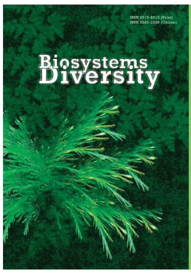

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Radial increment dynamics in *Pinus sylvestris* stands within the Northern Steppe of Ukraine

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The parameters of periodic increment (5-years) and peculiarities of its change depending on age, diameter, height and volume of trunk of Scots pine are determined. The influence of climate conditions (air temperature and precipitation) on the dynamics of radial increment change of Scots pine trees are established. The results of experimental studies, obtained from 20 temporary sample plots of pine stands within the Northern Steppe of Ukraine are presented. We conducted an estimate of radial increment of Scots pine trunks as a basis for development of normative and information support for assessment of biotic productivity of this category of forest. All selected sample trees had different age and biometric parameters. The age of sample trees ranged from 9 to 90 years; diameter at breast height – from 4.0 to 41.7 cm; height – from 4.2 to 30.0 m, trunk volume – from 0.002 to 1.748 m^3. It is found that the radial increment of pine stem was significantly dependent on tree age. The highest values of radial increment of Scots pine trees were observed for trees aged up to 20 years. With increasing age, radial increment had a decreasing trend, including 90-year old trees. Regression models of the dependence of radial increment of pine trees on the age and diameter are presented. In the article, the dependence of the values of radial increment of sample trees from types of forest are demonstrated. The highest values of Scots pine radial increment was observed in sugruds and gruds, which were presented in tree samples of 20 years. Comparative analysis of radial increment change in the trees of one age category, which grew in different conditions, was conducted. The older trees had the maximum increment in the conditions of dry sugrud, and the minimum increment in conditions of fresh subor. Also in this article we used generalized chronology of Scots pine radial increment reflecting regional variability of growth in pine trees. The results supplemented the research obtained earlier with new data on the dependence of the pine radial growth rate on forest-biometric parameters. These experimental data, their graph-analytical evaluation yielded an information basis for modeling the radial increment of pine trees, created on the basis of dependence of this parameter on biometric indexes – age and diameter at breast height.

Keywords: radial increment; Scots pine; Steppe zone; biometric indexes; forest types.

Introduction

The changes in radial increment of trees by influence of the differrences in natural and climatic conditions is widely used in meteorology and forestry, and provides excellent opportunities for study of dendroindicators (Schweingruber, 1996; Chmielewski & Rötzer, 2001; Metsaranta & Lieffers, 2009). Long-term tendencies of the changes in the increment of the trees present a view of the condition of plantations and the direction of the productive process of formation of the phytomass reserves.

In the harsh conditions of steppe ecosystems, trees have no light competition and the thickness of the root-inhabited layer is insignificant, causing highly unfavourable thermal and trophic conditions for the root system. This condition indicates not an increase in biological competetion, but rather its decrease for such conditions include no trophic or thermal potential for the formation of significant differences in the growth conditions of individual trees. Therefore, we can say that the plants in dry habitats are the most precise in reflecting the changes of climatic conditions, and in these ecotopes, the effect of non-climatic factors on growth decreases (Creber & Chaloner, 1987; Bigler et al., 2006; Brunner et al., 2009).

A significant number of authors have shown the important role of dendroclimatological research. At the same time, researchers have noted that the analysis of the tree radial growth response to climate is crucial. In their study, Sun & Liu (2016) used the tree-ring width of *Pinus armandii*, North-Central China, to explore the response differences of tree growth to climatic factors at daily, pentad, dekad and monthly timescales. Skomarkova et al. (2009) presented the dendroclimatic research results on annual growth rings of spruce, fir, pine, birch and aspen growing in the middle taiga subzone of Central Siberia. The influence of climate variables (precipitation, air humidity, temperature) and soil water content on intra-annual dynamics of tree-ring development in Scots pine was determined by Antonova & Stasava (1993); Linderholm (2001); Stravinskienė & Šimatonytė (2008); Oberhuber& Gruber (2010). The study by Henttonenet al. (2014) presented a spatial approach for analyzing variations in the annual radial increments of trees across a latitudinal transect in the Nordic countries.

