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INFLUENCE OF CLIMATIC FACTORS ON THE FORMATION OF SCOTS PINE (*PINUS SYLVESTRIS* L.) AND NORWAY SPRUCE (*PICEA ABIES* KARST.) RADIAL GROWTH ELEMENTS IN THE BOREAL ZONE OF RUSSIA

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Abstract

We studied the influence of average temperatures and precipitation of the growing season on the formation of macrostructural elements of radial growth in Scots pine and Norway spruce stands of Leningrad region located in the boreal zone of the European part of Russia. Denroclimatic studies were carried out using the results of wood samples analysis from forest stands on two-layer soils collected during 60 years. The digitized parameters of wood samples were processed in a GIS system, which made it possible to obtain an array of generalized dendrochronologies. A rank correlation analysis of the data obtained was carried out using the Spearman's test. To simulate the combined effect of the amount of precipitation and average temperatures on the formation of the structural elements of radial growth, the method of the quadratic function was used. Depending on the composition of a stand, there was a different response to the selected meteorological factors during the study period. In pine stands, the effect of the average temperature of the growing season on the amount of annual radial growth was greater than in spruce stands. In spruce and pine stands with the participation of deciduous species, the structural elements of wood were more meteosensitive. The use of the quadratic function method made it possible to assess the combined effect of the total precipitation and average temperature of the growing season on the elements of radial growth of pine and spruce in the stands under study over the period of the experiment. Stands with various proportions of pine predominantly responded in the same way to changes in external factors associated with the climatic features of the region, which indicates the priority of their use in dendrochronological studies.

Key words: amount of precipitation, annual ring width, average temperature, early and late wood, statistical analysis.

Introduction

A great number of researchers noted the ability of annual growth rings to retain information about changes in the action of environmental factors (Byusgen 1906, Mikola 1962, Vikhrov and Protasevich 1965, Dergachev and Chistyakov 1993, Makinen et al. 2002, Grippa and Potakhin 2016). The obtained information, on one hand, is chronological, that is, it represents the variability of annual growth in time, the presence of temporary cyclical changes, and the direction of changes (Mielikäinen et al. 1996). On the other hand, this information is associated with exogenous and endogenous environmental factors (Eckstein et al. 1989).

Radial growth of stem wood of forest-forming woody plants is a complex integral indicator, to the formation of which the genotype of each particular plant and a complex of environmental factors contribute. Radial growth of trees is a bioindicator, and the characteristics of tree growth rings can show changes in the environment (Babushkina et al. 2010).

A large number of publications have been devoted to the variability of tree growth, but many issues remain debatable or poorly understood, due to the diversity of both forest biogeocoenoses and the nature of environmental impacts, as well as the differences in research methods (Henttonen 1990, Demakov 2005, Vaganov et al. 2006, Zaytsev et al. 2020).

Climatic factors have a particularly strong effect on the growth rate. By deviating from the long-term average they produce response in plants (Mitryajkina 2005).

Since a complex of factors affects growth and development of plants during their life cycle, the relationship between the width of annual growth rings and climatic parameters is not always unambiguous.

Meteorological values such as air temperature and precipitation directly influence the development of dendrocoenoses (Miina 2000). However, the growth of the trunk mass of trees also depends on soil nutrients, moisture, depth of groundwater, vital state of a stand, etc. For this reason, the revealed correlations between the current radial growth and meteorological factors are, in fact, statistical, reflecting their influence on the intensity of the use of water-mineral soil resources in accordance with the vital state of the stand.

It has been noted that the growth rate of annual rings of Scots pine and Norway spruce of the same age growing in the Baltic region in different habitat conditions was not the same against the background of changes in weather factors (Bitvinskas 1974, 1984).

Variability in radial growth of coniferous trees in Central and Eastern Europe and in Northern Fennoscandia was mainly associated with changes in the sum of positive temperatures of the growing season (Mikola 1962; Makinen et al. 2000, 2001, 2002, 2003). In contrast, in Central Europe variation in growth of conifers was mainly correlated with precipitation (Eckstein et al. 1989, Kahle 1994, Kahle and Spiecker 1996). Studies of precipitation effect on annual radial growth of Norway spruce carried out in southern and central Finland have also revealed that damage and dying off of spruce in drought-sensitive areas in the southern part of the country could be primarily related to low precipitation rather than temperature fluctuations (Mikola 1962; Henttonen 1990; Mielikäinen et al. 1996; Miina 2000; Makinen et al. 2000, 2001, 2002, 2003).

Makinen et al. (2002, 2003) studied changes in radial growth of Norway spruce (*Picea abies* (L.) Karst.) and its dependence on various climatic variables. The researchers compared forest stands in southwestern and eastern Germany, Norway and Finland. Climate models included local temperature and precipitation, and temperature anomalies. Trees growing in moderate conditions have been found to be less responsive to climate change. Changes in spruce growth were clearly correlated with temperature.

When the Baltic countries were considered, on moist soil growth of Scots pine was more sensitive to precipitation of the previous year (Daukane and Elferts 2011).

Studies of interannual differences in growth of Scots pine tree rings at the northern border of the range under the conditions of the European North have revealed consistency in long-term growth and the same response to changes in environmental conditions (Tyukavina and Lezhneva 2014, Tyukavina 2015). In different growing conditions, pine reacted to unfavourable factors more synchronously than to optimal ones.

According to a number of authors, in the taiga geocomplexes of the European North of Russia, the amount of radial growth of wood is limited by the ratio of heat and moisture, both in the atmosphere and in the soil, especially during the growing season (Grippa and Potakhin 2016, Chudakov et al. 2020).

The analysis of wood samples collected from large territories by scientists from different countries made it possible to consider tree growth as an indicator of the dynamics of biological systems in space and time in connection with changes in natural conditions and anthropogenic influences at the local, regional and global scales (Martínez-Sancho et al. 2020).

In connection with the above, it is necessary for forestry practice to determine stands with less dependence on variations of limiting meteorological factors. The aim of the study was to analyse the influence of meteorological parameters on the formation of annual growth and its structural elements in Norway spruce and Scots pine stands of various compositions.

