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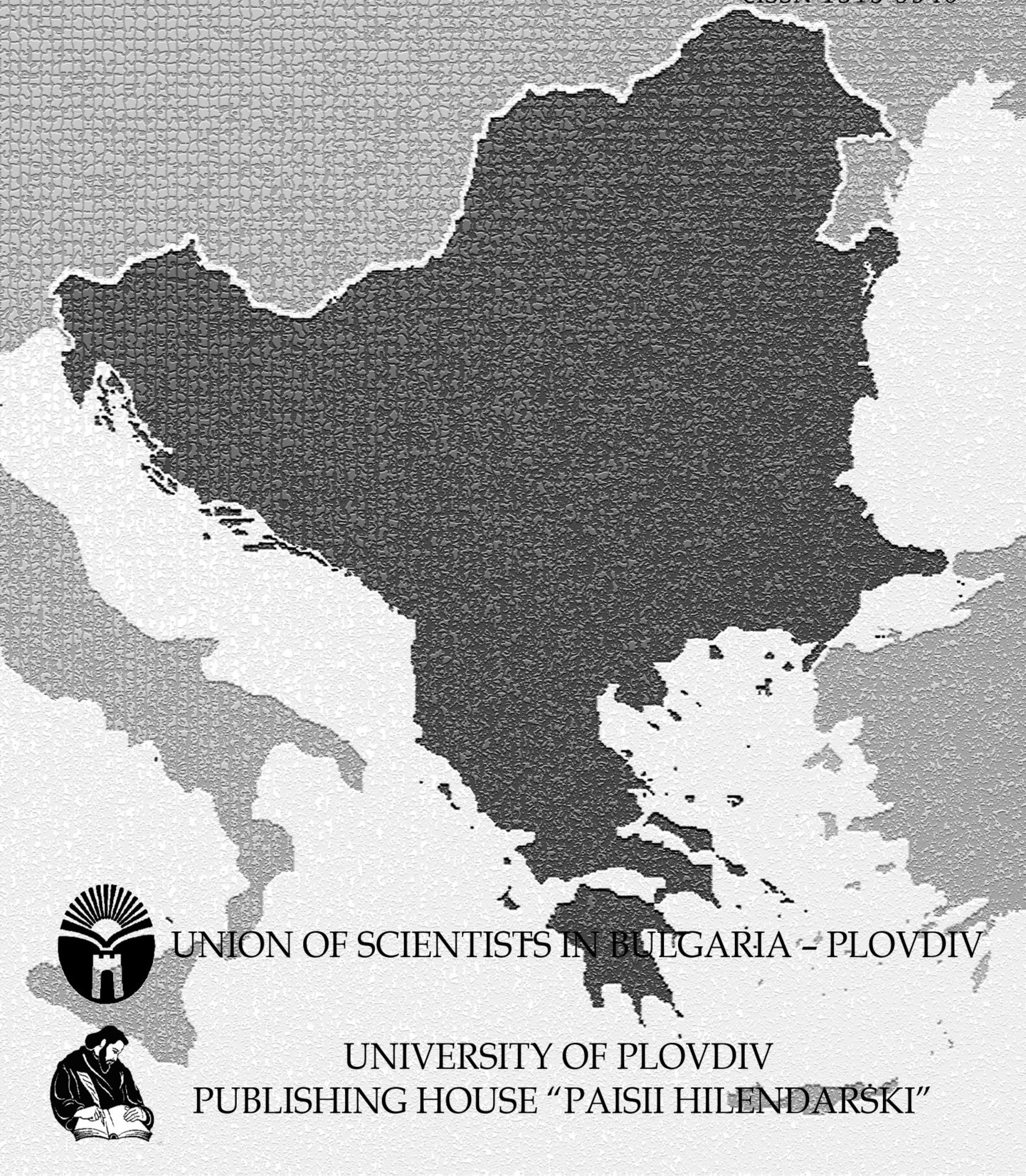

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Effect of Stand Density and Diversity on the Tree Ratio of Height to Diameter Relationship in the Park Stands of Southern Ukraine

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Abstract. The article investigated the influence of factors on the dependence of tree height on tree diameter in a park stand. The role of tree damage, density, and stand diversity as predictors in the dependence of tree height on its diameter was revealed. The hypothesis of the scale dependence of the influence of stand density on plant growth was tested. The number of plants that are within a radius of 3, 5, 7, 10 meters was determined for each of the recorded plant specimens. The diversity according Shannon of the plant community was estimated based on the information on the species composition of plants within a radius of 10 meters from the focal plant. The age of plants in the community was positively correlated with the diversity of vegetation in the surroundings of a particular plant. About 74.1% of the trees were found to have the signs of pathological damage. The best model to explain tree damage was a model that included as predictors plant species, its age, the diversity of the surrounding stand, and its density estimated from a 7-m radius sampling site. The GLM approach allowed to reveal that 83% of tree height variation can be explained by the information on tree and shrub species, plant condition (healthy plant or damaged one), its diameter and stand density. The stand density and the square of this index were found to be statistically significant predictors if the density was calculated for a sample area with a radius of 7 meters.

