharkiv, Ukraine*

[3] *Polissia National University, Zhytomyr, Ukraine*

[4] *National University of Life and Environmental Sciences of Ukraine, Kyiv, Ukraine*

ABSTRACT

Introduction. Forest fires are one of the key destabilizing factors affecting the functioning of forest ecosystems, influencing their productivity, biodiversity, and ecosystem services. Under the conditions of climate change and increasing anthropogenic pressure, particularly due to military actions in Ukraine, the frequency and intensity of fires are rising, which necessitates the study of post-fire processes in the forests of **Polissya.**
The aim of the research is to determine the patterns of surface fire impact on the radial growth of Scots pine in middle-aged pine stands of **Polissya.**
Methods. The study is based on a combination of dendrochronological analysis, forest inventory methods, and statistical data processing. Cores were collected from the fire-damaged stand and from a control (undamaged) stand. Local tree-ring chronologies were developed, and indexing using moving-average smoothing was applied. The dynamics of latewood, earlywood, and annual rings were compared between the fire-damaged plot and the control plot for the period 2020–2024. Correlation and regression analyses between growth indices and char height on the stem were performed.
Results. A significant reduction in radial growth was found in the year of the fire and in the following period, with a maximum depression in 2023, which was exacerbated by dry climatic conditions. Latewood turned out to be the most sensitive indicator of fire impact, as its width in the damaged stand was significantly smaller compared to the control. Growth recovery for trees that remained viable occurred within two years. A statistically significant relationship was found between latewood indices and char height. Although the char height on the damaged stand varied within the range of 175–250 mm, i.e., the damage can be classified as moderate to severe, the radial growth recovery of the trees that remained alive occurred within two years. This is because the depth of bark charring was shallow, and the middle-aged pine stands have thick bark that protected the cambium, phloem, and conductive tissues of the wood from fire damage. Moreover,

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as a result of sanitary felling after the fire, 14% of the trees were lost, which improved light conditions and nutrient availability for the remaining trees. The differences between earlywood and annual ring widths in the damaged stand and the control were insignificant during the pre-fire period, the year of the fire, and the post-fire period. The largest - was found for 2023, when the difference was 22%.
Analysis of the latewood/earlywood ratio showed a decrease in this index for the damaged plot in the year of the fire (2022) and the first post-fire year (2023), indicating that this index is suitable for characterizing the impact of stress factors (fires, drought years, etc.) on the radial growth of Scots pine trees.
Conclusions. The impact of the 2022 fire on middle-aged Scots pine stands under thermal stress conditions (temperature deviation of +13–28%) was studied. It was found that latewood is the most sensitive indicator of pyrogenic impact: in the year of the fire, its width decreased by 56% (to 0.20±0.04 mm), while earlywood parameters remained stable. A statistically significant regression relationship between latewood indices and char height was revealed. It is proved that if the cambium remains alive, trees restore their radial growth within two years, indicating their resistance.

Keywords:

radial growth, Pinus sylvestris L., surface fire, dendrochronology, latewood, post-fire dynamics, Polissya, landscape, forest, climate change, sanitary condition of trees, bioindication.

Introduction

Forest fires are among the most powerful factors transforming forest ecosystems, affecting their structure, functioning, and productivity. They cause significant ecological and economic losses, disrupt biogeochemical cycles, and increase greenhouse gas emissions, thereby contributing to global warming [1–3].

In the context of Ukraine, the problem of fires has gained particular urgency due to military aggression, which is accompanied by the large-scale use of incendiary weapons and the "scorched earth" tactic. According to current estimates, a significant proportion of forest ecosystems have been damaged or destroyed, which necessitates research into their post-fire recovery [4-6].

The forests of Polissya attract special attention, where the combination of sandy soils, increased flammability, and climate change (rising temperatures and precipitation deficits) creates preconditions for frequent fires. Despite a considerable number of studies, the issue of radial growth dynamics as an integral indicator of tree vitality after fire remains insufficiently addressed, especially for the conditions of Ukraine.

The aim of the research is to determine the patterns of surface fire impact on the radial growth of Scots pine in middle-aged pine stands of Polissya**.**

The object of the research is a middle-aged pure pine stand damaged by a surface fire in April 2022 and an undamaged stand.

The subject of the research is the response of the radial growth of Scots pine to the impact of a surface fire.

Analysis of recent research and publications. Tree radial growth is an integral indicator of their physiological state, which makes it possible to use it for bioindication of forest stands [7]. Tree recovery after fire is determined both by direct thermal damage and by climatic factors, primarily high temperatures and moisture deficit. In particular, studies of *Pinus pinaster* Aiton in Vesuvius National Park (southern Italy) have shown that in fire-damaged trees with significant crown deformation, suppression of cambial activity, reduced xylem production, delayed phenological phases, and decreased wood plasticity are observed compared to trees undamaged by fire. The authors concluded that substantial limitations of photosynthesis caused by crown defoliation combined with recurrent droughts lead to a sharp decline in radial growth and prevent the return of productivity to the level preceding the fire damage [8].