Material and Methods

To correctly identify the consequences of the influence of meteorological parameters on tree growth, only forest stands on similar soils and in similar hydrological conditions should be considered. The selection of sampling points is a key issue in dendroclimatic research. It determines sensitivity of trees under study to various environmental factors.

To study the influence of meteorological factors on annual growth of Scots pine and Norway spruce, studies were carried out in pure and mixed coniferous stands of the same age class (85–100 years) of the bilberry (*Vaccinium myrtillus* L.) series of forest types in the conditions of Oredezh plateau of Luga-Oredezhsky landscape region of Leningrad region located in the Northwest of the European part of Russia. Geographic coordinates of study area are 59°16’58” N and 30°14’24’’ E.

The natural stands under study have not been affected by human activities and grow on soils with two-layer structure. The landscape types under consideration are widespread in the boreal zone of Valdai glaciation area: within the moraine plain and along the tops and slopes of north-facing moraine hills. Two-layer sediments are rocks of a loamy or sandy composition of low thickness (30–70 cm) occurring on loams, which serve as the first impermeable horizon from the surface. The main distinguishing feature of the hydrological regime of drained soils on two-layer sediments is the presence of a surface soil-groundwater horizon in April-May and September-November which screens the loam located below (Chertov 1981).

The climate of the area is Atlantic-continental, with relatively mild winters with thaws and moderately warm summers. The prevailing winds are westerly and southerly. The average temperature is minus 8 °C in January and plus 17 °C in July. The annual amount of precipitation is 650-700 mm. The study used data from Belogorka meteorological station (Gatchinsky district of Leningrad region, Russia) located within a radius of 1–5 km from the study sites. The growing season lasts five month, from May 1 to September 30.

On 9 test sites with predominance of Scots pine, on 12 test sites with predominance of Norway spruce and on 1 mixed site with Scots pine and Norway spruce dominated by a deciduous species the growing stock, average heights and diameters of the forest forming species were measured and the species composition of stands determined. For dendroecological studies, 10–30 wood samples were taken from each tree species in experimental plots. The sample cores were taken at the height of 1.3 m from the root collar at least from 2 trees of each diameter class, taking into account the quantitative representation of the diameter class in the stand.

For the macroanatomical analysis of radial growths of Scots pine and Norway spruce the data from 60 years were used. On the basis of selected core samples, the anatomic structure was investigated and the dependences of changes in the annual structure of xylem on the main meteorological factors were calculated.

Previously prepared and sanded wood sample was glued into the holder and placed in the high-resolution scanner; the surface of the sample was scanned with an accuracy of 1200 dpi in full colour mode (16.7 million colours). The brightness and contrast of the digitized scans was then adjusted to ensure better differentiation of early- and latewood areas in the sample (Chudakov et al. 2020, Zaytsev et al. 2020).

To measure the wood macrostructure parameters, the obtained image was converted into a geo-information system (GIS) with a resolution equal to the scanning resolution (a relative 1 m on an electronic map was considered equal to 1 mm).

Using GIS tools, a line was drawn along the longitudinal axis of the core sample. The limits of the late- and earlywood areas were set at each annual growth ring. All measurements were done to the middle of the sample (center of the wood). The obtained data were verified using a high-precision electronic caliper with digital screen; the difference in measurement results between the two methods statistically was not significant. The created line was used to prepare a report in GIS, containing information on the distance between the points, i.e. in this case, values of late- and earlywood widths in mm.

Thus, as indicators characterizing the macrostructure of wood, we measured the average width of the annual layers and the content of the late and early xylem in the annual layer during the life of the tree. These indicators were determined for all wood samples taken from model trees in study plots. Later, the Microsoft Excel spreadsheet processor was used to systematize the obtained quantitative and qualitative data on the macrostructure of Scots pine and Norway spruce wood.

The obtained values of the amount of growth of trees were transformed into a generalized dendrochronological series characterizing the main features of the growth variability on the study sites, by using the method of averaging. This is the simplest and most reliable way to study the relationships between the amount of annual growth of wood and meteorological variables (Vaganov et al. 2006, Matskovsky 2015). To create a generalized dendrochronological series, the most representative undamaged trees were used.

The process of removing the age trend (standardization of tree-ring series) was not applied due to the conditional same age of the studied stands within 15 years. To study the influence of meteorological factors on the macrostructure of wood, data from 1960 to 2016 were used.

The main statistical characteristics of dendrochronological series were calculated for each stand from the width of annual growth rings using the STATGRAPHICS Centurion XVI, STATISTICA-11, Microsoft Excel 2007 programs.

To reflect the combined effect of the amount of precipitation and average temperature of the growing season on the amount of annual growth, we used the smoothing of point values of the function by the least squares method (Freedman 2005, Illowsky and Dean 2017). The method is based on minimizing the sum of squares of difference between an observed value and the fitted value provided by a model (Freedman 2005). By using this method, surface plots were created, reflecting the influence of meteorological parameters on the structural elements of Scots pine and Norway spruce xylem.

To assess the quantitative relationship between the studied phenomena, the Spearman's rank correlation analysis was used. The rank correlation coefficients were calculated using the formula (1):

$$r_S = 1 - \frac{6 \cdot \sum d_t^2}{n \cdot (n^2 - 1)}, \qquad (1)$$

where: d_t is the difference in the ranks of each pair of compared values; n is the number of measurements, pcs.

r_S coefficient reflects the directionality of the relationship between two variables measured on a rank scale (Illowsky and Dean 2017). When using the coefficient of rank correlation, the strength of the association between two variables is conditionally estimated. Specifically, the values of the r_S coefficient equal to 0.3 or less indicate a weak association between variables; the values of 0.4–0.7 are indicators of a moderate association, and the values of 0.7 and above indicate a strong association (Mitzel 2013, Zang and Biondi 2013). A negative value of the r_S coefficient indicates the possible presence of inverse correlation.

Results and Discussion

Abrupt changes in the annual growth rate of coniferous species of the boreal zone are most pronounced over a period of many centuries. In general, abnormal changes in the radial growth of wood on the background of fluctuations in meteorological factors during the observation period in the studied stands were not observed, which is associated with a period of observation less than 100 years.

