

## How Actinometric Processes Impact Geographical Trial Plantations?

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This study analyzes the long-term measurement data of direct, diffuse, and total solar radiation recorded at the Minsk meteorological station from 1954 to 2023 (70 years). We investigated the relationship between variations in these radiation components and changes in the annual ring width of Scots pine (*Pinus sylvestris* L.) from different provenances. The trees were grown in a geographical trial plantation located in the Berezinsko-Predpolessky geobotanical region of the Republic of Belarus. The annual influence of incoming solar radiation on the radial growth of Scots pine of different geographical origins was assessed. A moderate to strong negative correlation was established between the tree-ring width of several Scots pine climatotypes and the intensity of direct radiation. All studied climatotypes were divided into two groups based on the sensitivity of their radial growth to direct solar radiation. Climatotypes with an average continentality index in the range of 46–55%, as well as those belonging to the Siberian and Lapland subspecies, showed a negative reaction to an increase in the proportion of direct radiation. Furthermore, the obtained datasets contribute to the AgroForest Landscape Restoration Library (AFLR-Library).

**Keywords:** climatotype, provenance, solar radiation, annual ring width, AFLR-Library

### 1 Introduction

Geographical trial plantations are a fundamental tool for studying the adaptive potential of forest trees and form a critical link between contemporary forestry practices (Novikova, 2023) and future sustainable forest management. Their success is influenced by a complex interplay of biotic factors, such as provenance and ecotype (Park et al., 2017), and abiotic factors, including climatic and geographic conditions (Yazıcı et al., 2023; Bilir & Yazıcı, 2024). Among abiotic factors, solar radiation is the primary energy source for photosynthesis, directly driving tree growth (Novikov, 2019). However, the specific impact of different solar radiation components – direct and diffuse – on the radial growth of various tree provenances within common garden experiments remains insufficiently studied, representing a significant research gap.

Incoming solar radiation (Essery & Marks, 2007) plays an important role in photochemical (De Muer et al., 1997) and physico-geographical processes occurring on the Earth's surface and in the atmosphere, and is also a key factor in both climatic changes and the role of forests (Matyushevskaya et al., 2020) on mitigating (Basnet et al., 2025) these changes.

For trees, the intensity and spectral quality of light are key environmental factors. Scots pine (*Pinus sylvestris* L.), with its vast Eurasian range, comprises subspecies and varieties of different geographical origins that exhibit distinct requirements for photoperiod and light intensity (Matyushevskaya et al., 2020). While dendroclimatic studies traditionally focus on temperature and precipitation, the influence of solar radiation regimes on long-term radial growth dynamics has received less attention (Kiselyov et al., 2010, 2012). Some studies

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suggest a connection between solar activity cycles and tree growth (Timofeev, 2003), and the ratio of direct to diffuse radiation may be a critical limiting factor, especially under changing climatic conditions (Matyushevskaya et al., 2020).

Therefore, the objective of this study is to evaluate the specific effects of direct and diffuse solar radiation components on the radial growth of Scots pine trees of various geographical provenances grown in a common trial plantation. This approach allows for isolating the radiation effect from other local environmental variables, providing novel insights into the climatic adaptation of different pine climatotypes.

## 2 Material and Methods

### 2.1 Data Collection

The study was conducted in a geographical trial plantation of Scots pine established in 1958 in the Minsk region, Republic of Belarus (for details, see Rabko et al., 2024). The site is located within the Berezinsko-Predpolessky geobotanical region. The plantation features 17 climatotypes (provenances) of Scots pine, with origins spanning 48°–62° north latitude and 22°–111° east longitude.

To assess the effect of solar radiation on radial growth, we obtained and analyzed actinometric data (total, diffuse, and direct solar radiation) from the Minsk meteorological station for the period 1954–2023.

The trees were approximately 65 years old at the time of sampling. The annual ring width was measured from wood cores extracted from 10 to 15 model trees per climatotype, following standard dendrochronological methods (Tishin & Chizhikova, 2018). Typically, two cores per tree were extracted at breast height (1.3 m) from opposite sides. Additionally, 17 dominant model trees were felled, and cross-sectional discs were collected at heights of 1.3 m, 6 m, 12 m, 18 m, and 24 m for detailed analysis.

