Spatial variation of soil temperature fields in a urban park

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Abstract. Soil temperature is the most important factor that regulates the rate of physical, chemical and biological processes in the soil. A peculiarity of the urban environment is the occurrence of “heat islands”. The increased temperature of urban environment significantly changes environmental conditions and contributes to the activation of phenomena that lead to the acceleration of global climate change. The aim of the work is to reveal the patterns of spatial variation of soil temperature in a city park at the different scale levels. Soil temperature was measured on a regular grid with different lags between measurement points. The measurement results were processed using geostatistical methods to quantify the spatial process at different scales. The results obtained allowed to quantify the patterns of spatial variability of temperature fields at different hierarchical levels. Scale-dependent effects of soil temperature variation were identified. The role of stand density, litter depth, and soil moisture on soil temperature variation was found. The results of the study are the basis for developing an optimal soil temperature measurement plan for environmental monitoring purposes. Suggestions were also made for the management of park stands in order to reduce the temperature load. The spatial variation in soil temperature demonstrates the occurrence of scale-dependent patterns. The spatial organization of temperature fields must be taken into account for optimal environmental monitoring and urban environmental management strategies. The soil temperature regime is characterised by a significant level of stability compared to air temperature. The soil temperature fields in an artificial park plantation are characterized by spatial patterns of a complex nature. The temperature field presents a spatial component that is invariant to time. It is most likely that the spatial variability of soil properties induced by natural factors and recreation are the cause of the generation of this pattern. Also in the soil temperature field there is a spatial pattern, which reflects the different sensitivity of the soil to the seasonal trend of temperature change. The generation of this pattern is due to the different insulating capacity of the forest litter in the park plantation. The results obtained point to the important role of leaf litter as a factor in the dynamics of the soil temperature regime. It is hypothesized that leaf litter in the park contributes to the enhancement of carbon sequestration during winter time.

1. Introduction

Soil temperature is one of the key factors determining the functioning of ecological systems [1,2] and affects both the vegetation and animal communities of soils [3]. The temperature regime strongly influences the intensity of soil processes, both mechanical and geochemical as well as biological [4,5]. Soil temperature is one of the important factors affecting soil properties and the processes involved in plant growth and regulates the physical, chemical and biological processes in the soil [6–8]. Soil temperature affects interspheric gas exchange processes between the
atmosphere and the soil [9,10]. The soil temperature plays an important role in plant nutrition [11, 12]. Soil temperature affects the activity of soil micro-organisms and root architecture, which modulates mutualistic and pathogenic interactions between plants and soil biota [13,14]. According to the Van’t Hoff rule, the speed of chemical reactions is accelerated by a factor of 2 to 3 when the temperature rises by 10°C. Soil warming can change the relationship between some plant species and soil animals [15,16]. An increase in soil temperature leads to a decrease in α-diversity of plant and invertebrate communities, which was caused by a decrease in plant species richness and an increase in the dominance of some invertebrate species in warmer habitats [3,17]. Such soil processes as sorption and desorption [18], gas solubility [19], the ratio of solid and liquid phases in the soil [20], peptization and coagulation of colloids [21] depend on temperature.