Using the obtained data set on the macrostructural elements of Scots pine and Norway spruce wood, Spearman's rank correlation analysis was carried out of the effect of the sum of temperatures and precipitation over the growing season on the parameters of wood macrostructure (Table 1).

In Scots pine stands, the strongest relationship was observed between air temperature and the amount of annual growth and the early wood zone. When the proportion of latewood was considered, statistically significant relationship was observed only in mixed forest stands with participation of deciduous species. With a decrease in the proportion of pine in stand composition, the influence of average temperature of the growing season on the formation of the elements of radial growth increases, which is probably associated with an increase in phytocoenotic tension from other tree species. At the same time, in a forest stand with 20 % of pine trees the relationship between the amount of annual growth of pine and temperature was not significant, which probably indicates a strong influence of other species on the habitat.

Table 1. Spearman's rank correlation coefficients r_s for wood macrostructure indicators and weather conditions on double layer soils.

Stand composition	Early wood		Late wood		Annual growth rate	
	Meteorological factors					
	Temperature	Precipitation	Temperature	Precipitation	Temperature	Precipitation
Pine-dominated stands						
90P10S	**-0.31**	-0.05	-0.25	-0.21	**-0.30**	-0.08
80P20S	**-0.31**	-0.14	-0.23	-0.14	**-0.30**	-0.13
80P10S10B	**-0.35**	-0.09	**-0.32**	-0.06	**-0.33**	-0.07
40P40S10B10A	**-0.37**	-0.08	**-0.34**	-0.04	**-0.35**	-0.07
20P10S60B10A	-0.19	-0.13	-0.13	-0.10	-0.17	-0.12
Spruce-dominated stands						
100% Spruce	0.13	0.01	0.02	**0.37**	0.14	0.10
90S10P+B,A	0.24	-0.09	0.20	-0.03	0.26	-0.08
80S20P+B,A	-0.25	0.02	-0.03	0.09	-0.23	0.05
80S10B10A+P	-0.25	-0.13	-0.26	-0.07	**-0.26**	-0.13
70S20P10B+A	0.20	0.21	0.23	0.17	0.19	0.20
60S(10P20A10B/ 30B10A)	**0.35**	-0.03	**0.32**	-0.01	**0.35**	-0.03
50S50P	0.19	-0.04	0.15	-0.06	0.17	-0.03
40S30P20A10B	-0.18	0.04	**-0.29**	0.06	-0.22	0.05

Note: S – Norway spruce, *Picea abies* Karst.; P – Scots pine, *Pinus sylvestris* L.; B – silver birch, *Betula pendula* Rott.; A – aspen, *Populus tremula* L. Here and further marked bold coefficients are statistically significant at $p = 0.05$.

According to the results of the Spearman's analysis, the influence of the amount of precipitation of the growing season on the formation of elements of annual radial growth was not statistically significant at $p < 0.05$ level.

Similarly to pine stands, in forest stands with various shares of spruce, the main factor influencing radial growth of spruce wood was the average temperature of the growing season.

There was a tendency to an increase in its importance for the formation of zones of early spruce wood with a decrease in the share of spruce in the composition of a dendrocoenosis from 100 to 60 %.

In contrast to pine stands, the influence of the average temperature on the width of annual growth rings in spruce stands was noted only in two variants of the composition of spruce stands (80S10B10A+P, 60%S10P20A10B/60%S30B10A).

In spruce stands with a share of deciduous species (60%S10P20A10B/60%S-30B10A), the contribution of positive temperatures over the growing season was significant for all studied elements of annual radial growth.

The influence of precipitation on the macrostructure of spruce wood was manifested only in pure stands at the level of the latewood zone, in contrast to pine stands with no significant correlations.

The study carried out using the apparatus of nonparametric statistics showed that the effect of the amount of precipitation on the formation of the macrostructure of annual growth rings of pine and spruce was weak and insignificant at the level of $p < 0.05$ in most variants of the stands. At the same time, the influence of the average temperature had a greater influence on radial growth of these species. Concurrently, both positive temperatures and moisture supply are required for the formation of wood during the growing seasons. This contradiction can be explained by the fact that the combined effect of the amount of precipitation and the average temperature of the growing season is nonlinear. To reflect this complex mutual directionality, the quadratic function equations were used to construct a surface plot reflecting the effect of both meteorological parameters on the structural elements of pine xylem. By the shape of the surface and its slope, one can visually investigate the combined influence of the parameters on the elements of annual radial growth in tree-ring chronologies.

For forest stands with various proportions of pine, the surface plots of the quadratic function showed different nature of the combined effect of the total precipitation and average temperature on the formation of elements of the macrostructure of annual growth rings. The bending of the surface reflects the fluctuations in the thickness of the structural elements of the xylem, depending on the amount of precipitation and the average temperature in the compared variants of dendrochronology.

In pine stands with various proportions of accompanying species in the same hydrological conditions on the same two-layer soils, the directionality of the influence of meteorological parameters on the formation of radial growth and the zone of earlywood in pine was nearly the same. However, the influence of meteorological factors on the formation of the latewood zone was different. The surface plots differ in the influence of average temperatures on its formation.

In forest stands with 90 % of pine, an increase in the increment of all elements of pine xylem was observed at the average temperature in the range of 12–13 °C, regardless of the amount of precipitation during the growing season (Fig. 1). In these forest stands, a decrease in all elements of radial growth was observed at high values of the average temperature and precipitation.

When the composition of a forest stand was 80 % pine and 20 % spruce (80P20S), with a smaller share of pine in the stand, an increase in the amount of annual growth of pine was more noticeable at low values of precipitation (Fig. 2). When the latewood zone was considered, the effect of the average temperature of 12–13 °C on its growth against the background of precipitation of the growing season of 200–300 mm was observed. In a stand with an admixture of silver birch under similar soil conditions, the influence of meteorological factors on pine growth was similar to that in a pure pine stand.