### 2.2 Data Analysis

Pearson correlation analysis was performed between the mean annual values of total (Q), diffuse (D), and direct (S) solar radiation and the mean annual ring width indices for each of the 17 climatotypes. Statistical significance was assessed at  $p < 0.05$ . We also calculated correlation coefficients with a 1- and 2-year lags for direct radiation to identify delayed effects. All statistical analyses were conducted using the SPSS statistical package (version 20, IBM Corp.).

## 3 Results and Discussion

### 3.1 Results

Analysis of solar radiation data over the study period revealed significant interannual fluctuations. The average annual total radiation (Q) was 3688.9 MJ/m<sup>2</sup>, with approximately 80% occurring during the growing season. The maximum level of total radiation was recorded in 1963 and 2002, while the minimum occurred in 1977 and 2020. These maximum and minimum levels are associated with respective increase and decrease in the proportion of direct radiation during these periods (Figure 1).

In 1963, when the maximum of total radiation was observed, the proportion of direct radiation was 52.8%, compared to 58.8% in 2023. On average, diffuse radiation constituted 52%, but this ratio varies significantly over time. From 1954 to 1994, diffuse radiation predominated, accounting for up to 73% in some years. Since 1995, the proportion of direct radiation has been increasing, which ranges from 52 to 60% during this period.

Analysis of the effect of solar radiation on radial growth revealed a positive correlation between diffuse radiation levels and annual ring width (Table 1).

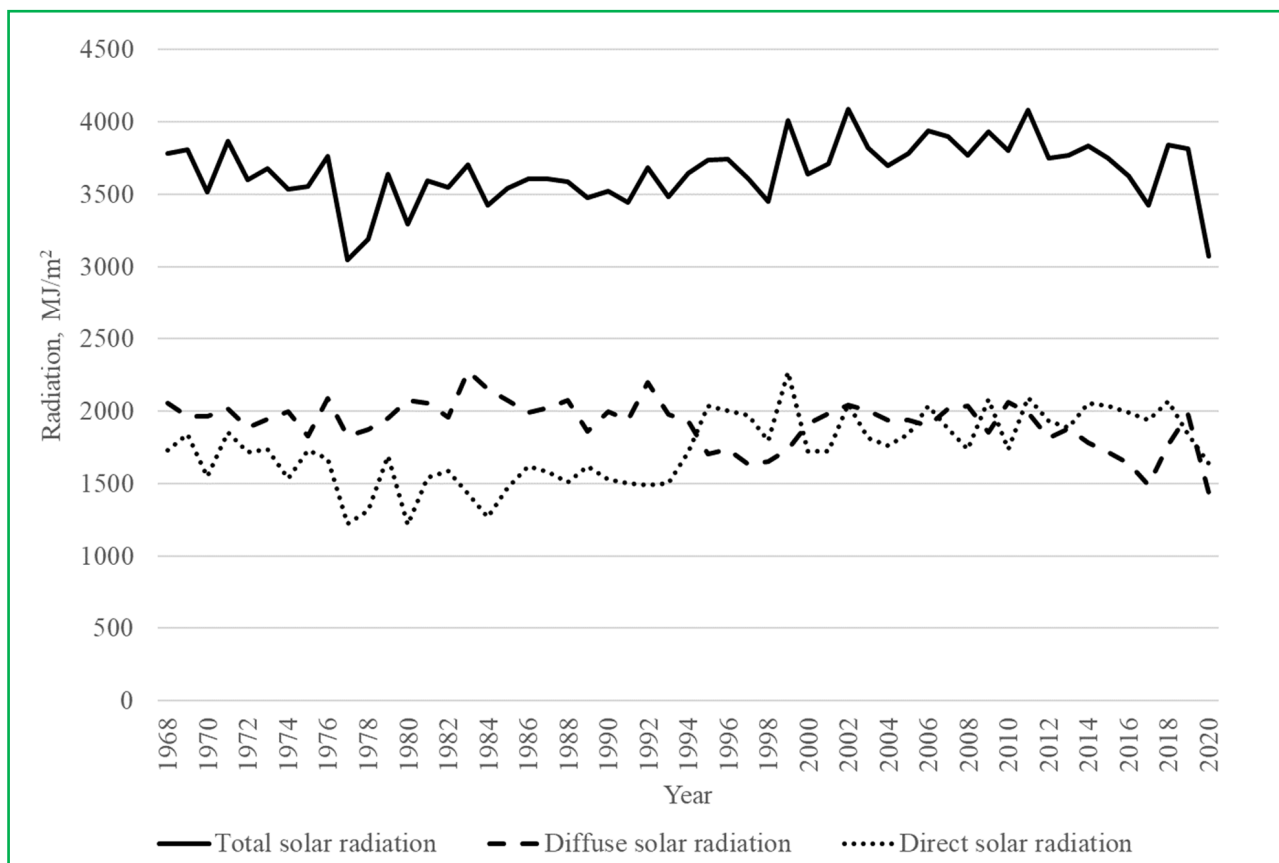
The strongest positive correlation was found for the Poltava climatotype (correlation coefficient 0.56). Tomsk, Estonian, and Belgorod climatotypes also showed a positive response to an increase in diffuse radiation (with correlation coefficients of  $r = 0.49$ ,  $0.45$ , and  $0.43$ , respectively).