Soil temperature is influenced by factors from two groups: these are factors that determine the amount of heat reaching the soil surface and factors that influence the amount of heat transferred along the soil profile [22,23]. The factors that influence the amount of heat that reaches the soil surface are the colour of the soil surface [24], mulching [25], the amount of solar radiation [1,26,27] the slope of the soil surface [28,29], the vegetation cover [30,31], the organic matter content of the soil [32] and the intensity of evaporation from the soil surface [33,34]. The amount of radiation received by the soil affects soil temperature, biological processes such as: seed germination, seedling emergence, plant root growth and nutrient availability. Factors influencing the amount of heat dissipated from the soil down the profile are moisture content and bulk density [35]. Soil temperature changes the decomposition rate of organic matter and mineralization of various organic materials in the soil. Soil temperature also affects the retention, transmission and availability of soil water to plants. There was no effect of temperature on vegetation projective cover at the community level, which was due to contrasting effects at the population level [3]. Soil thermal regime is one of the most important factors in soil formations [36] and living conditions for terrestrial biota [37,38]. A significant horizontal variation in the temperature of the upper soil horizons was found, which in forest ecosystems is related to the spatial heterogeneity of the tree stand and the understorey [39,40]. The studies of temperature fields with long time series began with the advent of programmable sensors. Most of these studies are related to the task of determining the properties of agricultural land [41], or accompany a study of soil processes, e.g. salinity [42]. The spatial variability of the soil temperature regime of natural communities is related to the thinness of the forest cover [43] and shrub canopy, with local soil properties. There are also studies devoted to the problem of spatial variation of soil temperature [44] and analysis of spatial and spatio-temporal temperature fields [45]. However, such studies are rare, and the nature of spatial variation in soil temperature for many areas and terrestrial ecosystems remains unknown.

2. Research aim and objectives
Parkland has important ecological functions in the urban environment [46–48]. The degree of transformation of ecological systems under the influence of anthropogenic pressure is characterised by the concept of hemeroby [49,50]. In addition to factors influencing the urban environment, park areas are also influenced by the recreational function [51–53]. To some extent, the function of recreation and other ecological functions of urban parks are antagonistic [54,55]. Obviously, in the management of parkland it is necessary to look for the optimal solutions, as a result of which the parks can effectively perform both ecological functions and be an area for recreation. In this aspect, the role of the soil temperature regime of park plantations is a key one, but one that has been little researched.

The aim of the work is to reveal the patterns of spatial variation of soil temperature in a city park at the different scale levels.
3. Material and methods
The research was conducted from 18 November 2021 to 3 January 2022 in Oak Grove Park (Zaporozhye, Ukraine). The park (47°48'C 35°10'B) was founded on 1 May 1959. In the park, apart from the oaks, there is a variety of flora. The total area of the park is 57 hectares of forest, of which five hectares are classified as natural reserves. The soil temperature was measured within the polygon, which consisted of 10 transects of 20 measuring points each. The distance between the measuring points in the transect was 2 metres. The distance between the transects was 2 metres. Thus, the experimental polygon was a regular grid with 2×2 meter cells of 10×20 meters in size. The temperature measurements were taken during the day between 12pm and 1pm, at a time when the change in daytime temperature was the smallest. The measurements were made in the soil at the depth of 3-4 cm with an electronic thermometer on November 18 and 28, December 7, 12, and 20, 2021 and January 3, 2022.

The descriptive statistics and principal component analysis were performed using Statsoft 12.0 software. The variogram parameters were calculated and mapping was performed in Surfer 15.0 software.

4. Results
During the study period, precipitation fell on 47.8% of days. Daily precipitation ranged from 0.1 to 13 mm (figure 1, A). Air temperature varied from -16.3 to +17.6°C. Mean daily temperature ranged from -9.15 to +12.3°C (figure 1, B). The general trend of temperature change was a seasonal temperature decrease with significant temperature variations over a short period of time. Thus, drops in mean daily temperatures of 12–15°C occurred in 3–4 days in some cases. Clear skies occurred 11.3% of the time. Fog occurred 4.9% of the time. Cloudiness range of 3–6 was 14.7% of the time, while cloudiness of 8 was 10.7% of the time, cloudiness of 9 was 34.0% and cloudiness of 10 was 24.4% of the time.