In forest stands with 20–40 % of pine and 30–60 % of deciduous species, a different reaction of width formation of zones of late- and earlywood under the influence of meteorological factors was observed (Fig. 3). With 40 % of pine, the maximum increment was observed at a minimum of average temperatures and maximums

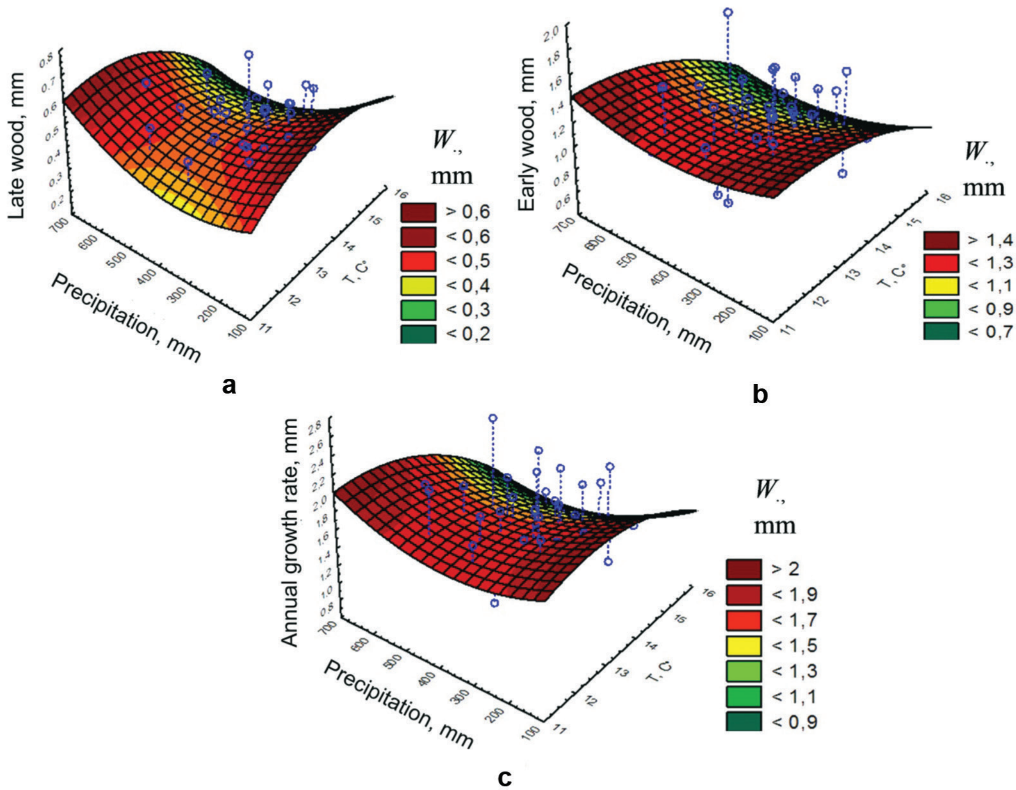

Fig. 1. Relationship between pine wood growth and meteorological parameters in forest stands with 90 % share of pine (90%P10%S).

and minimums of the amount of precipitation of the growing period. In forest stands with 20 % of pine and a predominance of deciduous species, a different relationship between the development of the elements of radial growth and weather conditions was observed. The share of latewood increased at a maximum amount of precipitation against the background of a minimum of the average temperature. The contribution of the average temperature to the formation of earlywood zone against the background of a minimum amount of precipitation was insignificant.

For forest stands with various proportions of spruce, the graphs of the quadratic function showing the relationship between the parameters of the macrostructure of spruce wood and meteorological factors demonstrated different nature of the effect of weather conditions, depending on the share of spruce in the stand. Pure spruce stands were characterized by a maximum radial wood growth at high average temperatures (Fig. 4). When spruce latewood was considered, the greatest increase was observed at a maximum of the average temperature and the total precipitation of the growing season of 400–500 mm. When the spruce early wood was considered, the greatest increase was observed at a maximum precipitation.

In a spruce stand with the participation of other species, the nature of the joint