Key words: recreation, allometry, park management, ecosystem services, optimal density.

Introduction

Urban trees deliver ecosystem services including environmental regulation, resource provisioning, increasing biodiversity, and aesthetic enhancement (Song et al., 2020; Willis & Petrokofsky, 2017). The transformation of forest cover and the replacement of natural vegetation by buildings, roads, exotic vegetation, and other urban infrastructures is one of the greatest dangers to global biodiversity (Pereira et al., 2012). The trees in parks support biodiversity, store carbon, and improve microclimatic conditions (Heo et al., 2019; Kunakh et al., 2021). The trees in park plantations provide carbon sequestration by storing carbon as biomass (Nowak & Crane, 2002). As more and more land is set aside for urban development, identifying the effective wildlife management tools for urban forests becomes crucial for providing urban forest habitat to sustain bird and other wildlife populations (Lerman et al., 2014). The strategies for conserving and maintaining ecosystem services include efforts to reduce fragmentation, such as the creation of ecological networks. The parklands provide a landscape matrix that reduces fragmentation and contributes to biodiversity conservation (Watts et al., 2010). The formation of sustainable forest plantations in the urban environment provides normal living conditions for urban residents.

During the inventory process, landscape managers gather detailed information about trees that is needed for research and management (Berland & Lange, 2017; McPherson, 2014). The height to diameter ratio (HDR) is a tree-level slenderness index and is used to assess the stability of trees and stands (Vospernik et al., 2010). The variation in tree height-diameter ratios is important for a wide range of forest ecological problems. The variability in tree height-diameter ratios explains plant acclimation to the environment and tree competition for resources (Canham et al., 2006). Information about HDR is necessary to better understand forest ecological processes in a forest stand because this indicator depends on tree species, stand age, stand structure and density, soil type and moisture content, litter thickness, slope, elevation and exposure, stand development stage, climatic and natural disturbances (light, wind, snow, icing), forest care and species origin (Burton, 1993; Henry & Aarssen, 1999; Kamimura & Shiraishi, 2007).

Theoretical considerations and empirical studies of the height-diameter relationship show that it can be represented by an allometric function of diameter to the power of 2/3 (Greenhill, 1881; Norberg, 1988; O'Brien et al., 1995). The diameter of a tree's trunk can easily be measured (Song et al., 2020). The important tree parameters such as biomass and total leaf area can only be measured by destructive sampling. The allometric relationships allow to find the relationship between these parameters and can be used to study how tree biomass and structure change during growth (Mcpherson & Peper, 2012), and how the tree performance and benefits change over time (McPherson et al., 2016). An elastic stability and bending require trees to take a shape in which length increases in proportion to diameter in the power of 2/3 (McMahon, 1973). This relationship is appropriate for describing the properties of a column with equal bending and buckling resistance, which is a valid model for the tree trunks exposed to wind (Schniewind, 1962; Jaouen et al., 2007) and snow (King & Loucks, 1978; Fournier et al., 2013) in addition to gravity (Alméras & Fournier, 2009; Dargahi et al., 2019). Such a column maintains elastic similarity along the trunk (Rich, 1987). An elastic similarity results in $b=2/3$ and allows the tree to maintain a constant safety factor on both fracture and bending under the weight of the tree and wind force (McMahon, 1973; Dahle et al., 2017). There are also biological mechanisms beyond purely structural reasons for the existence of allometric dependence. Trees evolved not so much to align strength along the trunk (Fisler et al., 2020) as to even out damage to ensure survival (Vogt et al., 2015). Below the crown, this biological requirement is the same as the mechanical requirement, because in this range a break would destruct the tree to death. Inside the crown, the situation is different. The trees can survive the loss of a significant portion of the crown. Therefore, storing mass in the upper part of the trunk and crown is not biologically reasonable. Indeed, trees often lose their tops, most often in the upper third of the crown.