Soil temperature varied within a much narrower range than air temperature (table 1). There was no correlation between soil temperature and air temperature measured with a lag of one day to 7. The lowest soil temperature was recorded on November 18 and it was 1.99±0.06°C. The highest soil temperature was recorded on December 7 and was 3.16±0.06°C. The range of variability of soil temperature within the polygon was 2.5–4.3°C. The distribution of soil temperature indices within the polygon was symmetrical, except for December 20, when the distribution was shifted to the left (figure 2). The distribution was kurtosis-free on 18 November, while on the other dates the distribution was negative kurtosis, indicating bimodality.

| Date       | Mean ±st.error | Minimum | Maximum | CV, % ±st.error | Skewness ±st.error | Kurtosis ±st.error | PC1 | PC2       |
|------------|----------------|---------|---------|-----------------|--------------------|-------------------|-----|-----------|
| 18.11.2021 | 1.99±0.06      | 0.10    | 4.20    | 40.13 ±0.17     | 0.21±0.17          | 0.08±0.34         | -0.58 | -0.68     |
| 28.11.2021 | 2.81±0.05      | 1.40    | 4.50    | 26.07 ±0.17     | -0.65±0.34         | -0.36             | -0.78 |           |
| 07.12.2021 | 3.16±0.04      | 1.90    | 4.40    | 19.92 ±0.17     | -0.73±0.34         | -0.74             | -0.43 |           |
| 12.12.2021 | 2.93±0.05      | 1.20    | 4.50    | 24.75 ±0.17     | -0.66±0.34         | -0.73             | 0.42  |           |
| 20.12.2021 | 2.52±0.05      | 0.90    | 4.20    | 30.13 ±0.17     | -0.47±0.34         | -0.84             | 0.36  |           |
| 03.01.2022 | 2.17±0.07      | 0.00    | 4.30    | 46.45 ±0.17     | -0.80±0.34         | -0.78             | 0.49  |           |

The principal component analysis allowed the extraction of two components whose eigenvalues exceeded unity.
Figure 1. Dynamics of mean precipitation and mean daily temperature in the study area. Abscissa 1 shows November 1, 2021; 2 and following are subsequent dates; axis of ordinates are daily precipitation, mm (A) and mean daily temperature, °C (B). Arrows show soil temperature dates: November 18 and 28, December 7, 12, and 20, 2021 and January 3, 2022.

The principal component 1 described 47.6% of the variation in soil temperatures. The temperature values for all survey dates had a high correlation with this principal component of the same sign. Thus, the principal component 1 reflects a time invariant pattern of soil temperature variability. The principal component 2 describes 30.2% of the variation in temperature indices. The correlation coefficients with this principal component show a stable trend of variability over time. In the initial stages, the measurements showed negative correlation coefficients with PC2. The correlation coefficients changed to positive over time. Thus, the principal component 2 reflected the temporal aspect of this soil temperature variability.

The variograms showed the presence of a spatial component of soil temperature variation
(figure 3). The variogram parameter range decreased consistently with time from 27.1 to 18.6 m (table 2). The spatial dependence level (SDL) decreased with time from 77.6 to 57.4%. The general pattern of soil temperature variability was very stable over time (figure 4). The PC1 variation pattern was characterised by a range which was 14.8 m and the SDL was 74.7%. The spatial variation of PC1 displayed a time invariant pattern of soil temperature (figure 5).

![Histograms of the distribution of soil temperature indicators on different dates.](image)

**Figure 2.** Histograms of the distribution of soil temperature indicators on different dates.

The PC2 variogram was characterised by a Range that was 12.7 metres and the SDL was 66.3%. The spatial variation of PC2 displayed a time-variant soil temperature pattern.

5. **Discussion**
During the study period, air temperature showed considerable variability, whereas soil temperature was subject to much less variability. The coefficient of variation of air temperature was 237%, while the level of variation of the soil temperature was much less and ranged between
Figure 3. Variograms of the soil temperature indicators on different dates (November 18 and 28, December 7, 12, and 20, 2021, and January 3, 2022) and the values of the principal components 1 and 2. Abscissa axis is lag (m), ordinate axis is semivariation. Spherical model.