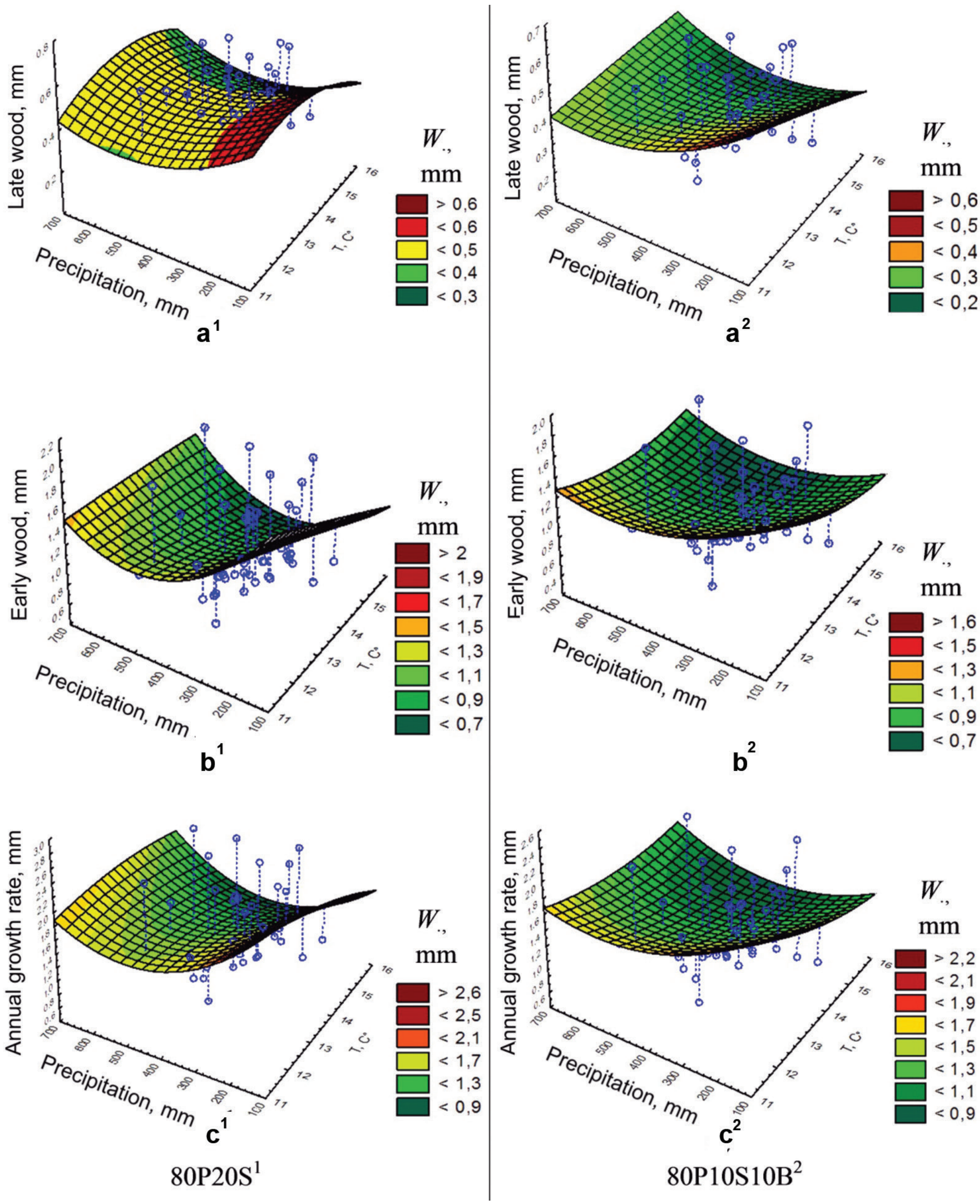

Fig. 2. Relationship between pine wood growth and meteorological parameters in forest stands with 80 % share of pine.

influence of meteorological factors was different. The greatest radial growth was recorded at a maximum average temperature and the total precipitation of the growing season of 200–350 mm (Fig. 5). However, in these stands an increase in the

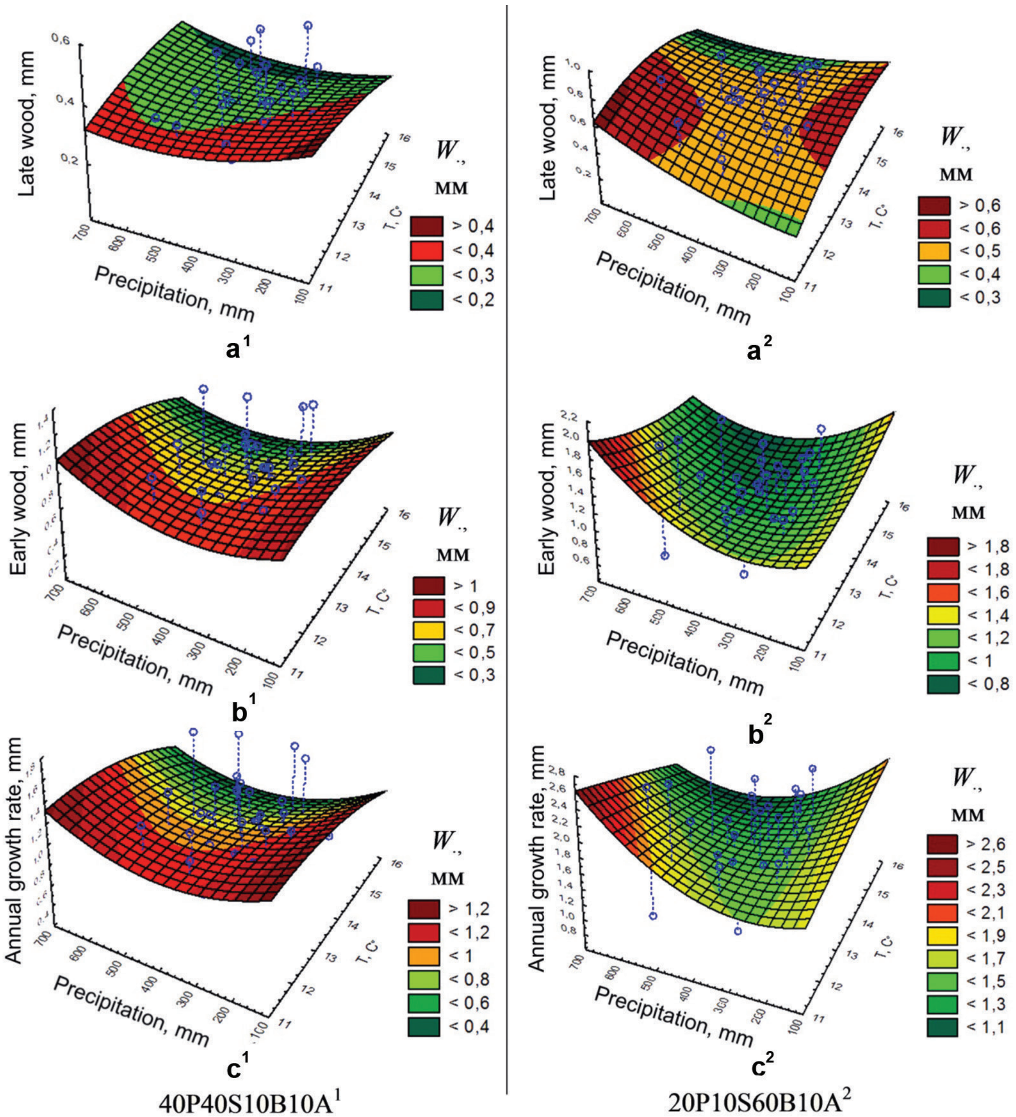

Fig. 3. Relationship between pine wood growth and meteorological parameters in forest stands with the different share of pine in the stand composition.

size of radial growth elements of spruce wood was also observed at lower average temperatures.

Forest stands with a 70 % share of spruce and various shares of accompanying species responded differently to meteorological factors acting during the formation of annual growth rings (Fig. 5).