The intensity of direct radiation also significantly affected the radial growth of Scots pine from various origins. Higher proportions of direct radiation were associated with reduced tree-ring width, indicating decreased radial growth (with significant negative correlations for the Estonian ( $r = -0.59$ ), Kursk ( $r = -0.57$ ), Belgorod ( $r = -0.54$ ), Poltava ( $r = -0.50$ ), Grodno ( $r = -0.49$ ), Tomsk ( $r = -0.43$ ), Arkhangelsk ( $r = -0.42$ ), and Bashkir ( $r = -0.40$ ) climatotypes).

Analysis of correlations with a temporal lag revealed consistent patterns for certain climatotypes (Table 2).

Based on their sensitivity to direct solar radiation, the studied climatotypes were divided into two groups.

The first group includes climatotypes showing a statistically significant negative correlation between annual ring width and direct radiation indices both for the current year and with 1- and 2-year lags. This group includes the Estonian ( $r = -0.59$ ;  $r = -0.60$ ;  $r = -0.53$ ), Poltava ( $r = -0.55$ ;  $r = -0.69$ ;  $r = -0.64$ ), Kursk ( $r = -0.53$ ;  $r = -0.53$ ;  $r = -0.61$ ), Belgorod ( $r = -0.53$ ;  $r = -0.51$ ;  $r = -0.53$ ), Arkhangelsk ( $r = -0.50$ ;  $r = -0.57$ ;  $r = -0.45$ ), Grodno ( $r = -0.47$ ;  $r = -0.54$ ;



**Figure 1** Interannual variation in total, direct, and diffuse solar radiation (MJ/m<sup>2</sup>)

**Table 1** Correlation coefficients between the annual ring width of Scots pine and solar radiation components

Climatype	Correlation coefficient of the annual ring width:*		
	diffuse radiation	direct radiation	total radiation
Arkhangelsk	+0.36	<b>-0.42</b>	-0.30
Leningrad	+0.13	+0.10	+0.23
Tomsk	<b>+0.49</b>	<b>-0.43</b>	-0.19
Vologda	+0.10	-0.01	+0.01
Estonia	<b>+0.45</b>	<b>-0.59</b>	<b>-0.40</b>
Latvia	-0.02	+0.26	+0.29
Vitebsk	+0.10	-0.03	+0.03
Minsk	+0.16	-0.16	+0.31
Ulyanovsk	-0.13	+0.19	-0.01
Bashkir	+0.35	<b>-0.40</b>	-0.24
Grodno	+0.37	<b>-0.49</b>	-0.34
Kursk	-0.07	<b>-0.57</b>	<b>-0.41</b>
Belgorod	<b>+0.43</b>	<b>-0.54</b>	-0.34
Volgograd	+0.34	-0.25	-0.09
Rostov	+0.27	-0.26	-0.17
Khmel'nitsky	-0.07	+0.05	+0.04
Poltava	<b>+0.56</b>	<b>-0.50</b>	-0.25