19.9–46.5%. No correlation between the soil and air temperature was found. This is due to the fact that the studies were conducted in the cold period of the year, when the seasonal trend of air temperature change was stabilized and the main aspect of variability of meteorological conditions were significant temperature fluctuations, when short-term periods of warming alternated with periods of abrupt cooling.
Table 2. Parameters of variogram of spatial variation of soil temperature and principal components 1 and 2. SDL – spatial dependence level calculated as ratio of Partial sill to the sum of Partial sill and Nagget (in %).

| Parameter | 18.11 | 28.11 | 7.12  | 12.12 | 20.12 | 03.01 | PC1  | PC2  |
|-----------|-------|-------|-------|-------|-------|-------|------|------|
| Nagget    | 0.13  | 0.11  | 0.09  | 0.21  | 0.22  | 0.40  | 0.19 | 0.31 |
| Partial sill | 0.45 | 0.35  | 0.23  | 0.35  | 0.31  | 0.54  | 0.56 | 0.61 |
| Range, m  | 27.1  | 25.8  | 25.1  | 23.8  | 20.5  | 18.6  | 14.8 | 12.7 |
| SDL, %     | 77.6  | 76.1  | 71.9  | 62.5  | 58.5  | 57.4  | 74.7 | 66.3 |

The soil should be noted to have a high heat capacity, which provides considerable stability over time of the soil temperature regime. Soil is a powerful heat reservoir, acting as an energy store during the day and a source of heat through surface radiation at night. During the warm season the soil accumulates energy and during the cold season the soil radiates it to the atmosphere [56]. The soil temperature depends on the ratio of energy absorbed and energy lost from the soil [57,58]. Soil temperature oscillates over the course of the year and every day due to fluctuations in air temperature and solar radiation [56,59]. The overall trend of soil temperature variability corresponds to the seasonal climate variability: the soil temperature is generally decreasing, but the rate of this decrease is very low and much less than the air temperature variability. The decline is not monotonic, but deviations from the decreasing temperature trend are much smaller than large variations in air temperature. Urban green spaces are regarded as a suitable way of reducing the urban heat island effect and providing comfort for residents. In addition to cooling the actual space, urban green spaces are also capable of affecting the surrounding area, a phenomenon called the urban green space cooling effect [60]. Our results provide a broader perspective on the influence of parkland on the temperature regime of urban environments. Our results indicate that the soil of the park plantation acts as a stabiliser of the temperature regime of the urban environment. The positive soil temperature preserves the possibility of biological processes in the soil. Previous findings indicate that winter climate change will be a key driver of nitrogen dynamics in forest ecosystems over the next 50–100 years, with important consequences for ecosystem productivity [61]. The diversity of soil macrofauna in winter is strongly correlated with soil temperature and microbial biomass, and the abundance of soil macrofauna correlates significantly with the water content of the soil. Vegetation type and soil microbial dynamics have a strong influence on the diversity of soil macrofauna communities in winter, which further influences soil nutrient cycling and ecological processes [62]. The biological processes in winter in the conditions of the steppe zone of Ukraine occur at a sufficient level of moisture due to both the seasonal maximum of precipitation and a much lower level of water evaporation from the soil surface, which is proportional to the soil temperature. The favourable moisture conditions create a combination of aerobic and anaerobic conditions in the soil, which is most likely to promote the activity of humification and carbon sequestration processes in the soil.