HDR is an index that is used to assess the sustainability of trees and stands (Sharma et al., 2019). Silvicultural systems that lead to high HD trees increase the risk of wind damage (Schelhaas, 2008; Wonn & O'Hara, 2001). High HDR values indicate that either the trees grew in a crowded stand with mutual support of neighboring trees, or they grew in an extremely open stand with no significant competition (Valinger &

Fridman, 2011; Vospernik et al., 2010). The variability in height to diameter ratio within and between habitat types may be either an adaptive or passive response to environmental gradients such as light, elevation, slope, aspect, or proximity to the coast (Schmidt et al., 2011). The ratio of tree height to trunk diameter also depends on the density of the stand: in a dense stand, trees with the same diameter are higher than in a less dense stand (Zeide & Vanderschaaf, 2002). The ratio of tree height and diameter is more variable in multi-species and multi-layered forests than in single-age, single-layer, and monodominant stands. The relationship between individual tree height and diameter in multispecies forests depends on the spatial distribution of trees in the stand, which is complicated by disturbances and changing stand dynamics (Schmidt et al., 2011). The relationship between height and diameter depends on height, aspect, slope, climate, and competition (Huang et al., 2000; Temesgen & Gadow, 2004). A stand at the forest edge, a stand in a large gap, or an unstable fragment of a stand are characterized by HDR features (Lohmander & Helles, 1987; Mitchell, 2013). HDR varies with tree spacing, even for the same species in the same stand, and extreme HDR can reach both extremely free stands and crowded stands (Nykänen et al., 1997). HDR also varies considerably in trees with an upper or lower canopy layer in the stand (Schmidt et al., 2010). HDR also depends on the root system of the tree, the width and length of the crown (Nykänen et al., 1997). The greatest influence on HDR is the distance between trees, competition, and stand density (Mäkinen et al., 2002; Slodicak & Novak, 2006).

The use of HDR information is essential for effective silviculture and forest management. By understanding the extent to which trees and stands are more susceptible to snow, icing, and wind damage, forest managers can better develop silvicultural prescriptions based on a range of HDRs (Nykänen et al., 1997; Valinger & Fridman, 1997; Wonn & O'Hara, 2001). HDR can be used to assess the efficiency and effectiveness of thinning, as thinning significantly affects HDR, both mid-stems and even the top layer of trees in a stand (Opio et al., 2000). The ratio of height to diameter is considered as an alternative to conventional procedures for assessing competition between cultivated trees and other vegetation (Opio et al., 2003). In addition, HDR can be used as an important predictor to describe the effects of competition in various forest models (MacDonald et al., 1990; Morris & MacDonald, 1991; Temesgen et al., 2005; Yang & Huang, 2018). HDR is used to assess tree viability and health. A tree with a higher HDR may have lower overall viability (Opio et al., 2000). HDR derived from any empirical HDR model can be viewed as a reference value that can be compared to HDR derived from tree height and diameter increase models, as well as height-diameter dependence models. Since HDR correlates significantly with tree crown ratio, trees with unfavorable properties of both HDR and crown ratio can be removed (Opio et al., 2003).

Thus, current knowledge suggests that HDR in natural forests or artificial plantations depends on tree species, stand age, stand structure, stand density, and a variety of other ecological parameters. The natural forests are examples of the most diverse ecological communities, while the forest plantations tend to be monodominant ecosystems. Urban parks have an intermediate position in terms of diversity between the natural forests and artificial plantations. However, there is very little information about what HDR in an urban park depends on. The objective of the study was to identify the factors that affect the dependence of tree height in a park stand on its diameter. We formulated the following hypotheses. Hypothesis 1. The probability of damage to trees in urban park plantations is decreased in more diverse stands. Hypothesis 2. The ratio of tree height to tree diameter depends negatively on damage, density, and positively on stand diversity. Hypothesis 3. The effect of urban park stand density is scale-dependent.

Materials and Methods

The Park-Monument of the landscape art of local importance "Healing Springs" was created by the decision of the Zaporizhzhya regional council from August 17, 1999 № 7 with the purpose of protection of the artificially created forest-park zone with natural healing springs. The park area of 3 hectares is located in the northern part of the village Terpeniya of Melitopol district of Zaporizhzhya region (Fig. 1). The area of the Park has a geometrically irregular configuration and extends from north-west to south-east for 392 m, and from north to south for 177 m. The average multi-year air temperature varied up to 2005 within 9.5°C, from 2005 till present time it was recorded at the level of 11.5°C. The average temperature in January was from –3.3°C to –3.5°C, in July 23.8°C with a tendency to increase. Since 2005, the minimum temperature was recorded at –26.3 (23.01.2006), and the maximum was 41°C (07.08.2010) (Solonenko et al., 2020). The temperature regime is unstable, especially in the spring and autumn periods, which negatively affects the artificial tree and shrub plantations (Koshelev et al., 2020a; Mirzoeva & Zhukov, 2021). Soil presented by Luvic chernozem developed in loess under native vegetation on ravine slopes (Soil profile classification according to IUSS Working Group WRB, 2015). In addition to precipitation, they receive surface runoff from the surrounding areas; groundwater may be encountered within 23 m (Yakovenko & Zhukov, 2021).