In the stands with composition 80S20P, the greatest increase in spruce diameter was observed at the total precipitation of 300–500 mm and a minimum and maximum average temperature of the growing season. However, in contrast to the early-

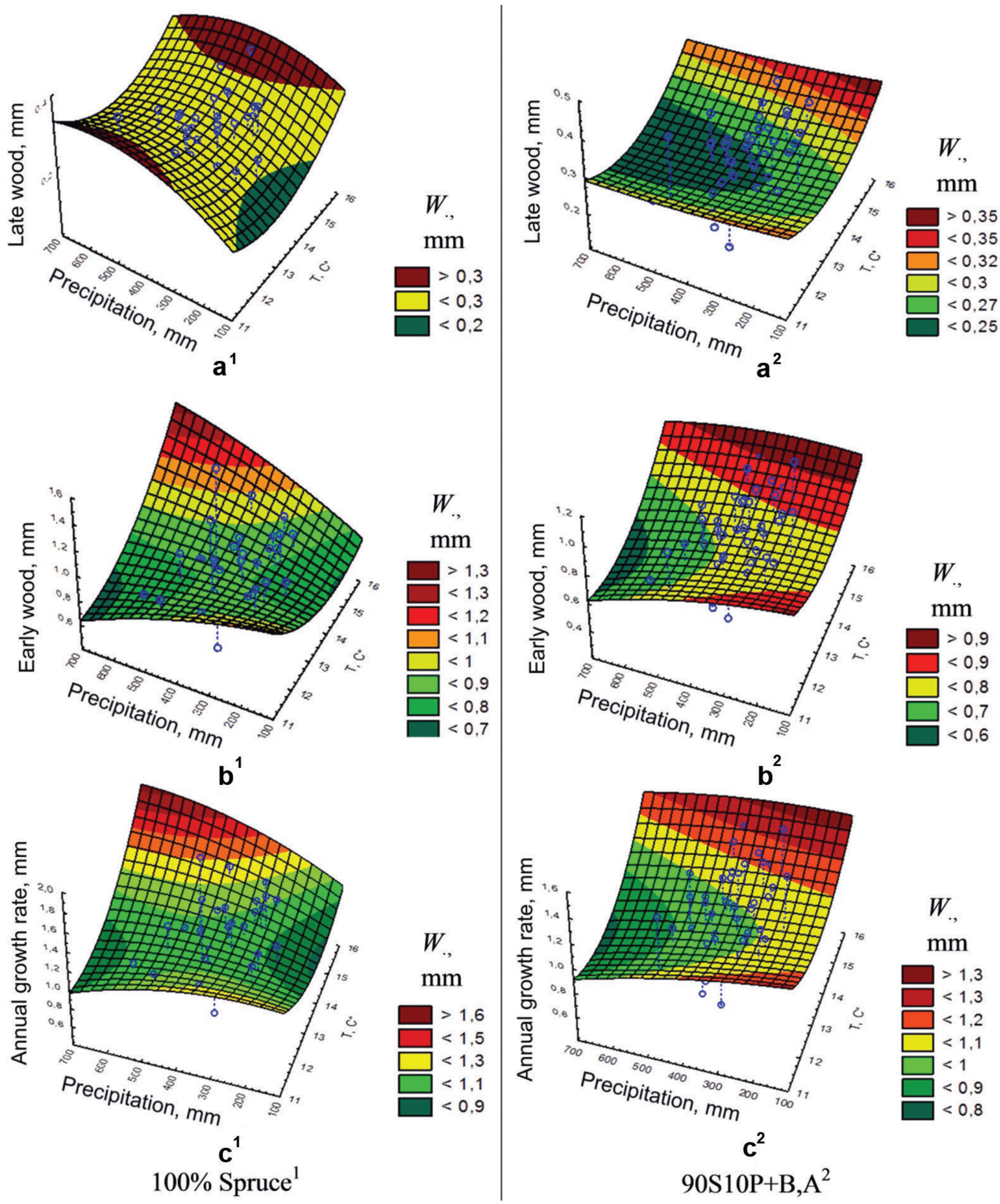

Fig. 4. Relationship between spruce wood growth and meteorological parameters in forest stands with a 90–100 % share of pine.

wood zone, an increase in the late wood zone was associated with an increase in the average temperature and precipitation.

In a spruce stand with the participation of deciduous species (80S10B10A+P), a maximum amount of annual growth was observed at lower average temperatures against the background of the entire in-