The soil temperature field in the park plantation is not uniform and has a spatial regularity that results from the superposition of two components: the spatial component, which is invariant in time, and the spatial component, which indicates the varying intensity of temperature variability processes over time. This result is of particular importance because an increase in paired soil temperature difference between sites stimulates greater species turnover in plant and invertebrate communities [3]. The overall trend of decreasing temperature coincides with the trend of decreasing spatial component of soil temperature variability. When explaining the
spatial heterogeneity of the soil temperature field, the factors of soil properties heterogeneity come to the fore. In warm seasons, the factors that redistribute solar energy to the soil surface are crucial. These include the structure of tree crowns, shrub and grass cover, and forest litter. In late autumn and winter, the role of solar radiation as a factor of soil thermal regime is greatly reduced. We found that fog and cloud cover of 8-10 points were observed 74.1\% of the time. Moreover, it should be noted that in deciduous forest stands, the role of tree crowns as a factor distributing solar energy strongly decreases after the fall of leaves. An increase in soil temperature resulted in a decrease in the mean body mass of invertebrates and an increase in the total invertebrate community, which did not result in an overall change in community biomass [3]. Thus, the study of soil spatial heterogeneity in late autumn and winter allows us to evaluate the role of soil factors in forming spatial temperature patterns.

The soil thermal conductivity depends on the ratio of solid, liquid and gaseous soil phases.
Accordingly, we can explain the spatial patterns of soil temperature by the heterogeneity of the soil phase ratio, which is reflected in soil indices such as density, compactness and moisture content. The recreational load and technological processes in the park plantation are significant factors that influence the physical condition of the soil cover. Also important is the relaxation potential of the soil after recreational load, which depends on the granulometric and aggregate structure of the soil, the organic matter content and the activity of the soil biota. Also drivers of soil property variability are trees, which transmit wind energy through trunk oscillation to the root system, and oscillation attenuation energy causes changes in physical properties as the trees move away from the trunk. A positive stable soil temperature maintains conditions for active soil animals, which change soil properties as they burrow and involve dead organic matter in the soil profile. The activity of terrestrial biota decays after the onset of late autumn, but the activity of soil animals in the soil continues into winter, all the more so as the observed soil temperatures were positive.

Anthropogenic and natural factors in the park can alter the microrelief of the soil [63], which affects the redistribution of moisture [64,65]. The role of water increases considerably in the arid zone in winter, when rainfall is much higher than in summer. As a rule, the intensity of rain at this time is low, but drops of light rain have a greater destructive power than drops of intense rain, because in the latter case, intense rainfall results in a thin layer of water covering the soil, which has a protective function. In low-intensity rainfall, no protective layer of water is formed, the soil aggregates are destroyed and the soil is crusted due to colmatation [66]. The soil crust has a poor capacity for water infiltration, so it activates the lateral runoff [67], which greatly increases the role of microrelief as a factor regulating the distribution of moisture in space [68]. The role of recreational load, which leads to an increase in compactness and deterioration of the water-physical properties of the soil, should also be noted. The above-mentioned processes can explain formation of spatial temperature variability stable in time, which are described by PC1.

The occurrence of the principal component 2 reflects the existence of soil zones that differ in their cooling/heating dynamics over time. It is most likely that this difference can be explained by the unequal thickness of the leaf litter, which has a considerable thermal isolating capacity and affects the thermal regime of the soil [69]. Obviously, areas with a higher litter thickness will change their temperature more slowly, while areas with less or no litter thickness will cool more quickly or heat up more quickly [70]. The litter thickness depends on its redistribution within the space. Generally, the litter thickness is higher in the micro-depressions where the leaf litter accumulates. Also the thermal isolating capacity of the litter depends on its degree of

**Figure 5.** Spatial variation in the invariant component of temperature variability (principal component 1) and temporal component (principal component 2).
compactness and moisture content. The compactness changes under the influence of recreation and as a result of trophic activity of soil animals. Soil animals also regulate the litter storage, as they constantly macerate the litter or involve it in the soil profile [71]. The results allow us to determine the prospects for further research. Obtaining information about the spatial variability of the soil temperature fields of the park plantation during the whole year is undoubtedly necessary. We surveyed only a fragment of the end of autumn and beginning of winter. The observation of temperature dynamics under different meteorological conditions and at different phenological stages of living cover dynamics is important. It is necessary to clarify the role of the stand in the formation of temperature fields in different seasons of the year. In this regard, it is advisable to map the location of trees on the trial polygon and measure crown density and passing solar energy. It is also necessary to measure spatial variability of forest litter thickness and use the data obtained to explain spatial patterns of soil temperature. Information on soil properties such as moisture, density, soil penetration resistance, soil conductivity and aggregate structure can be expected to provide a better understanding of soil temperature variability processes.