Such an environmental factor as temperature plays the key role in responses of cambium activity and determines the onset and duration of wood formation in timberline areas (Deslauriers et al., 2008). The article of Begumet al. (2013) focused on temperature regulation on the timing of cambial reactivation and xylem differentiation in trees, and also highlights recent advances in understanding of seasonal changes in the resistance to cold of microtubules in trees.

A number of studies have shown that a set of meteorological conditions is heavily dependent on the changes in geophysical conditions, including solar activity (Ol', 1966). The dynamic of the radial increment of trees in different regions of the world is widely described in the literature. However, despite the fact that in many works the increment is analyzed in relation to the fluctuations of solar activity, such studies have been conducted using only materials of certain regions. Previously, the attempts to study the fluctuations in the increment of conifers were made using the upper and the northern border of the distribution of the Eurasian forests (Lovelius, 1997; Balybina & Karakhanyan, 2012; Kul'bachko et al., 2015; Brygadyrenko, 2016).

Due to the positive global trend of temperature increase, studies of the influence of climate on forest ecosystems of Europe in general and at the regional scale particularly are of high significance, especially in regions with hard dry conditions. One such region in Ukraine is the Northern Steppe (Dnipro region). It is characterized by a low extent of dendroecological study. In 1998, in this region data on radial increment of the Scots pine (*Pinus sylvestris* L.) and the analysis of its response to regional climatic and hydrological fluctuations were obtained by Lovelius & Gritsan (1998).

In this work we used generalized chronology of the radial increment reflecting regional variability of growth in pine trees, expanded the region of research, and supplemented existing research with new data on the dependence of the radial growth rate on forest-biometric parameters.

Materials and methods

This research was conducted in Scots pine (*Pinus sylvestris* L.) stands on four sites in Ukraine, Dnipro region. The climate in the area is temperate continental with mild winters with little snow and frequent thaws, the summers are hot and dry, with frequent downpours and strong south winds. The average annual temperature (during last 25 years) is 10.6 °C and total precipitation is 400–490 mm (Fig. 1).

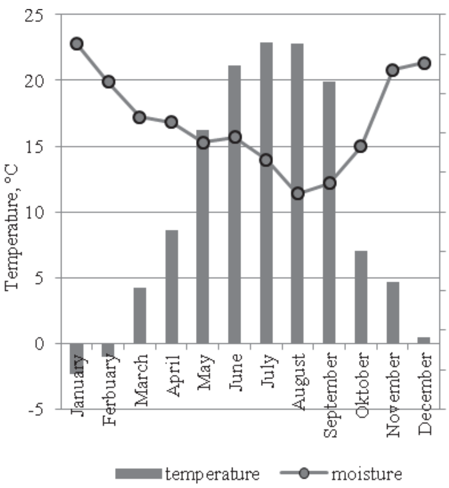

Fig. 1. Climatogram of Dnipro region

The research was based on successfully combined mensurational and biometric techniques, applied theoretical generalizations with statistical and mathematical methods (Lakida, 1996).

Soil fertility and humidity are parameters that composed the classification schemes of trophotops and hygrotops. Soil fertility is characterized bytrophogenic sequence and denoted as A (bor), B (subor), C (sugrud) and D (grud) and called trophotopes (Pogrebnyak, 1955). Each trophotope is represented by theforest site with equal soil fertility within its boundaries. "Bor" is a pure pine forest, characterized by very poor soil conditions, predominantly with sandy soil, sometimes loamy sands with a short rhizosphere zone and oligotrophic vegetation. "Subor" is a type of forest vegetation conditions, which is characterized by relatively poor soil conditions which are similar to those in coniferous forests (bor) but with a higher extent of oligo-mesotrophic vegetation with domination of oligotrophs. "Gruds" and "sugruds" are classification units of forest typology which characterise areas of the forest with highly and relatively high fertile soils respectively. The trophotopes are divided into six hygrotopes with indicators of soil moisture (indexes from 0 to 5) (Pogrebnyak, 1955). Hygrotope of 0 range corresponds to very dry (xerophilic) conditions, 1 – dry-mesic (meso-xerophilic), 2 – mesic (mesophilic), 3 – wet-mesic (meso-hygrophilic), 4 – wet (hygrophilic), 5 – swamp (ultrahygrophilic). According to this classification scheme, each research site of forest is characterized by trophotope and hygrotope (Brygadyrenko, 2014).