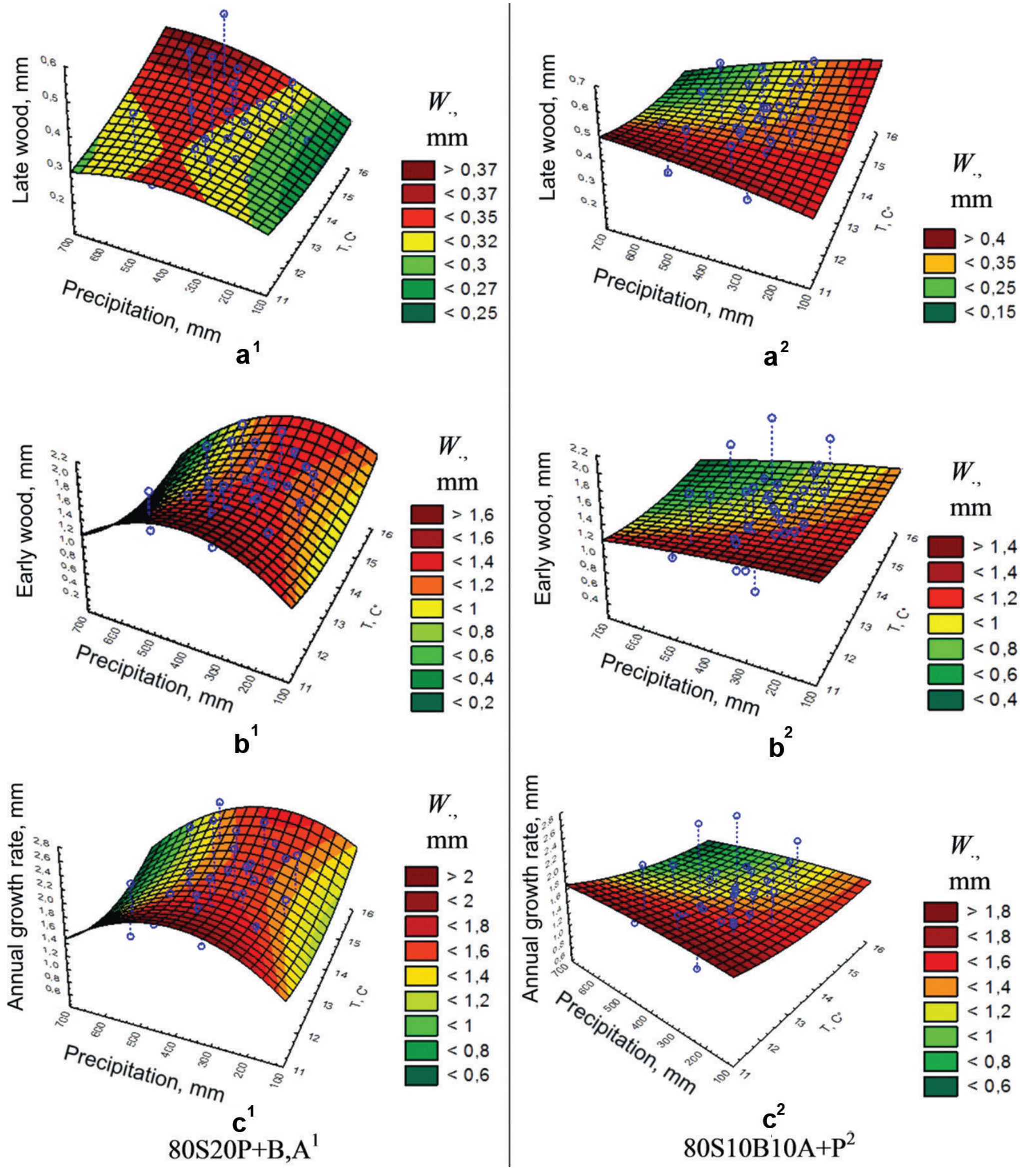

Fig. 5. Relationship between spruce wood growth and meteorological parameters in forest stands with 80 % share of spruce.

terval of the amount of precipitation. A maximum size of the latewood zone was reached at a high average temperature and the amount of precipitation of 200–300 mm.

In spruce stands with various proportions of deciduous species, there was a different response of annual growth rings to meteorological parameters (Fig. 6).

A stand with 70 % of spruce and 20 %

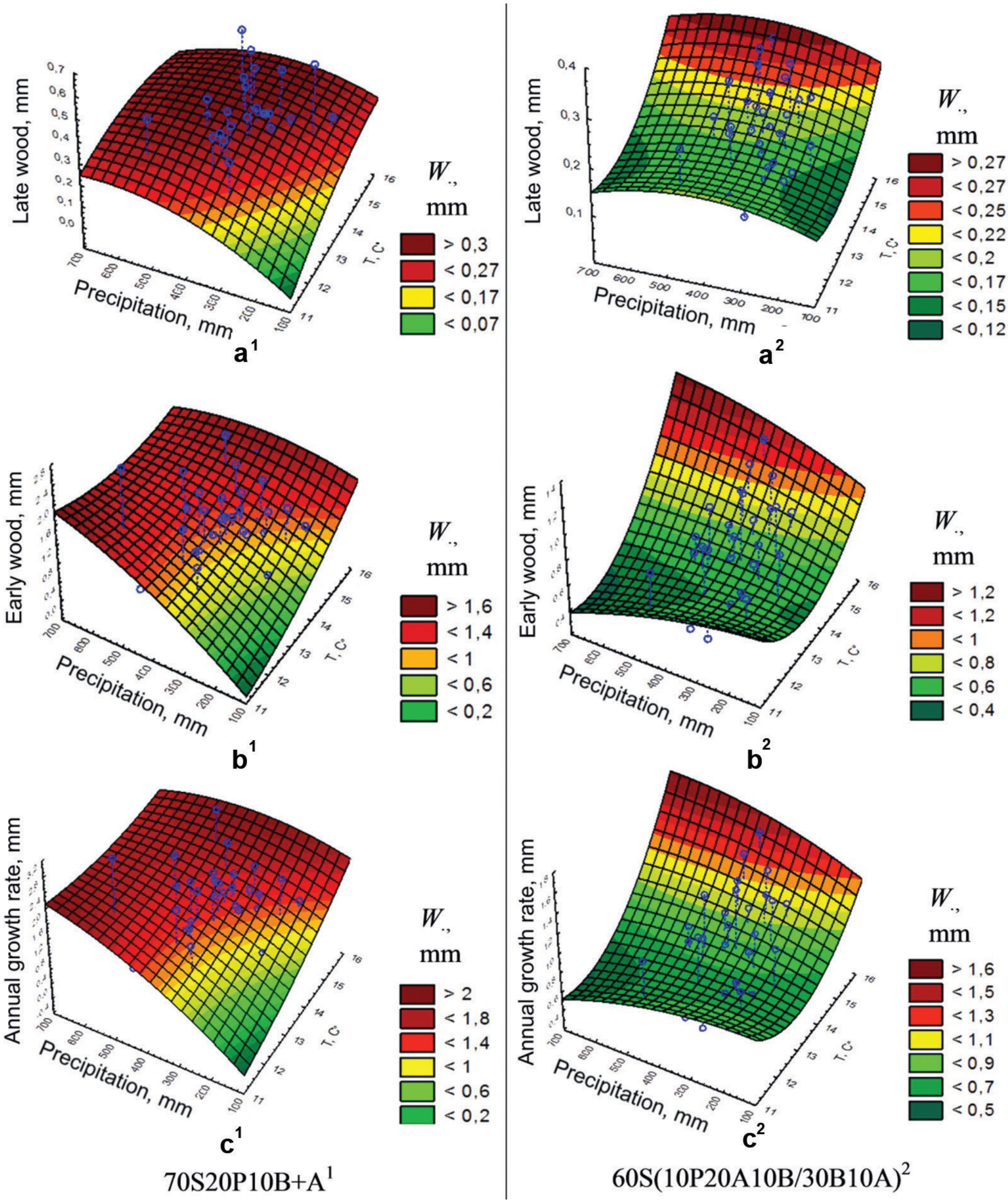

Fig. 6. Relationship between spruce wood growth and meteorological parameters in forest stands with 60–70 % share of spruce.

of pine and a lower percentage of deciduous species (70S20P10B+A) had a maximum amount of radial annual growth at an increase in the average temperature and precipitation of the growing period.

In a spruce stand with a large share of deciduous species, a more pronounced dependence of the amount of the annual radial growth and its elements on an increase in the average temperature was observed, with a lesser importance of the amount of precipitation.