6. Conclusion
The soil temperature regime is characterised by a significant level of stability compared to air temperature. The soil temperature fields in an artificial park plantation are characterized by spatial patterns of a complex nature. The temperature field presents a spatial component that is invariant to time. It is most likely that the spatial variability of soil properties induced by natural factors and recreation are the cause of the generation of this pattern. Also in the soil temperature field there is a spatial pattern, which reflects the different sensitivity of the soil to the seasonal trend of temperature change. The generation of this pattern is due to the different insulating capacity of the forest litter in the park plantation. The results obtained point to the important role of leaf litter as a factor in the dynamics of the soil temperature regime. It is hypothesized that leaf litter in the park contributes to the enhancement of carbon sequestration during winter time.

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References
[1] Brownmang O and Brown M 2018 Advances in Plants & Agriculture Research 8 34–37 URL https://doi.org/10.15406/apar.2018.08.00288
[2] Zhukov A and Gadorozhnaya G 2016 Ekológia (Bratislava) 35 263–278 URL https://doi.org/10.1515/eko-2016-0021
[3] Robinson S I, McLaughlin Ó B, Marteinsdóttir B and O’Gorman E J 2018 Journal of Animal Ecology 87 634–646 URL https://doi.org/10.1111/1365-2656.12798
[4] Pakhomov O Y, Kunah O M, Babchenko A V, Fedushko M P, Demchuk N I, Buzulha L S and Tkachenko O S 2019 Biosystems Diversity 27 322–328 URL https://doi.org/10.15421/011942
[5] Ponomareva T V, Litvintsev K Y, Finnikov K A, Yakimov N D, Sentyabov A V and Ponomarev E I 2021 Forests 12 994 URL https://doi.org/10.3390/f12080994
[6] Klein T, Kukkonen J, Dahl Å, Bossioli E, Bakanov A, Vik A F, Agnew P, Karatzas K D and Sofiev M 2012 AMBIO 41 851–864 URL https://doi.org/10.1007/s13280-012-0288-z
[7] Klimkina I, Kharytonov M and Zhukov O 2018 Environmental Research, Engineering and Management 74 82–93 URL https://doi.org/10.5755/j01.erez.74.2.19940
[8] Zhukov O, Kunah O, Dubinin A, Zhukova Y and Ganzha D 2019 Ekológia (Bratislava) 38 253–272 URL https://doi.org/10.2478/ekol-2019-0020
[9] Lehnert M 2013 Moravian Geographical Reports 21 27–36 URL https://doi.org/10.2478/mgr-2013-0014
[10] Zadorozhnaya G A, Andruşevych K V and Zhukov O V 2018 Folia Oecologica 45 46–52 URL https://doi.org/10.2478/foecol-2018-0005
[11] Rahman M N, Hangs R and Schoenau J 2020 *Journal of Plant Nutrition* **43** 823–833 URL: https://doi.org/10.1080/01904167.2020.1711941

[12] Zhukov O, Kunah O, Dubinina Y and Novikova V 2018 *Ekológia (Bratislava)* **37** 301–327

[13] Heinze J, Gensch S, Weber E and Joshi J 2016 *Journal of Plant Ecology* **10** URL https://doi.org/10.1093/jpe/rtw097

[14] Yorkina N, Zhukov O and Chrymsheva O 2019 *Ekológia (Bratislava)* **38** 1–10 URL https://doi.org/10.2478/eko-2019-0013