The general mechanism of tree damage by fires includes three main components: crown damage – high temperatures destroy buds and leaves (scorching) due to convective and radiant heating or direct contact with flames; stem damage – the heat flux penetrates through the bark, causing necrosis of the cambium and phloem, with bark thickness and charring depth serving as critical indicators; root damage – smouldering combustion of litter and organic debris near the tree base can destroy root systems [9].

Studying radial growth in fire-damaged stands allows for informed planning of forest management measures and specification of the required duration of monitoring of pine stands after pyrogenic impact. Modern dendroecological studies indicate that post-fire radial growth dynamics is a complex multifactorial process that depends on fire intensity, climatic conditions, competition levels, and biological species traits [10].

Materials and methods. The methods of comparative ecology, forest inventory, and dendrochronological methods were used [11, 12].

A surface fire occurred in a pine (*Pinus sylvestris* L.*)* stand of the "Korostyshiv Forestry" branch of the state enterprise "Forests of Ukraine" in April 2022. This is a pure, middle-aged pine stand growing in fresh mesic forest site conditions (fresh oak forest type). Cores were collected from the fire-damaged plot and from a control plot (Fig. 1).

The stand grows in fresh mesic forest site conditions. The fire occurred in April 2022. Fifteen cores from the fire-damaged plot and fifteen cores from the control plot were collected in September 2024.

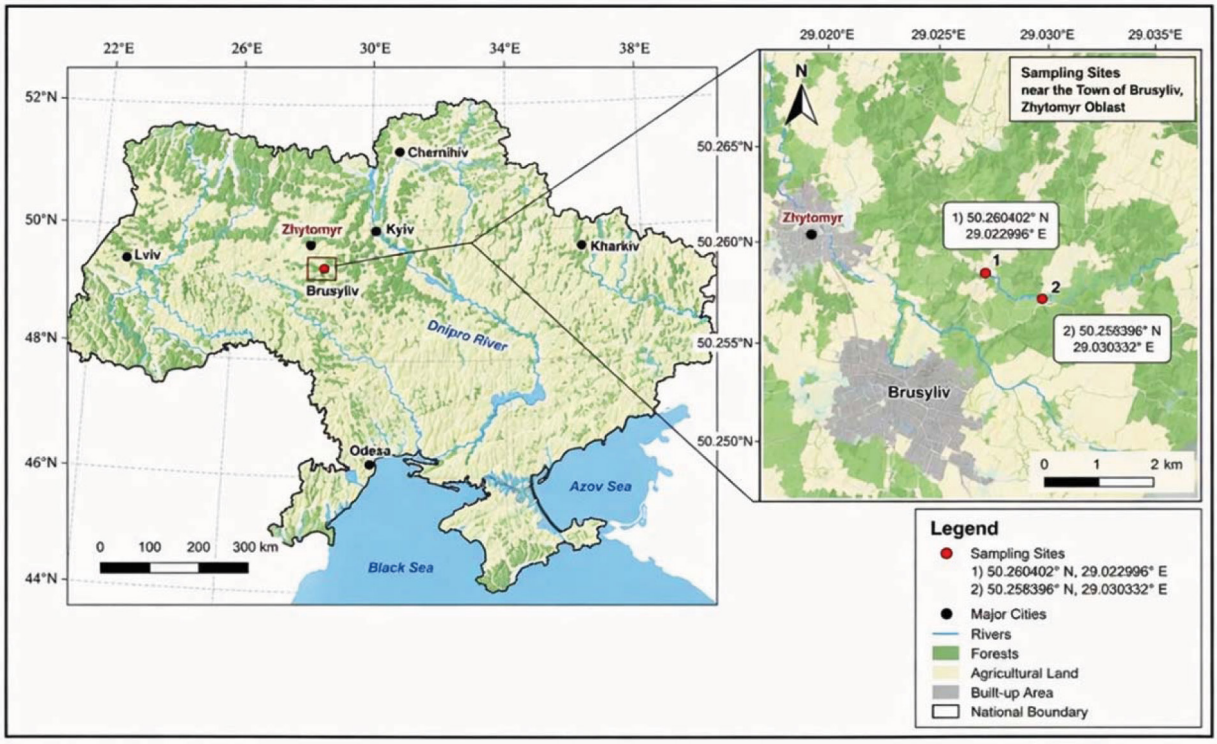


Fig. 1. Map of Ukraine showing the sampling sites.
Note: 1 – fire-damaged pine stand, 2 – control stand

