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Dependency between photosynthetic intensity of *Pinus nigra* subsp."*Pallasiana*"and environmental factors and their change during vegetation under conditions of the southern coast of the Crimea

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***Abstract*—The dependence of the net photosynthetic rate of *Pinus nigra* subsp. *pallasiana* on environmental factors, leaf temperature, transpiration and their change during the growing season were investigated under the conditions of the Southern Coast of the Crimea. The mapping of the response function of photosynthesis to environmental factors allowed for *Pinus nigra* subsp. *pallasiana* to obtain the numerical coefficients of nonlinear regression equations (models) of the relationship of the magnitude of net photosynthetic rate with the main environmental factors. The data obtained make it possible to interpret the rate of photosynthesis as a potential ecological and physiological characteristic of this species, which allows us to compare different types of plants growing under similar conditions, according to indicators measured using the same technique. *Pinus nigra* subsp. *pallasiana* has a high potential for photosynthesis to acclimatize to high temperatures. When the air temperature is above the optimum, the intensity of photosynthesis drops sharply. The critical temperature for the leaf is 38 degrees Celsius. After the termination of the period of active growth for June – October, the maximum value of net photosynthetic rate decreased by 15.4 percent, transpiration intensity – by 44.5 percent, leaf temperature – by 6.7 percent. At the same time, in comparison with June in October, the temperature-light optima shifted downward: air temperature by 21.5 percent, vapor pressure deficit by 40 percent and PAR by 23.1 percent.**

Keywords*—Pinus nigra subsp. pallasiana, net photosynthetic rate, temperature and light optima, ecological and physiological characteristics

1. Introduction

The climate features of the Southern Coast of the Crimea (SCC), which is a region of dry subtropics, make it possible to preserve natural vegetation, to establish new and reconstruct existing green spaces that are under the microclimate conditions formed by the environment [1]. When selecting such plant species, it is necessary to study various processes of vital activity in the conditions of their growth [2]. In parks, recreational forest, softwood forest of the SCC, the forest-forming species is Pallas pine or Crimean pine, which some authors consider a subspecies of black pines, namely *Pinus nigra* ssp. *pallasiana* (Lamb.) Holmboe, growing in the Caucasus and Balkan regions [3].

The extensive group of Mediterranean and Balkan black pines is a relict of the Tertiary era. There are a small number of papers on studying of the reaction of various species and subspecies of *Pinus nigra* subsp. to seasonal climate changes and their tolerance for summer drought under conditions dry subtropical Mediterranean region.

Black pine *Pinus nigra* subsp. *laricio* occupies a significant part of the forest area (3.5×10^6 ha) in the Mediterranean region, from Morocco to Turkey. To study the seasonal functioning and tolerance to summer drought (University of Corsica, France), field studies of this species in the natural mountain pine forest were conducted [4]. In response to the summer drought, there is a decrease in gas exchange and xylem flux, which is regulated by stomatal conductance. At the same time, water use efficiency increases and the mesophyll conductivity limitation decreases. Such a reaction to summer drought shows that *Pinus nigra* subsp. *laricio* is able to undergo physiological adaptation to climate change. In the Mediterranean basin, rainfall is expected to decrease by more than 25–30% by the end of the 21st century, probably accompanied by an increase of 4–5 °C at average annual temperatures [5]. These results provide an important basis for further understanding the ecophysiological responses to changing environmental factors.

Studies of carbon fluxes from leaf surface to landscape level under drought conditions [6] were conducted in Collserola Park, (Barcelona, Spain) on various species, including Aleppo pine (*Pinus halepensis* Mill.). The authors studied the dependence of seasonal acclimatization of photosynthesis and morphology in sunlit and shaded leaves in natural conditions. Severe drought induced early leaf aging and, at the same time, the leaf mass per unit area significantly increased. The shaded leaves had lower photosynthetic potentials and could not mitigate the negative effects during periods of stress. The conducted studies explain the response of vegetation to abiotic stresses and have great potential for reducing uncertainty in terrestrial biospheric models, especially in drought conditions.

A series of experiments were conducted in a semi-arid area at the experimental station of Peking Forestry University [7] to develop the scientific basis for growing seedlings and studying the effect of light intensity on photosynthetic characteristics and water use efficiency of *Pinus tabulaeformis* (homeland – Mediterranean basin, China). The research results have shown that the intensity of net photosynthesis and transpiration increased with increasing light intensity, however, due to lack of water in the soil, stomatal conductance decreases and can create a protective mechanism to prevent greater water consumption and gas exchange in leaves. It has been shown that *Pinus tabulaeformis* seedlings are particularly affected by strong light, which leads to growth inhibition. The obtained research results have allowed to develop a scientific basis for growing seedlings for regions with extreme environmental factors.