[15] Thakur M P, Reich P B, Wagg C, Fisichelli N A, Ciobanu M, Hobbie S E, Rich R L, Stefanski A and Eisenhauer N 2016 *Journal of Plant Ecology* **10** 670–680 URL https://doi.org/10.1093/jpe/rtw066

[16] Yorkina N, Maslikova K, Kunah O and Zhukov O 2018 *Ekológia (Bratislava)* **37** 301–327

[17] Zhukov O V, Kunah O M, Dubinina Y Y, Fedushko M P, Kotsun V I, Zhukova Y O and Potapenko O V 2019 *Folia Oecologica* **46** 101–114 URL https://doi.org/10.2478/foecol-2019-0013

[18] Broznič D and Milinčič 2012 *Journal of Environmental Science and Health, Part B* **47** 779–794 URL https://doi.org/10.1080/03601234.2012.676413

[19] Neira J, Ortiz M, Morales L and Acevedo E 2015 *Chilean journal of agricultural research* **75** 35–44 URL https://doi.org/10.4067/S0718-58392015000300005

[20] Yorkina N, Zhukov O, Fedushko M, Babchenko A and Umerova A 2021 *Ekológia (Bratislava)* **40** 178–188 URL https://doi.org/10.2478/eko-2021-0020

[21] Sándor R and Fodor N 2012 *The Scientific World Journal* **2012** 1–8 URL https://doi.org/10.1100/2012/590287

[22] Ramakrishna A, Tam H M, Wani S P and Long T D 2006 *Field Crops Research* **95** 115–125 URL https://doi.org/10.1016/j.fcr.2005.01.030

[23] Nikita-Martzopoulou C 1981 *Agricultural Meteorology* **24** 263–274 URL https://doi.org/10.1016/0002-1571(81)90050-9

[24] Oortuis R, Vaunat J, Hurlimann M, Lloret A, Moya J, Puig-Polo C and Fraccia A 2020 *Sustainability* **13** 1–8 URL https://doi.org/10.3390/su13010014

[25] Arkhangel'skaya T A and Umarova A B 2008 *Eurasian Soil Science* **41** 276–285 URL https://doi.org/10.1061/j.susc.2008.03009

[26] Karmakar R, Das I, Dutta D and Rakshit A 2016 *Science International* **4** 51–73 URL https://doi.org/10.15421/012101

[27] Kodzhaev A, Dakhov A and Zhukov O 2020 *Biosystems Diversity* **29** 1–9 URL https://doi.org/10.15421/012110

[28] Yin X and Arp P A 1993 *Canadian Journal of Forest Research* **23** 2521–2536 URL https://doi.org/10.1080/1093/93-313
[41] Mohanty B P, Klittich W M, Horton R and van Genuchten M T 1995 Soil Science Society of America Journal 59 752–759 URL https://doi.org/10.2136/sssaj1995.03615995005900030017x
[42] Dale R K and Miller D C 2007 Estuarine, Coastal and Shelf Science 72 283–298 URL https://doi.org/10.1016/j.ecss.2006.10.024
[43] Ma S, Concilio A, Oakley B, North M and Chen J 2010 Forest Ecology and Management 259 904–915 URL https://doi.org/10.1016/j.foreco.2009.11.030
[44] Redding T E, Hope G D, Fortin M J, Schmidt M G and Bailey W G 2003 Canadian Journal of Soil Science 83 121–130 URL https://doi.org/10.1016/S1543-3627(02)00056-6
[45] Seyfried M, Link T, Marks D and Murdock M 2016 Vadose Zone Journal 15 vzj2015.09.0128 URL https://doi.org/10.2136/vzj2015.09.0128
[46] Budakova V S, Yorkina N V, Telyuk P M, Umerova A K, Kunakh O M and Zhukov O V 2021 Biosystems Diversity 29 78–87 URL https://doi.org/10.15421/012111
[47] Kunakh O N, Kramarenko A V, Zadorozhnaya G A and Kramarenko A S 2018 Ruthenica 28 91–99
[48] Zhukov O, Kunah O, Dubininia Y and Novikova V 2018 Folia Oecologica 45 8–23
[49] Alasmary Z, Todd T, Hettiarachchi G M, Stefanovska T, Pidlisnyuk V, Roozeboom K, Erickson L, Davis L and Zhukov O 2020 Agronomy 10 1727 URL https://doi.org/10.3390/agronomy10111727
[50] Yorkina N V, Podorozhniy S M, Velcheva L G, Honcharenko Y V and Zhukov O V 2020 Biosystems Diversity 28 181–194 URL https://doi.org/10.15421/012024
[51] Kunakh O M, Yorkina N V, Zhukov O V, Turovtseva N M, Bredikhina Y L and Logvina-Byk T A 2020 Biosystems Diversity 28 3–8 URL https://doi.org/10.15421/012001
[52] Zhukov O V, Kunah O M and Dubininia Y Y 2017 Biosystems Diversity 25 328–341 URL https://doi.org/10.15421/011750
[53] Zhukov O, Kunah O, Dubininia Y, Ganga D and Zadorozhnaya G 2017 Ekologia (Bratislava) 36 352–365 URL https://doi.org/10.1515/eko-2017-0028
[54] Geiger R, Aron R and Todhunter P 2003 The climate near the ground (Rownaan and little field publishers, Inc)