During core collection, the diameter and height of each tree were also measured, and the sanitary condition category was determined. Six categories are distinguished: Category 1 – healthy trees (no signs of weakening): trees with a dense crown, normal growth, no damage to the stem or roots. Category 2 – weakened: crown of medium density, green needles, but reduced growth; minor mechanical damage may be present. Category 3 – severely weakened: open (sparse) crown, needles shortened or pale, presence of top dieback or isolated dead branches. Category 4 – dying trees: crown yellow or brown, needles shedding, more than 2/3 of the crown consists of dead branches, bark begins to peel off. Category 5 – fresh deadwood: trees that died in the current year. Needles dry (red or grey) or already fallen, bark may be infested with stem pests [13].

Cores were taken with a Pressler increment borer at a height of 1.3 m. They were then air-dried, and the widths of earlywood, latewood, and annual ring were measured using a HENSON measuring system with an accuracy of 0.01 mm. Local tree-ring chronologies were obtained for the fire-damaged and control plots.

The dynamics of latewood, earlywood, and annual ring layers were compared between the fire-damaged plot and the control plot over the period 2020–2024 (two years before the fire, the year of the fire (2022), and after the fire).

To remove the age trend and obtain indexed tree-ring chronologies, the 3-year moving average method was used [11].

Statistical data processing, correlation and regression analyses were performed to establish relationships between the indices of tree radial growth and the char height on the stems, as well as the categories of tree sanitary condition.

For the analysis, data from the Zhytomyr weather station (50°16′50″N, 28°39′32″E) were used. Precipitation and temperature normals were calculated for the period 1974–2004. Precipitation normals are a climatological method based on averaging data over a long-term period (usually 30 years or more) for a specific location. This helps to understand whether the current month or year is dry/wet or warm/cold [14].

Results

In order to establish the climatic normals of precipitation and temperature, the corresponding values were averaged over the period 1974–2024. It was found that in the year of the fire (2022), average temperatures were 13% above the normal, while precipitation was 7% below the normal. In 2023, these values were 21% and 33%, respectively; in 2024– 8% and 11%. Consequently, the most extreme year for tree radial growth was 2023 – the year following the fire (Fig. 2).

The unfavourable weather conditions for tree growth in 2023 likely exacerbated the depression of radial growth in the fire-damaged plot.

As of 2024 (the second year after the fire), the sanitary condition of trees in the pine stands on the damaged plot had deteriorated compared to

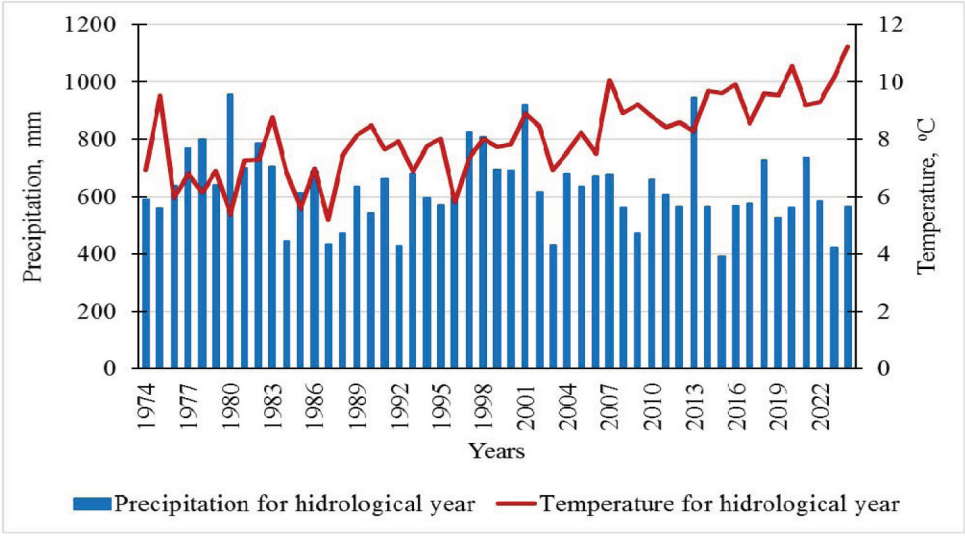


Fig. 2. Dynamics of temperatures and precipitation by hydrological years according to the data from the Zhytomyr weather station

the control. No completely healthy trees were found here (Fig. 3).