The Crimean sub-species of black pine has been widely used for afforestation programs in the southern steppe regions in the Ukraine and Russia [8]. For development the scientific basis for the effective growing *Pinus nigra* ssp. *pallasiana* it is necessary the studying changes various processes the vital activity of plants during the growing season and depending on changes in environmental conditions. The articles on studying of the reaction of Crimean pine on the seasonal change of environmental conditions are precious few [3, 8].

It is known that the rate of photosynthesis quickly responds to changes in external conditions and reflects the state of the plant at all stages of ontogenesis. It is believed that the maximum possible value the rate of photosynthesis is genetically determined [9, 10]. The intensity of the factors which help to achieve the optimum of nett-photosynthesis of intact plants can be considered as an ecological optimum for the studied genotype [9].

The aim of the work was to study dependence the rate of photosynthesis – *Pinus nigra* subsp. *pallasiana* on environmental factors (air temperature and vapor pressure deficit, photosynthetically active radiation), as well as intensity of transpiration and temperature of needles, allowing to determine the optimal and limiting conditions for plants growth in the Southern Coast of the Crimea.

II. Materials and Methods

Crimean pine (*Pinus nigra* subsp. *pallasiana* (Lamb.) Holmboe) is Mediterranean mountain, dominant species. The plant range includes the Crimea, mainly the southern slope of Yayla, the south of Ukraine and the Caucasus [5, 6]. The tree height is 20-30 (up to 45) m. The crown is wide, pyramidal; older trees have a flat, umbrella-shaped crown. The branches are horizontal, with upward curved shoots. The bark is black or dark brown, deeply grooved, reddish in the upper part of the trunk. Young shoots are yellow-brown, shiny. Buds are large with straight, unbent scales. The needles are dark green, very dense, somewhat curved, 8-12 cm long, 1.6-2.1 mm wide. Crimean pine blossoms in early May. The cones are large, with brown glossy shields and red. Seeds are dark gray, speckled, dull, larger than that of Scots pine. Cones ripen in August-September. In the area, mainly it grows on stony soils containing lime. It grows well on loamy and clay-limestone. Crimean pine is very light-loving and relatively moisture-loving. It develops well in both the lower and middle mountain and upper forest belts at altitudes of 500–900 m above sea level. At altitudes above 700 m, in conditions with high humidity and more frequent precipitation in the form of rain and snow, Crimean pine has the most intensive growth, and forms close-standing stands.

The studies were conducted in greenhouse conditions and field experience on the territory of the central branch of the Nikitsky Botanical Gardens. Plants were 3-4 years old seedlings, grown from cuttings. The duration of the experiments are June – October 2018.

For continuous automatic recording of gas exchange in intact leaves, plant growth and water balance, the photosynthesis monitor PTM-48A and the phytomonitor PM-11z were used [11]. The PTM-48A monitor system is equipped with four leaf cameras connected to the monitor. The working area of the standard LC-4B camera is 20 cm^2 and is applicable to a wide variety of leaves. Measurement of the total rate of photosynthesis was determined on young, intact leaves in the upper part of the shoot every 15–20 minutes. The natural concentration of CO_2 in the air was approximately 0.04%. The net photosynthetic rate (Pn, $\mu mol/(m^2\,s)$) and transpiration (E, $mg/(m^2\,s)$) in the photosynthetically active radiation (PAR) range from 0 to 2000 $\mu mol/(m^2\,s)$ were used to characterize leaf gas exchange. Photosynthetically active radiation and other environmental parameters: temperature and humidity were measured with sensors of meteo-module RTH-48 connected to the digital input of the PTM-48A system; needles temperature was measured with sensor LT-1P, connected to analog input PTM-48A.

Statistical data processing was performed using Statistica 10 (“Statsoft Inc.”, USA) and Microsoft Excel 2010 applied computer programs. The least squares and robust locally weighted regression methods (Statistica 10) were used to model and smooth the two-dimensional data. All calculations were carried out at a given level of significance $P \leq 0.05$.

III. Results and Discussion

To identify the dependencies of the photosynthesis intensity on the main environmental factors (air temperature and vapor pressure deficit, photosynthetically active radiation, as well as needle temperature and transpiration intensity), a series of experiments was carried out in greenhouse conditions. The obtained data will make it possible to interpret them with more confidence as a potential ecological and physiological characteristic of this species.