\* the correlation coefficients are statistically significant ( $p < 0.05$ ) in bold

**Table 2** Correlation coefficients between annual ring width of Scots pine and direct solar radiation indices with temporal lags

Climatype	Correlation coefficients of annual ring width indices and direct solar radiation indices*		
	in the year of the research	offset by 1-year	offset by 2-years
Arkhangelsk	<b>-0.50</b>	<b>-0.57</b>	<b>-0.45</b>
Leningrad	+0.06	+0.03	+0.31
Tomsk	<b>-0.45</b>	<b>-0.52</b>	<b>-0.42</b>
Vologda	-0.01	-0.15	-0.10
Estonia	<b>-0.59</b>	<b>-0.60</b>	<b>-0.53</b>
Latvia	+0.19	+0.22	+0.37
Vitebsk	-0.04	+0.12	+0.10
Minsk	+0.14	-0.01	+0.17
Ulyanovsk	-0.10	-0.10	+0.01
Bashkir	<b>-0.41</b>	<b>-0.44</b>	<b>-0.44</b>
Grodno	<b>-0.47</b>	<b>-0.54</b>	<b>-0.59</b>
Kursk	<b>-0.53</b>	<b>-0.53</b>	<b>-0.61</b>
Belgorod	<b>-0.53</b>	<b>-0.51</b>	<b>-0.53</b>
Volgograd	-0.28	-0.40	-0.24
Rostov	-0.22	-0.34	-0.27
Khmelnitsky	+0.10	+0.25	-0.01
Poltava	<b>-0.55</b>	<b>-0.69</b>	<b>-0.64</b>

\* the correlation coefficients are statistically significant ( $p < 0.05$ ) in bold

$r = -0.59$ ), Tomsk ( $r = -0.45$ ;  $r = -0.52$ ;  $r = -0.42$ ) and Bashkir ( $r = -0.41$ ;  $r = -0.44$ ;  $r = -0.44$ ) provenances.

The second group includes climatotypes where the correlation was weak, statistically insignificant, or absent for the current year and lagged years. This group includes the Leningrad, Vologda, Latvian, Minsk, Vitebsk, Ulyanovsk, Volgograd, Rostov and Khmel'nitsky provenances. The correlation coefficients for the study years, including 1- and 2-year lags, ranged from  $r = -0.40$  to  $+0.40$ .

### 3.2 Discussion

Our results clearly demonstrate that the radial growth response of Scots pine to solar radiation is not uniform but is strongly modulated by geographic provenance. The established negative correlation between direct radiation and annual ring width for a distinct group of climatotypes (Estonian, Poltava, Kursk, Belgorod, Arkhangelsk, Grodno, Tomsk, Bashkir) suggests a significant stress effect. This can be interpreted through physiological mechanisms: high-intensity direct radiation can lead to photoinhibition, damaging the photosynthetic apparatus with excess light energy. Furthermore, periods of high direct radiation are often associated with higher temperatures and increased vapor pressure deficit, potentially inducing stomatal closure and water stress, thereby limiting carbon assimilation

and radial growth, which is also observed under drought conditions in other coniferous species (Wang et al., 2020). The importance of microclimatic factors, including light and temperature, for tree growth depending on stand composition has been detailed in related studies (Cardoso, 2020).

Conversely, the positive correlation of several climatotypes (Poltava, Tomsk, Estonian, Belgorod) with diffuse radiation aligns with the known ecological benefits of diffuse light. Diffuse radiation penetrates the forest canopy more efficiently, improves light distribution within the crown, and reduces leaf-level heat load, potentially enhancing overall photosynthetic efficiency (Roderick et al., 2001). This is supported by research on the spectral composition of radiation under forest canopies, where stand structure (coniferous vs. deciduous) significantly influence shortwave radiation transmission and thus the understory light regime (Hovi & Rautiainen, 2020). Climatotypes originating from regions with predominantly cloudy conditions (e.g., Estonian, Grodno) showed the strongest negative reaction to direct radiation, indicating their adaptation to a diffuse light regime.