Scots pine trees of different sanitary condition categories responded differently on the fire-damaged plot. Weakened trees (category 2) quickly responded to the thinning of the stand caused by the fire, which was manifested in a growth surge in 2023, i.e., in the second year after the fire. Severely weakened or dying trees (categories 3 and 4) showed no significant response to the increased growing space and improved light conditions after the dieback of 14 % of the trees on the damaged plot (Fig. 4).

As noted above, the dynamics of latewood, earlywood, and annual ring layers were compared between the fire-damaged plot and the control plot for the period 2020–2024, i.e., for two years before the fire, the year of the fire (2022), and after the fire (Fig. 5).

In the year of the fire, 2022, the average latewood width on the fire-damaged plot was 0.20±0.04 mm, while on the control plot it was 0.45±0.08 mm, i.e., the difference was 56% and was significant (t_{fact}=2.7, $t_{theor.}$= 2.1 at the 0.05 significance level). In the following year, this difference between the respective wood layers also proved significant at the 0.05 level (t_{fact}=2.7, $t_{theor.}$= 2.1 at the 0.05 significance level), i.e., the latewood width in the damaged stand was 0.29±0.06 mm, while on the control it was 0.58±0.09 mm, meaning it decreased twofold compared to the control. In 2024, the difference between latewood layers in the damaged stand and the control became insignificant. Thus, latewood recovered for the trees that remained alive by the second year after the fire (see Fig. 5 A).

The differences between earlywood and annual ring widths in the damaged stand and the control were insignificant during the pre-fire period, the year of the fire, and the post-fire period. The largest difference in annual radial growth between the damaged and control sample plots was found for 2023, when the difference was 22% (see Fig. 5 B, C).

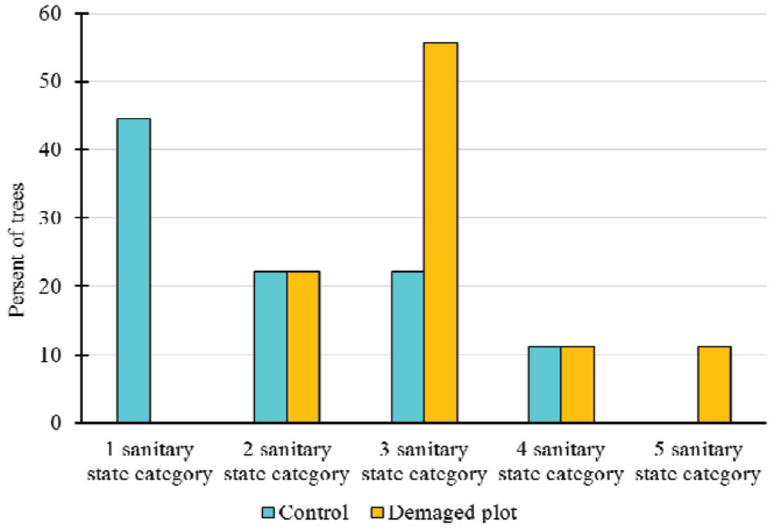


Fig. 3. Sanitary condition of trees on the sample plot damaged by a spring surface fire in 2022 and on the control plot for 2024.

The latewood layers of the trees that remained alive proved to be the most sensitive to fire impact.

Although the char height on the damaged stand varied within the range of 175–250 mm, i.e., the damage can be classified as moderate to severe, the radial growth recovery of the trees that remained alive occurred within two years. This is because the depth of bark charring was