In the surveyed forest stands we selected temporary sample plots (TSP) for Scots pine in existing grades of trophotopes and hygrotopes within stands of different ages. The delimitation of sampling units was carried out instrumentally with surface marking and binding to net of rides. The research sites were located in four enterprises within the jurisdiction of the State Agency of Forest Resources: Dniprovskiy, Novomoskovskiy, Vasilkovskiy. A total of 20 TSP (50 × 50 m) were established in pine stands: Dniprovskiy enterprise – six plots, Novomoskovskiy enterprise – ten plots, Vasilkovskiy enterprise – four plots. The research data was collected through felling and fraction-wise processing of sample trees.The choice of three sample trees on the sample plot was conducted byr the principles of ranges of thickness (diameter 1.3 m) of tree stems. Then the height (h) and diameter at breast height of the selected trees were measured. After felling the model trees on the sample plots, the dendrometric measurements of the trees were conducted by measuring six diameter and radial increments for the last five years at the root collar (D_0), 1.3 m (D_{bh}), 0.1 h, 0.25 h, 0.50 h and 0.75 h of trees. The mathematical models of radial increment were statistically verified using the program Statistica (StatSoft Inc., USA).

To assess the influence of climate on the dynamics of radial increment change, we used monthly climatic data on the surface air temperature and precipitation (moisture). The data of the Dnipro meteorological station at the airport for the period 2011–2015 was used. The average monthly temperature and monthly air humidity values for the Dnipro region are presented in Figure 1. The warmest month (22.9 °C) was July, and the coldest (–2.3 °C) and the most humid (92.8%) month – January. The minimum moisture was noted in August.

Results

For studying the radial increment of Scots pine, we selected and measured 60 model pines. The age of the model pines varied from 9 to 90 years, the majority of the studied trees belonged to the average age group of 40 to 80 years. The radial increment of the trunk was measured on model pines which had a wide amplitude of fluctuation of forest inventory parameters: age, height, diameter and volume of trunk (Fig. 2).

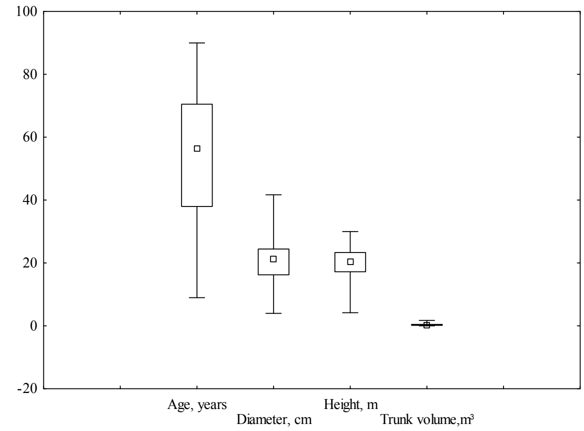

Fig. 2. Interval estimate of biometric indexes of Scots pine model trees: box plots show the range, median, and 25% and 75% quartiles of basic density

The diameter of the model pines ranged from 4.0 to 41.7 cm, the trunk height – 4.2 to 30.0 m, trunk volume – 0.002 to 1.748 m^3. In general, the selected model pines were characterized as plantations of young, average, premature and mature age.

The wide range of the forest inventory parameters of the model pines allowed us to determine the parameters of periodic increment (5-years) and peculiarities of its change depending on age, diameter, height and volume of trunk of Scots pine (Fig. 3). Informative models of the dependence of radial increment on the age and diameter were carried out. The obtained coefficients determination (R^2 = 0.50) for calculation of radial increment for sample trees of Scots pine is demonstrated by the following equations:

$$Z = 2.4104 \bullet \exp(-0.0207\,a) \bullet \exp(0.0014d),$$

The trees grew in soils different in moisture (significantly dry (0) to humid (3) and soils of different fertility (A, B, C and D), i.e. in different types of forest vegetation conditions. The ranges of dependence of the values of radial increment of sample trees on types of the forest is demonstrated in Figure 4. As we can see on the diagram, the highest values of radial increment of Scots pine were observed in sugruds and also in gruds of dry hygrotopes. This fact is explained by the presence of young trees aged up to 20 years in these types of forest vegetation conditions, for as mentionned earlier, they have the highest growth intensity.