Analysis of the literature source has shown that the relationship between leaf growth and photosynthesis intensity depends on the life form of the plant. Thus, in perennial evergreens, maximum photosynthesis (Pmax) occurs most often after the completion of leaf formation by area and biomass. This statement is true for both deciduous evergreens and conifers [12]. CO_2 exchange is a function of the response to the impact of the mentioned above environmental factors. The surfaces of the response function Pn, constructed in the XYZ coordinates, and 10 projections of slices of this surface with planes

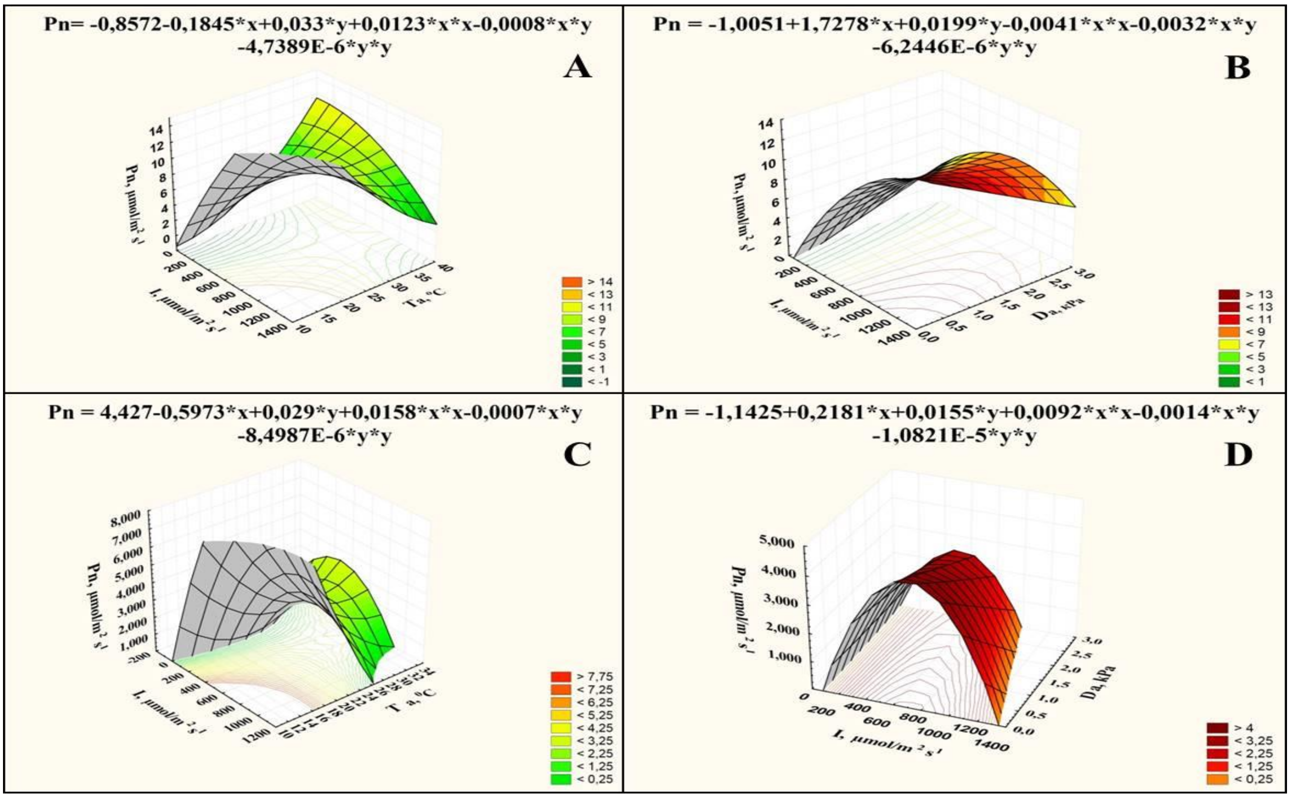

Fig. 1.*Surface of a quadratic function Pn = f(I,Ta) – June (A), October (C) and Pn = f(I,Da) – June (B), October (D) and the cut contours on the Ta–I (A, C) and Da–I (B, D) planes. Numerical coefficients of nonlinear regression equations of these models are shown above the diagrams Pinus nigra subsp. pallasiana*

perpendicular to the Z axis, allow for each allowable combination of the indicated above factors to obtain the corresponding photosynthesis value for this combination. This area is called the optimum zone and it contains points that have values more than 90% of maximum photosynthesis. Analysis of the calculated equations made it possible to determine the conditions and levels of the potential maxima and the boundaries of the areas of optimum for photosynthesis.