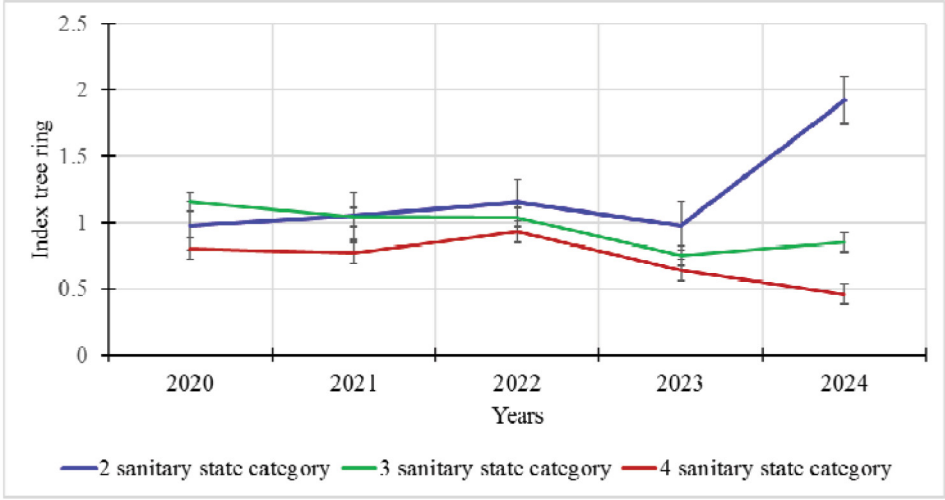
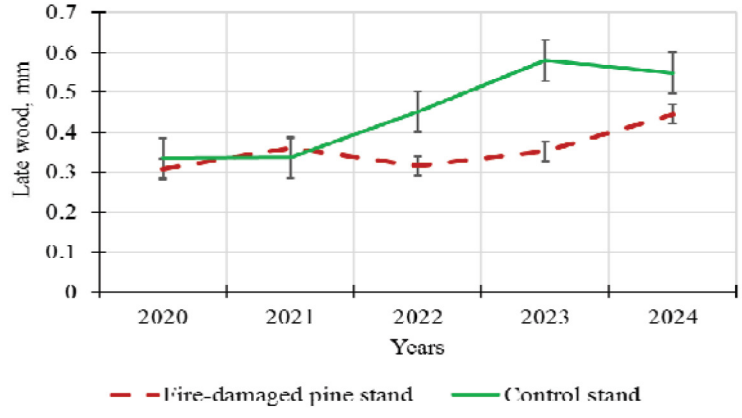
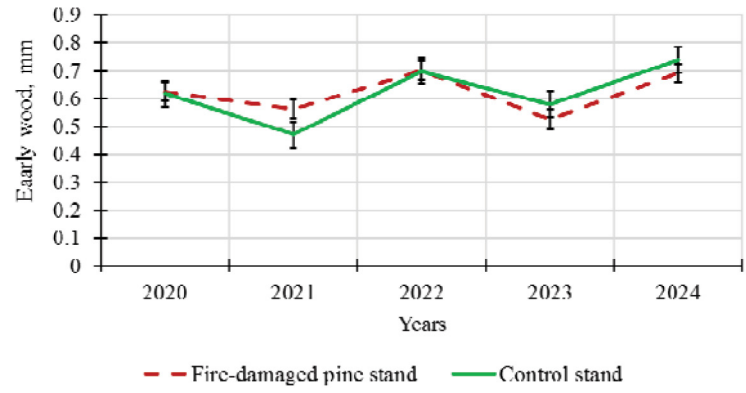


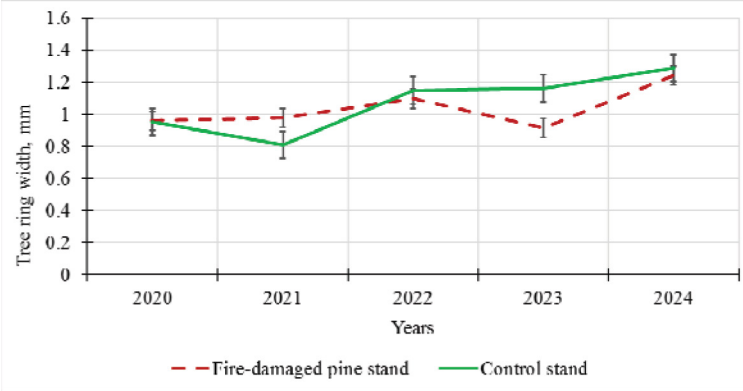
Fig. 4. Dynamics of radial growth of Scots pine on the fire-damaged plot in 2022 by sanitary condition categories



A) Dynamics of latewood layers in the fire-damaged stand and the control stand



B) Dynamics of earlywood layers in the fire-damaged stand and the control stand



C) Dynamics of annual ring layers in the fire-damaged stand and the control stand

Fig. 5. Dynamics of latewood, earlywood, and annual layers in the fire-damaged stand and the control stand

shallow, and the middle-aged pine stands have thick bark that protected the cambium, phloem, and conductive tissues of the wood from fire damage. Moreover, as a result of sanitary felling after the fire, 14% of the trees were lost, which improved light conditions and nutrient availability for the remaining trees.

Analysis of the latewood/earlywood ratio showed a decrease in this index for the damaged plot in the year of the fire (2022) and the first post-fire year (2023), indicating that this index is suitable for characterizing the impact of stress factors (fires, drought years, etc.) on the radial growth of Scots pine (Fig. 6).