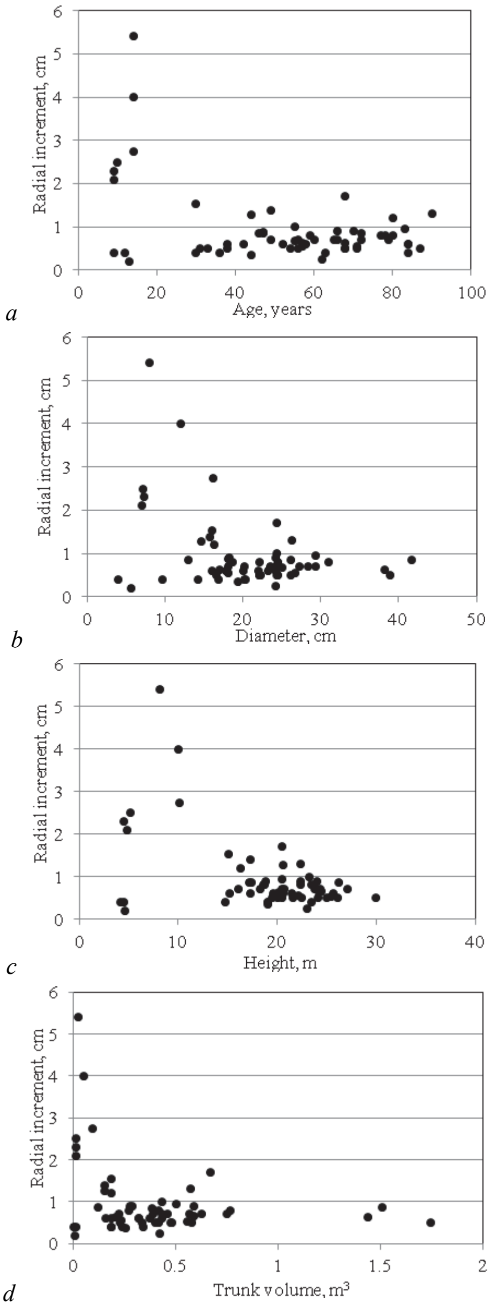

Fig. 3. Dependence of radial increment of Scots pine modal tree on age (*a*), diameter (*b*), height (*c*), trunk volume (*d*)

For a more precise impression of the influence of the forest vegetation condition types on the studied parameter of radial increment, we conducted a comparative analysis of its change in the trees of one age category, which grew in different conditions. We selected trees of the average age group, aged from 41 to 60 and 61–80 years. Within the single age group, significant fluctuations were observed depending on growth of model pines in soils of different fertility and moisture conditions. At the same time, the two different studied age groups have differently directed trend lines of the studied parameter. Therefore, the older tree age category was observed to have the maximum increment in the conditions of dry sugrud, and the minimum increment in conditions of fresh subor. The trees of the 41–60 years category had maximum increment typical for Scots pine trees growing in the conditions of humid subors.

Discussion

The timing of the start of the season is essential for growth and formation of wood. Therefore, it is the first half of the season when the growth and the intensity of cell division in the meristem of most coniferous trees are the highest. The weather conditions of certain seasons have individual peculiarities, i.e. a specific temperature course and intraseasonal distribution of precipitations. These peculiarities determine the timing of the beginning of cell divisions in the meristems, growth speed in separate intervals of the season, timing of the ending of growth and the seasonal course of the growth curve in general. On the whole, increase or decrease in the growth processes over separate intervals of the season is caused by a combination of temperature and moisture impacts.