Fig. 1 shows the surface of the quadratic function dependence of the net photosynthetic rate (Pn) from PAR (I), air temperature (Ta) and vapor pressure deficit (Da): Pn = f (I, Ta, Da) as well as the contours projections of the slices in the plane. In June (Fig.1A) it can be seen that for Pn = f (I, Ta), the optimum of photosynthesis is at the air temperature Ta = 23–28 °C and I = 400–300 µmol/(m^2 s), Pn = 11–13 µmol/(m^2 s). In October (Fig. 1C) at the Ta = 17–22 °C, I = 350–1000 µmol/(m^2 s), Pn = 9.5–11 µmol/(m^2 s).

The optimum of photosynthesis Pn = f (I, Da) in June (Fig. 1.B) is at Da = 0.5–1.5 kPa, I = 400–1300 µmol/(m^2 s) and is 11–13 µmol/(m^2 s), in October (Fig. 1D) Da = 0.3–0.9 kPa, I = 350–1000 µmol/(m^2 s), Pn = 9.5–11 µmol/(m^2 s).

Fig. 2 shows the surface of the quadratic function dependence of the net photosynthetic rate from PAR, needle temperature (Tn) and transpiration intensity (E): Pn = f (I, Ta, E) and the contours of the slices in the plane. In June (Fig. 2A) for Pn = f (I, Tn) photosynthesis optimum is at Tn = 25–30 °C, I = 400–1300 µmol/(m^2 s), Pn = 11–13 µmol/(m^2 s). In October (Fig. 2C): Tn = 23–28 °C, I = 350–1100 µmol/(m^2 s), Pn = 9.5–11 µmol/(m^2 s).

Studies have shown that as the vegetation phases of a plant change from June to October, weather conditions, needle aging, temperature-light optima and photosynthesis intensity also change.

The optimum temperature of photosynthesis for most plants for which photosynthesis goes along C3-way, is approximately 22–28 °C, and for those ones with photosynthesis goes along C4-way it is higher (35–45 °C and higher) [13].

Analysis of the results has shown (Fig. 2A) that for *Pinus nigra* subsp. *pallasiana* the critical temperature of the leaf is 38 °C.

Fig. 2B shows the surface of the quadratic function dependence of the net photosynthetic rate from PAR and the transpiration Pn = f (I, E) and the contours of the