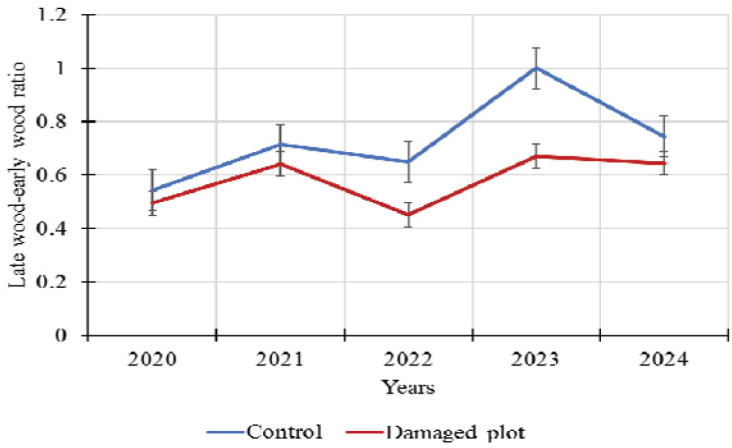


Fig. 6. Latewood/earlywood ratio

Latewood proved to be the most sensitive to changes in environmental conditions. A regression relationship between latewood indices and char height on the stems was established for the year of the fire (2022), which is described by a third-order curve (η=0.73±0.25, $t_{fact.}$= 2.87, $t_{theor.}$= 2.37, $t_{fact} > t_{reop}$ at the 0.05 significance level) (Fig. 7).

A regression relationship between latewood indices and char height on the stems was established for the year after the fire (2023), which is described by a third-order curve (η=0.78±0.25, $t_{fact.}$= 2.87, $t_{theor.}$= 2.37, $t_{fact.} > t_{theor.}$ at the 0.05 significance level) (Fig. 8).

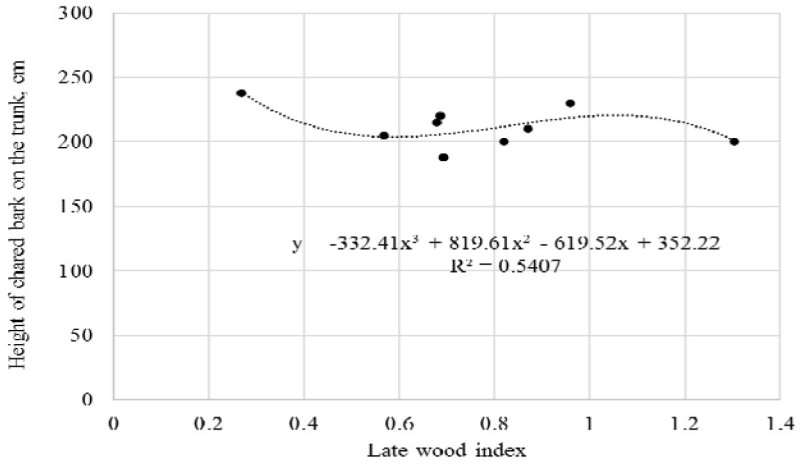


Fig. 7. Regression dependence of the late wood indices for 2022 (year of fire) and the height of the bark char on the trunks

Discussion

Our results are in good agreement with current understanding of fire effects on radial growth of various pine species in arid and Mediterranean regions. In particular, a study of *Pinus radiata* in the Jonkershoek Valley (Western Cape Province, South Africa), which has a Mediterranean-type climate with warm, dry summers and wet, mild winters, demonstrated a significant growth reduction directly in the year of the fire and the following year. Recovery of radial growth was expected as early as the second year after the fire, with a pronounced interaction between the degree of fire damage and precipitation amount. Importantly, char height on the stem – an indicator of scorching intensity – correlated with a significant narrowing of annual rings and a decrease in the latewood proportion [15].

In contrast, for Scots pine in young stands of the Left-Bank Forest-Steppe of Ukraine, the recovery process proved to be longer: after a surface fire in May 2011, the surviving trees were able to return to the radial growth level recorded before the disturbance only in the sixth year, during 2014–2016 [16,17]. Such differences in recovery time may be explained by both species-specific traits and differences in climatic conditions and fire severity.

It should be emphasised that fires not only directly cause local tissue necrosis, but also trigger a systemic stress response of the entire tree, which is reflected in the multi-year dynamics of annual ring width [18]. Dendrochronological studies reveal the ecophysiological mechanisms of such a response: for example, heavily defoliated trees not only reduce radial growth but also alter their water consumption regime due to significant crown damage [19]. In our case, we used sanitary condition categories that integrally characterise, among other things, the crown condition. It was

found that statistically significant recovery of annual wood increment after the fire was observed only in trees classified as Category 2 (weakened). In contrast, healthy trees (Category 1) were completely absent on the fire-affected plot.