In stands with equal proportions of spruce and pine (50S50P), a maximum amount of annual radial growth in spruce was observed under the influence of maximums and minimums of the average temperature against the background of the total amount of precipitation of 300–500 mm (Fig. 7).

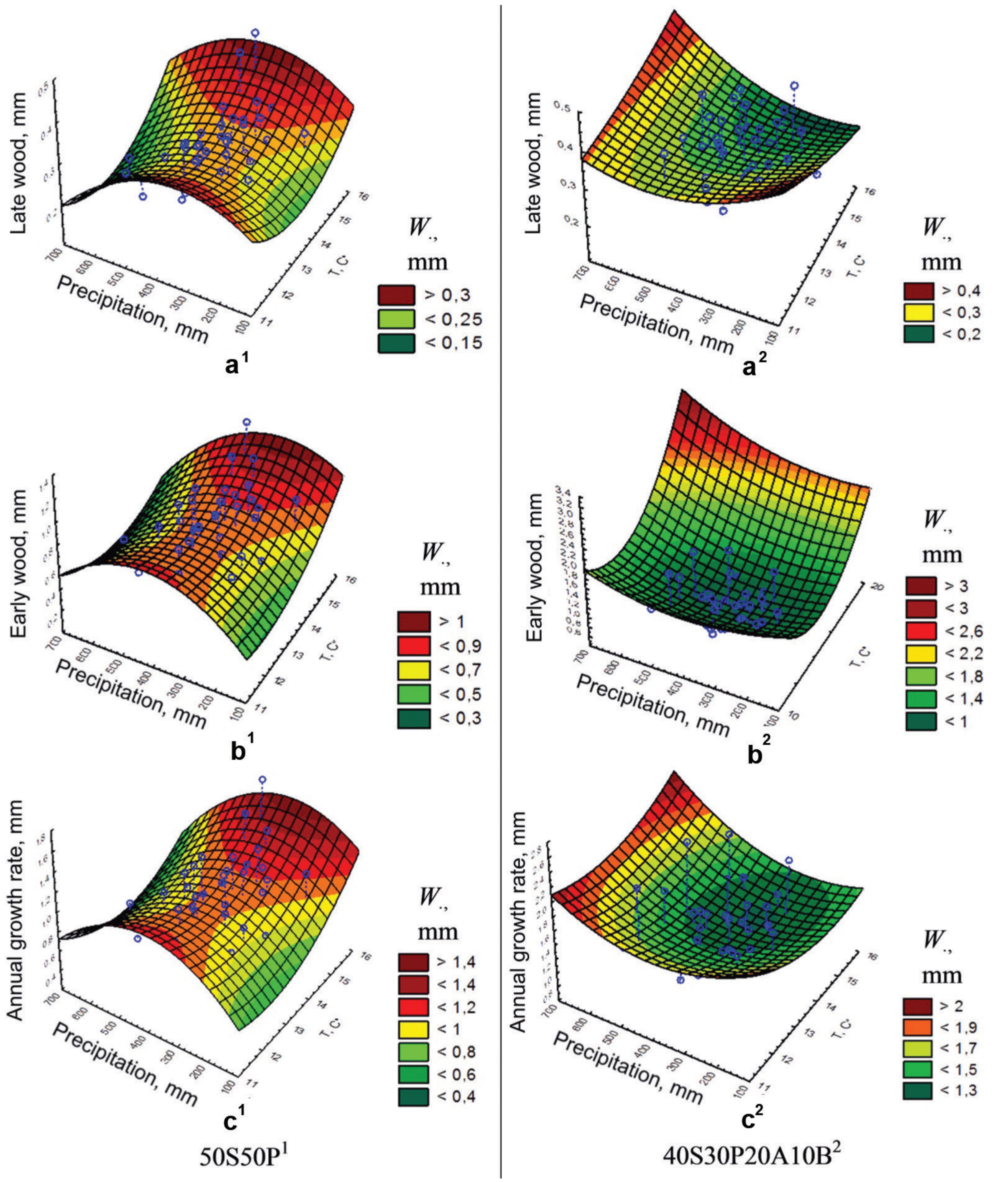

Fig. 7. Relationship between spruce wood growth and meteorological parameters in forest stands with 40–50 % share of spruce

In a stand with 40 % of spruce, 30 % of pine, 20 % of aspen, and 10 % of birch (40S30P20A10B), the greatest amount of annual radial growth in spruce was observed at a maximum amount of precipitation and an increase in the average temperature. In spruce, the average temperature had a greater influence on the formation of the zone of earlywood than the zone of latewood.

Conclusion

The study revealed the nonlinear nature of the influence of the total precipitation and average positive temperature of the growing season on the formation of macrostructural elements of Scots pine and Norway spruce wood in forest stands with various species composition growing on two-layer soils. The response of pine and spruce to the combined effect of weather factors manifested in the formation of zones of earlywood and latewood was different. In the boreal zone, the study of the influence of climatic factors using methods of dendrochronological observations is most preferably carried out by studying changes in the annual growth of Scots pine, as this species is most sensitive to the fluctuations of weather changes in the region.

In the case of spruce, a significant effect of precipitation on the growth of macrostructural elements of wood was observed only in pure stands. The greatest meteosensitivity was observed in stands with the share of spruce below 60 % under the given soil conditions. The largest number of statistically significant values of Spearman's correlation coefficient for the relationship between the width of macrostructural elements of spruce and meteorological parameters was observed in spruce stands with the participation of deciduous species.

In stands with various proportions of pine, the influence of the average temperature of the growing season on the formation of structural elements of wood was more pronounced than in spruce stands. The influence of precipitation alone, i.e. without taking into account positive temperatures during the growing season, on the formation of the elements of annual radial growth was practically unnoticeable.

The modelling of the combined influence of the meteorological factors under study using graphical representation of the quadratic function allows us to visually investigate the influence of those factors on the formation of macrostructural elements of pine and spruce wood.

The tree-ring chronologies of pine growing in mixed stands obtained from a set of trees mainly react to changes in external factors associated with the climatic features of the region in the same way, which indicates the priority of their use in dendrochronological studies.

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