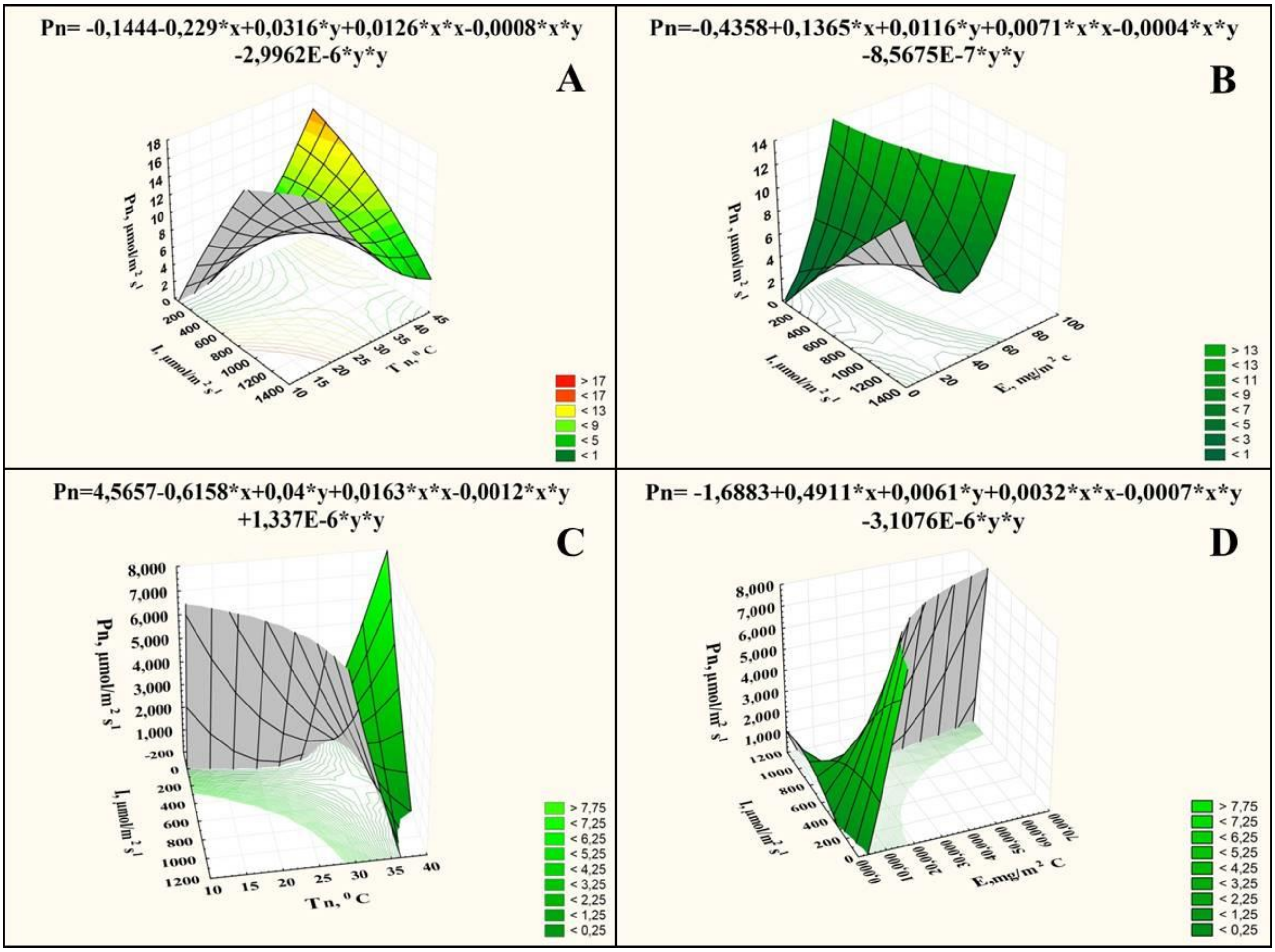

Fig. 2. *Surface of a quadratic function Pn = f(I, Tn) – June (A), October (C) and Pn = f(I,E) – June (B), October (D) and the cut contours on the Tn–I (A, C) and E–I (B, D) planes. Numerical coefficients of nonlinear regression equations of these models are shown above the diagrams Pinus nigra subsp. pallasiana*

sections on the plane in June. At E = 40–90 mg/(m^2 s), I = 400–1300 μmol/(m^2 s), Pn = 11–13 μmol/(m^2 s). In October (Fig. 2D) E = 25–50 mg/(m^2 s), I = 350-1000 μmol/(m^2 s), Pn = 9.5–11 μmol/(m^2 s).

The dynamics of changes in the optima of net photosynthesis and environmental factors during the vegetation of the plant is shown in the table.

TABLE I. DYNAMICS OF CHANGES IN NET PHOTOSYNTHETIC RATE, TRANSPIRATION, LEAF TEMPERATURE AND ENVIRONMENTAL FACTORS DURING VEGETATION

Parameter, unit	Month of measurement	
	June	*October*
Ta, °C	23–28	17–22
Da, kPa	0.5–1.5	0.3–0.9
I, μmol/(m^2 s)	400–1300	350–1000
Tn, °C	25–30	23–28
E, mg/(m s))	40–90	25–50
Pn, μmol/(m^2 s)	11.0–13.0	9.5–11.0

During of the growing season the optimal value of the net photosynthetic rate for period June – October decreased by 15.4% (see in table), transpiration intensity – by 44.5%, air temperature (Ta) – by 21.5%, vapor pressure deficit (Da) – by 40.0%, needles temperature (Tn) – by 6.7%, photosynthetically active radiation – by 23.1%.

IV. CONCLUSIONS

For different plant species, there is some genetically determined critical value of the optimal photosynthesis temperature. *Pinus nigra* subsp. *pallasiana* has a relatively high potential for photosynthesis to acclimate to elevated temperatures. When the temperature of the leaf is above the optimum, the intensity of photosynthesis drops sharply. For *Pinus nigra* subsp. *pallasiana* the critical leaf temperature is 38 °C. After the termination of the period of active growth for June – October, the maximum value of net photosynthetic rate decreased by 15.4%, transpiration intensity – by 44.5%, leaf temperature – by 6.7%. At the same time, in comparison with June, in October the temperature-light optima shifted downwards: air temperature by 21.5%, vapor pressure deficit 40%, and PAR by 23.1%

The conducted studies confirm the reasons for these changes: changes in the vegetation phase of the plant, weather conditions, and leaf aging, which lead to a change in the temperature-light optima for the intensity of photosynthesis [13].

The data obtained make it possible to interpret the rate of photosynthesis as a potential ecological and physiological characteristic of this species, which allows us to compare different types of plants growing under similar conditions, according to indicators measured using the same technique.

With the introduction of this species to different regions, the results of the conducted studies make it possible to compare the hydrothermal characteristics obtained by us with the climatic conditions of a particular region and to evaluate the possibilities of its growth.

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