Additional evidence of the decisive role of defoliation and drought is provided by results obtained for *Pinus pinaster* in hot and dry areas of the Mediterranean. Comparison of burned trees with significant crown deformation with undamaged specimens revealed a reduction in both radial growth and photosynthetic activity for three years after the fire. Monitoring of cambial activity showed that hot and dry periods exacerbated the negative effects: the affected trees decreased xylem production, delayed growth phenology, and reduced wood plasticity. This indicates that the combination of substantial photosynthetic limitations due to defoliation and recurrent droughts can lead to prolonged growth suppression and prevent the return of productivity to pre-disturbance levels. Similarly, other researchers emphasise that drought can exacerbate the negative effects of fires on growth [20]

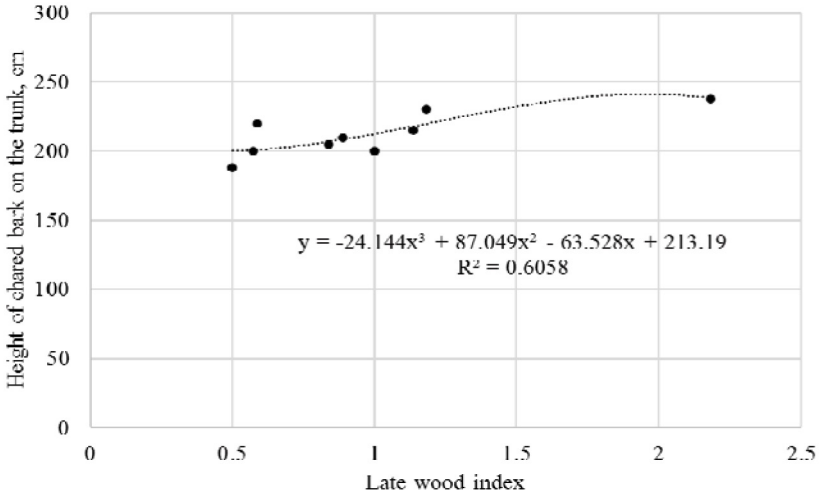


Fig. 8. Regression relationship between latewood indices for 2022 (the year of the fire) and char height on the stems

At the same time, there are factors that mitigate stress effects. In particular, a reduction in intra- and interspecific competition after the loss of part of the stand can partially compensate for the adverse effects of warming by reducing moisture deficit due to lower overall resource consumption by neighbouring vegetation [21]. Moreover, fire resistance depends significantly on the species. For instance, data on *Pinus nigra* confirm its characteristic ability to withstand surface fires without critical consequences for growth [22]. In our case, middle-aged Scots pine trees have sufficiently thick bark so that, under conditions of shallow charring depth, even a char height of 200–250 mm on the stem did not cause dieback of the surviving individuals. Thus, the combination of species adaptations, reduced competition, and favourable weather conditions in the post-fire period determines the trajectory of radial growth recovery.

Conclusions

1. The period 2022–2024 was characterised by progressive thermal stress: the temperature deviation from the normal increased from 13% to 28%. The most extreme year was 2023 (precipitation deficit of 33%), which exacerbated the negative impact of the pyrogenic factor on radial growth.

2. The fire led to a complete loss of the healthy tree category on the damaged plot by 2024. The total mortality due to the fire and subsequent sanitary felling amounted to 14%.

3. Latewood proved to be the most sensitive indicator of fire: in the year of stress, its width decreased by 56% compared to the control (0.20±0.04 mm and. 0.45±0.08 mm). At the same time, earlywood and annual ring parameters did not show statistically significant changes.

4. In the second year after the fire (2024), the difference in latewood width between the plots disappeared. This confirms the high adaptive capacity of middle-aged Scots pines to restore radial growth provided the cambium remains viable.

5. The latewood/earlywood ratio has been proven to be a reliable marker of pyrogenic stress. The statistically significant regression relationship between latewood indices and char height (2022–2023) allows this indicator to be used for quantitative assessment of the degree of tree damage.

Внесок авторів: всі автори зробили рівний внесок у цю роботу
Конфлікт інтересів: автори засвідчують, що, незважаючи на те, що один із авторів статті є членом редакційної колегії цього журналу, процес рецензування, прийняття рішення щодо

Author Contributions: All authors contributed equally to this work
Conflict of Interest: The authors certifies that, although one of the authors of the article is a member of the editorial board of this journal, the peer review, publication decision, and editorial pro-

публікації та редагування проводилися незалежно, без його участі чи впливу. Будь-які потенційні конфлікти інтересів були повністю усунені шляхом зовнішнього контролю процесу.

Декларація про використання генеративного штучного інтелекту: Автори використовували інструменти генеративного штучного інтелекту (GenAI) для допоміжної роботи: моделі ChatGPT-5.5 (OpenAI, 2026) виключно для мовного редагування, структурного впорядкування тексту; Grammarly – для перевірки правильності перекладу тексту. Усі результати роботи з цими інструментами були ретельно контрольовані, перевірені та, за необхідності, відредаговані авторами. Весь науковий контент, матеріали та висновки були створені авторами. Автори несуть повну відповідальність за зміст та цілісність публікації.

cesses were conducted independently, without their participation or influence. Any potential conflicts of interest were fully mitigated through external oversight of the process.