The division of climatotypes into two sensitivity groups is a novel contribution. The "sensitive" group primarily consists of climatotypes from regions with moderate continentality (46–55%) or belonging to the Siberian and Lapland subspecies. Their negative response may

reflect a mismatch between their adaptive traits (e.g., photoperiodic responses, xeromorphic adaptations) and the high-light conditions at the trial site. Research on other pine species also demonstrates that root system adaptation and likely associated physiological traits are highly dependent on the climatic conditions of the population's origin (Lombardi et al., 2021). The "less sensitive" group includes local climatypes (Minsk, Vitebsk) and those from steppe regions with high continentality (~60%), which may possess better physiological adaptations to cope with higher radiative load (Körner, 2012).

The data indicate that provenances from areas with climatic conditions similar to the trial site (continentality index 38–45%), as well as steppe climatypes with high continentality (~60%), are less affected by solar radiation fluctuations.

Climatypes with moderate continentality (46–55%) and those belonging to the Siberian and Lapland subspecies react negatively to an increase in direct radiation. The exception is the Estonian and Grodno climatypes, which originate from mild, humid climates but are strongly negatively affected by direct solar radiation. These trees belong to forest regions (Western Belarusian and Coastal) where cloudy days with a greater proportion of diffuse solar radiation prevail.

Our findings support and extend previous research. The noted decrease in pine productivity after 1998 coincides with an increase in the proportion of direct radiation in our dataset (Matyushevskaya et al., 2020). The importance of helioclimate factors in radial growth is confirmed and detailed by our provenance-specific analysis (Mitryaikina, 2006). From a practical forestry perspective, these results underscore the importance of considering solar radiation regimes when selecting provenances for afforestation and climate-smart forestry (Rineau et al., 2019). Provenances less sensitive to increases in direct radiation might be more resilient in a future climate with potentially clearer skies in some regions. This conclusion aligns with contemporary calls to account for biophysical effects of forests, such as albedo and radiation regimes, in forest management to achieve a net climate benefit (Kalliokoski et al., 2020).

#### 4 Conclusions

This study provides evidence that actinometric processes, specifically the balance between direct and diffuse solar radiation, significantly impact radial growth in geographical plantations of Scots pine.

1. Direct solar radiation acts as a limiting factor for the radial increment of a distinct group of Scots pine climatypes, primarily those from regions of

moderate continentality (46–55%) and belonging to the Siberian and Lapland subspecies.

2. Diffuse solar radiation shows a positive relationship with the growth of several climatypes, suggesting its beneficial role in photosynthetic efficiency under plantation conditions.
3. The response is geographically structured, allowing for the classification of climatypes into radiation-sensitive and less-sensitive groups. This has direct implications for provenance selection and sustainable forest management under changing climatic conditions.
4. The generated data on the correlation between actinometric parameters and the growth of different provenances provides valuable empirical input for modeling growth dynamics and enriching specialized databases such as the AFLR-Library.

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#### Conflict of Interest

The authors declare that there is no conflict of interest.

#### Author Contributions

Siarhei U. Rabko: conceptualization, formal analysis, funding acquisition, methodology, project administration, writing – original draft, writing – review & editing; Liliya F. Paplauskaya: conceptualization, formal analysis, methodology, resources, supervision, validation, writing – original draft, writing – review & editing; Pavel V. Tupik: data curation, validation, visualization, writing – original draft, writing – review & editing; Nebi Bilir: formal

analysis, methodology, validation, writing – original draft, writing – review & editing; Tatyana P. Novikova: conceptualization data curation, formal analysis, investigation, validation, visualization, writing – original draft, writing – review & editing; Arthur I. Novikov: conceptualization, formal analysis, funding acquisition, writing – original draft, writing – review & editing.

### AI and AI-Assisted Technologies Use Declaration

No generative AI tools or AI-assisted technologies were used during the preparation of the manuscript.

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