[55] Oliver S, Oliver H, Wallace J and Roberts A 1987 Agricultural and Forest Meteorology 39 257–269 URL https://doi.org/10.1016/0025-1214(87)90042-6
[56] Barman D, Kundu D, Pal S, Pal S, Chakraborty A, Jha A, Mazumdar S, Saha R and Bhattacharyya P 2017 International Agrophysics 31 9–22 URL https://doi.org/10.1515/ijag-2016-0034
[57] Aram F, Higueras García E, Solgi E and Mansournia S 2019 Heliyon 5 e01339 URL https://doi.org/10.1016/j.heliyon.2019.e01339
[58] Durán J, Morse J L, Groffman P M, Campbell J L, Christenson L M, Driscoll C T, Fahey T J, Fisk M C, Mitchell M J and Templer P H 2014 Global Change Biology 20 3568–3577 URL https://doi.org/10.1111/gcb.12624
[59] Hu X, Yin P, Zeng S and Tong C 2018 IOP Conference Series: Earth and Environmental Science 170 022125 URL https://doi.org/10.1088/1755-1315/170/2/022125
[60] Salesa D and Cerdá A 2020 Journal of Environmental Management 271 110990 URL https://doi.org/10.1016/j.jenvman.2020.110990
[61] Bennett J A, Maherali H, Reinhart K O, Lekberg Y, Hart M M and Klironomos J 2017 Science 355 181–184 URL https://doi.org/10.1126/science.aai2812
[62] Mansouri M, Javadi S A, Jafari M and Arzani H 2021 SN Applied Sciences 3 381 URL https://doi.org/10.1007/s42452-021-04322-z
[63] Ho S, Fister W, Eckardt F, Palmer A and Kuhn N 2020 Land 9 503 URL https://doi.org/10.3390/land9120503
[64] Helalia A M, Letey J and Graham R 1988 Soil Science Society of America Journal 52 251–255 URL https://doi.org/10.2136/sssaj1988.03615995005200010044x
[65] Négyesi G, Szabó S, Buró B, Mohammed S, Lóki J, Rajkai K and Holb I J 2021 Agronomy 11 935 URL https://doi.org/10.3390/agronomy11050935
[66] MacKinney A L 1929 Ecology 10 312–321 URL https://doi.org/10.1088/1755-1315/1049/1/012056
[71] Xiao W, Ge X, Zeng L, Huang Z, Lei J, Zhou B and Li M 2014 PLoS ONE 9 e101890 URL https://doi.org/10.1371/journal.pone.0101890