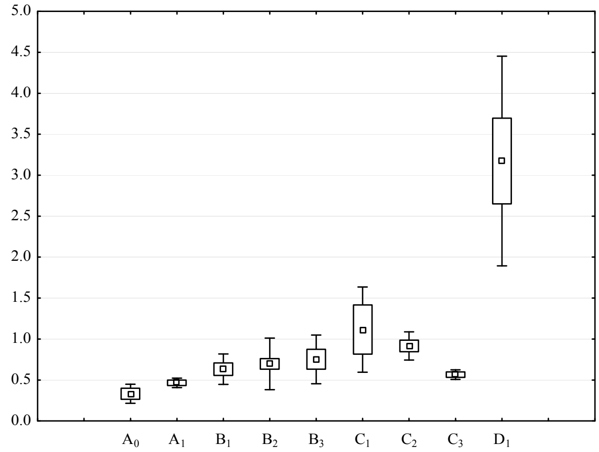

Fig. 4. Interval estimate of dependence of radial increment values of Scots pine model trees on site indexes: box plots show the range, mean, mean ± standard errors, and mean ± standard deviation of radial increment

Earlier, our research proved the important role of climatic factors, such as temperature and air moisture, affecting the radial increment of Scots pine in the conditions of the Northern Ukrainian Steppe (Lovelius & Gritsan, 1998). Figure 5 presents two dendrological climate graphs.

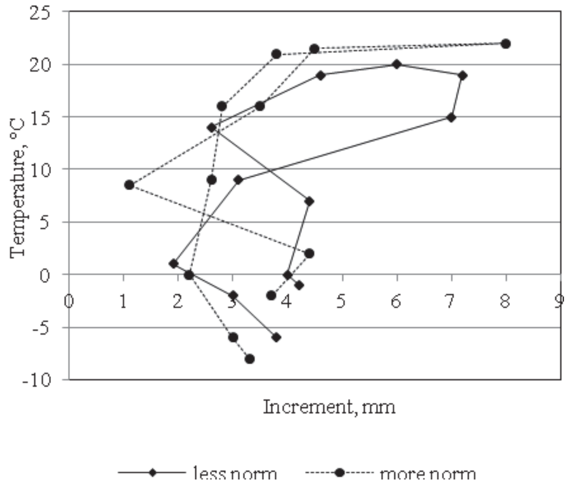

Fig. 5. Dendroclimatogram "temperature-precipitation" in the years with the pine increment with more and less than the norm for hydrologic year

We determined the peculiarities of distribution of heat and moisture regime in the years with opposite anomalies of the radial increment of pines. The distribution of temperature and precipitation during the cold part of the year is most clearly manifested in December and January.

On the example of Samars'ky Coniferous Forest located on the territory of the Novomoskovs'k forestry, we demonstrated the soil moisture impact on the changes in radial increment of Scots pine (Lovelius & Gritsan, 1998). The data analysis showed the total probability of repeatability of increment values in the whole annual layer of the pines from different ecotopes according to the classification of forest types (Fig. 6). The biotope formed in dry condition (A_0) was characterized by an azonal complex of soils of the arena with growth locations of pines on dune tops and underdeveloped sod-steppe soils with thinned-out herbal stand of psammophiles. Fresh and humid conditions in subor ($B_{2–3}$)

was characterized of low areas of the relief, where chernozem-meadow soils were developed with vegetation typical for steppe meadows; they had specific characteristics of the total probability of the increment of the whole annual layer of pine and its seasonal parts.

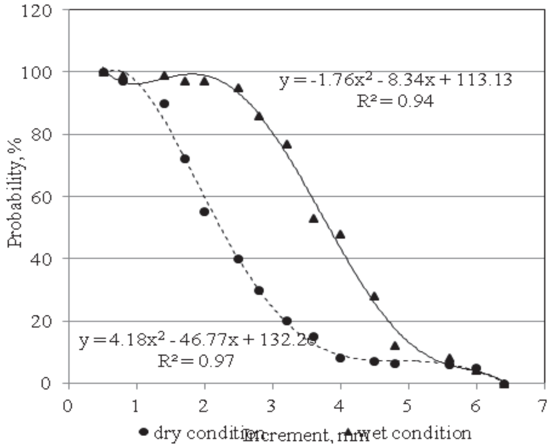

Fig. 6. The total probability of repeatability of pine annual increment in different conditions

A general view of the graph of the total probability allowed accurate determination of the range in which the pine increment changed and of the proportions of its seasonal parts in habitat conditions with different levels of moisture were. Therefore, if we compare the increment values of the annual ring in Figure 6 after passing the 50% level, it will be as follows:

$$\frac{A_{0-1}}{B_{2-3}} = \frac{2{,}4}{4{,}1} = 58{,}5\%$$

In general, our researches showed that range of pine increment fluctuations is slightly higher for dry growth locations (A_0) – 30–180% compared to the humid locations (B_2) – 50–170%, although these differences occurred only in 2% of the total number of observations.