Declaration of use of generative artificial intelligence: The authors utilized generative artificial intelligence (GenAI) tools in a supportive capacity: the ChatGPT-5.5 model (OpenAI, 2026) exclusively for language editing and structural text organization; Grammarly – to verify the correctness of the text translation. All outputs from these tools were carefully supervised, reviewed, and, where necessary, edited by the authors. All scientific content, materials, and conclusions were created by the authors. The authors retain full responsibility for the content and integrity of the publication.

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Вплив низової пожежі на радіальний приріст сосни звичайної в Поліських ландшафтах

Ірина Коваль[1], https://orcid.org/0000-0001-6328-1418, e-mail: koval_iryna@ukr.net

д. с.-г. н., пров. наук. співробітник сектору екології лісу відділу лісівництва та економіки лісового господарства

Надія Максименко[2], http://orcid.org/0000-0002-7921-9990, e-mail: maksymenko@karazin.ua

д. геогр. н., професор, зав. кафедри екологічного моніторингу та заповідної справи

Іван Мартинчук[3], https://orcid.org/0000-0002-1370-677X, e-mail: martynchuk.ivan@gmail.com

к. екон. н., проректор з науково-педагогічної роботи, соціального та гуманітарного розвитку, доцент кафедри лісового та садово-паркового господарства

Олена Андреєва[3], https://orcid.org/0000-0003-0851-800X, e-mail: andreeva-lena15@ukr.net

д. с.-г. н., професор кафедри лісового та садово-паркового господарства

Світлана Матковська[3], https://orcid.org/0000-0002-8019-5498, e-mail: matkovcka@ukr.net

к. с.-г. н., доцент кафедри лісового та садово-паркового господарства

Андрій Лащенко[4], https://orcid.org/0000-0002-7638-6400, e-mail: lashchenko@nubip.edu.ua

к. с.-г. н., доцент кафедри таксації лісу та лісового менеджменту

[1] *Український науково-дослідний інститут лісового господарства та агролісомеліорації ім. Г.М. Висоцького, Харків, Україна;*

[2] *Харківський національний університет імені В.Н. Каразіна, Харків, Україна*

3 Поліський національний університет, Житомир, Україна

[4] *Національний університет біоресурсів і природокористування України, Київ, Україна*

АНОТАЦІЯ

Лісові пожежі є одним із ключових дестабілізуючих чинників функціонування лісових екосистем, впливаючи на їх продуктивність, біорізноманіття та екосистемні послуги. В умовах кліматичних змін і посилення антропогенного навантаження, зокрема воєнних дій в Україні, частота та інтенсивність пожеж зростають, що зумовлює необхідність дослідження постпірогенних процесів у лісах Полісся. Метою роботи є – встановити особливості впливу низової пожежі на радіальний приріст сосни звичайної (*Pinus sylvestris* L.) у середньовікових деревостанах Поліських ландшафтів. Дослідження базується на поєднанні дендрохронологічного аналізу, методів лісової таксації та статистичної обробки даних. Відібрано керни з пошкодженого пожежею та контрольного насаджень. Побудовано локальні деревно-кільцеві хронології, застосовано індексацію з використанням ковзного згладжування. Виконано кореляційний і регресійний аналіз між показниками приросту та висотою нагару на стовбурі. Встановлено суттєве зниження радіального приросту у рік пожежі та наступний період, з максимальною депресією у 2023 році, що було посилено посушливими кліматичними умовами. Найбільш чутливим індикатором впливу пожежі виявилася пізня деревина, товщина якої у пошкодженому насадженні була достовірно меншою порівняно з контролем. Відновлення приросту відбулося протягом двох років для дерев, що зберегли життєздатність. Виявлено статистично значущу залежність між індексами пізньої деревини та висотою нагару. Ослаблені дерева (II категорії) демонстрували позитивну реакцію на зменшення конкуренції, тоді як сильно ослаблені – не відновлювали приріст. Досліджено вплив пожежі 2022 р. на середньовікові соснові насадження в умовах термічного стресу (відхилення температури +13–28%). Встановлено, що пізня деревина є найбільш чутливим індикатором пірогенного впливу: у рік пожежі її ширина скоротилася на 56% (до 0,20±0,04 мм), тоді як параметри ранньої деревини залишилися стабільними. Виявлено статистично значущу регресійну залежність між індексами пізньої деревини та висотою нагару. Доведено, що за умови збереження камбію дерева відновлюють радіальний приріст протягом двох років, що свідчить про їхню високу резистентність.

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