Annual values of the deviations of the increment from the norm indicate a clear pattern in increment changes among pines located at a considerable distance from one another. This proves the significance of large-scale changes in natural processes, which are reflected in the increment characteristics of trees in the steppe zone.

The effect of solar activity on radial growth in the conditions of the steppe zone on the example of Scots pine had been studied by Lovelius & Gritsan (1998). Long-term studies on the condition of the forest ecosystems on the southern border of the distribution of the Scots pine in steppe coniferous forests, particularly the Samarsky, Velykoanadol'-sky, Dibrovs'kyand Slav'ianohors'ky forests, have allowed us to determine clearly manifested characteristics of the similarities in radial increment fluctuations. Obtaining a combined series of annual layers of each of the coniferous forests was followed by the normalisation of the measurements using calculation of the deviations of the increment from the 10 year average value of calendar decades. A change in the conditions of moisture is likely to be related to a long term tendency of a decrease in the productivity of trunk wood in steppe pine tree stands. It was necessary to determine how the radial increment values were distributed in the periods of maximum and minimum solar activities in the steppe zone. It was suggested that increment increases during periods of maximum solar activity and decreases during periods of minimum activity. The fluctuation range of this parameter of the 69-year period is 64%. Therefore, to solve the problem of distribution of extreme conditions, the authors used the familiar method of "combined" epochs, and the dates of extremes of solar activity over an 11-year cycle according to Vitinskiy (1997) were used as frames. In general, the increment distribution had a clearly manifested direction. The extreme values are observed after 11 years.

Accuracy and amplitude between the extreme values give an impression that an increase in criticality of the habitat conditions intensifies the relations between the processes of woody plants` growth and geophysical parameters of the environment. Previously, this situation was found during the analysis of coniferous trees in the upper border of the forest in the Eurasian mountains, and of Scots pine in the upper swamps of North-West Russia and in Kamchatka (Lovelius, 1997). During the period of maximum-minimum, the extreme conditions occur precisely in year zero. Even without any additional graphic processing, the extrema are seen clearly, although in the period of the minimum, the phase of the increment decrease is slightly "deformed". During the period of maximum, the count of the increment increase phase begins 3 years before an extremus and the phase of increase finishes in +1st year. The phase of increment decrease occurs in +7th year. The trees' increment distribution in the 11 year cycle of solar activity on the example of the studied material of the steppe zone indicated the formation of clearly seen fluctuations strongly related to the solar activity cycles, so the higher the criticality of the habitat conditions, the clearer the plants' reaction to it. The determined parameters of changes in Scots pines' increment during an 11 year cycle allow one to recommend that forest plantations be created during the period of maximum starting from the 2nd to +1st year in the steppe, or from +1st to +4th year after the minimum, when the tree stand of Scots pines functions the best. Refinement of the solar activity extrema allow one to correct the long-term prediction of development of tree stands and periods of forestry work.

In general, using trees as a functional nucleus of the biosphere and as "the biosphere`s memory" of the changes in geomagnetic and solar activities which have occurred over the last hundreds and thousands of years is of great significance.

Conclusions

As the age, diameter, height and volume of a model tree's trunk increase, its diameter increment decreases. The maximum indicators of radial increment were observed for plantations of the young stand age category. The older trees showed significant decrease in the increment indicators of all the studied forest inventory parameters and relatively stable or stable growth to a mature age. Dependence of the values of radial increment of sample trees on types of forest demonstrated the highest values of radial increment of Scots pine in sugruds and gruds and is explained by the presence here the youngest samples aged up to 20 years. Model pines of same age group had the maximum increment in the conditions of dry sugrud, and the minimum – in fresh subor.The obtained data are an informational base for modeling and determining the volumes of production of trees and tree stands of Scots pine in the region of study, which allows one to predict the tempi of carbohydrate accumulation in this category of tree stand.

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