The transition of the average daily air temperature through 0°C occurs in spring on March 12, and in winter on December 5. Number of days with average daily temperature above 0°C is more than 270 days (Koshelev et al., 2020b).

The transition of the average daily air temperature over 10 ° C occurs in spring on April 20, and in autumn on October 17, and the number of days with a temperature above 10°C is 180 days. The sum of active air temperatures above 10°C exceeds 3200°C. The duration of frost-free period in the air is about 200 days. According to the scheme of agroclimatic zoning, the study area is located within the very warm and very dry agroclimatic area. The precipitation pattern is continental in character, with maximums in spring and summer and minimums in winter. The annual precipitation is unstable and fluctuates within 320–360 mm. The lowest precipitation is observed in March–April (25–30 mm). Then a gradual increase in precipitation begins, which lasts until June. Precipitation falls in the form of rain and snow, in the summer period there are often showers (Shcherbyna et al., 2021).

The assessment of the state of damage to trees and shrubs in the park was conducted in accordance with municipal standards that are specified in the "Instruction on technical inventory of green areas of SCN 03.08.007–2007 in cities and towns of urban type in Ukraine (2007) (Instruction, 2002). According to the Instruction damaged trees were determined by the following attributes: trees are very weakened, trunks curved, crowns poorly developed, dry and drying branches, growth of one-year shoots is insignificant, mechanically damaged trunks, there are hollows. During the inventory, the following information was recorded to the accounting information: the number of the accounting area (quarter), plant coordinates, type of plantings, species name of trees or shrubs, age, height, trunk diameter at 1.3 m height, number of trees in the quarter and their state. Species name of trees and shrubs were given according to the database The Plant List (TPL). During the tree survey, the length of the trunk circumference was measured, and then the trunk diameter was calculated using the formula C = 2πR. Tree heights were measured with a Nikon "Forestry 550" laser rangefinder. The age of the trees was determined by the analysis of biometric indicators (measurements of the stem diameter and height) (Erokhina et al., 1987). The ecological groups of trees and shrubs were represented according to V. Tarasov (Tarasov, 2012). The information obtained is summarized in a geographic database in ArcMap 10.8. ESRI Inc.

The number of plants that are within a radius of 3, 5, 7, 10 meters was determined for each of the recorded plant specimens (focal plant). Smaller distances are limited by the resolution of the tree coordinate record. Preliminary calculations showed that distances greater than 10 meters give statistically poorer results than estimates based on 10 meters, so we chose this distance as the upper limit. Based on the data obtained, the density of the stand was calculated:

$$H = \sum_{i=1}^{S} (-1 \times \frac{n_i}{N} \times log_2 \frac{n_i}{N}),$$

where H is Shannon diversity index, S is the species number, i is sequence number of the species in the community, n_i is the number of specimens of the i-species, N is the number of all plants within 10 meters of the focal plant.

To explain the probability of plant damage, Generalized Additive Models (GAMs) were tested with plant species identity, plant age, diversity of the surrounding plant community within 10 meters, and stand density (within 3, 5, 7, and 10 meters of the focal plant). Akaike weights were used to select the best model (Wagenmakers & Farrell, 2004).

The dependence of the height was described by an allometric function on the diameter in the power b equal to 2/3 (Greenhill, 1881; Zeide & Vanderschaaf, 2002):

$$H = a\ D^b,$$

where H – tree height, D – tree diameter, a and b – allometric coefficients.

The species identity of the plant, plant condition (healthy and damaged), and stand density (within 3, 5, 7, and 10 meters of the focal plant) were considered as additional predictors of the height-diameter relationship. For statistical analyses, the information on 13 plant species that were encountered more than 10 times was used. A total of 14 species were encountered less than 10 times, so information about them was used only for the ecological analysis. The dependence was fitted using the General Linear Model (GLM). The descriptive statistics, GLM, and GAMs were calculated using the software program Statistica (Statsoft).

Results

The plant community in the park was represented by 27 species of trees and shrubs (Table 1).

The most frequent species was *Ulmus caprinifolia*. This species accounted for 35.0% of the total number of tree specimens within the park (Table 2, 3). *Acer negundo* and *Crataegus pentagyna* were also important in the plant community, accounting for 20.9 and 11.1%, respectively. Phanerophytes accounted for 66.7% of the community species, and nanophanerophytes accounted for 33.3%, respectively. Mesotrophs (74.1%) dominated among the ecological groups that were distinguished on the basis of plant preference for soil fertility conditions. Accordingly, megatrophs were 25.9%. In respect to preference of moisture conditions, mesoxerophytes prevailed in the community (42.2% of the total number of species) and the proportion of xeromesophytes was very high in the community (33.3%).

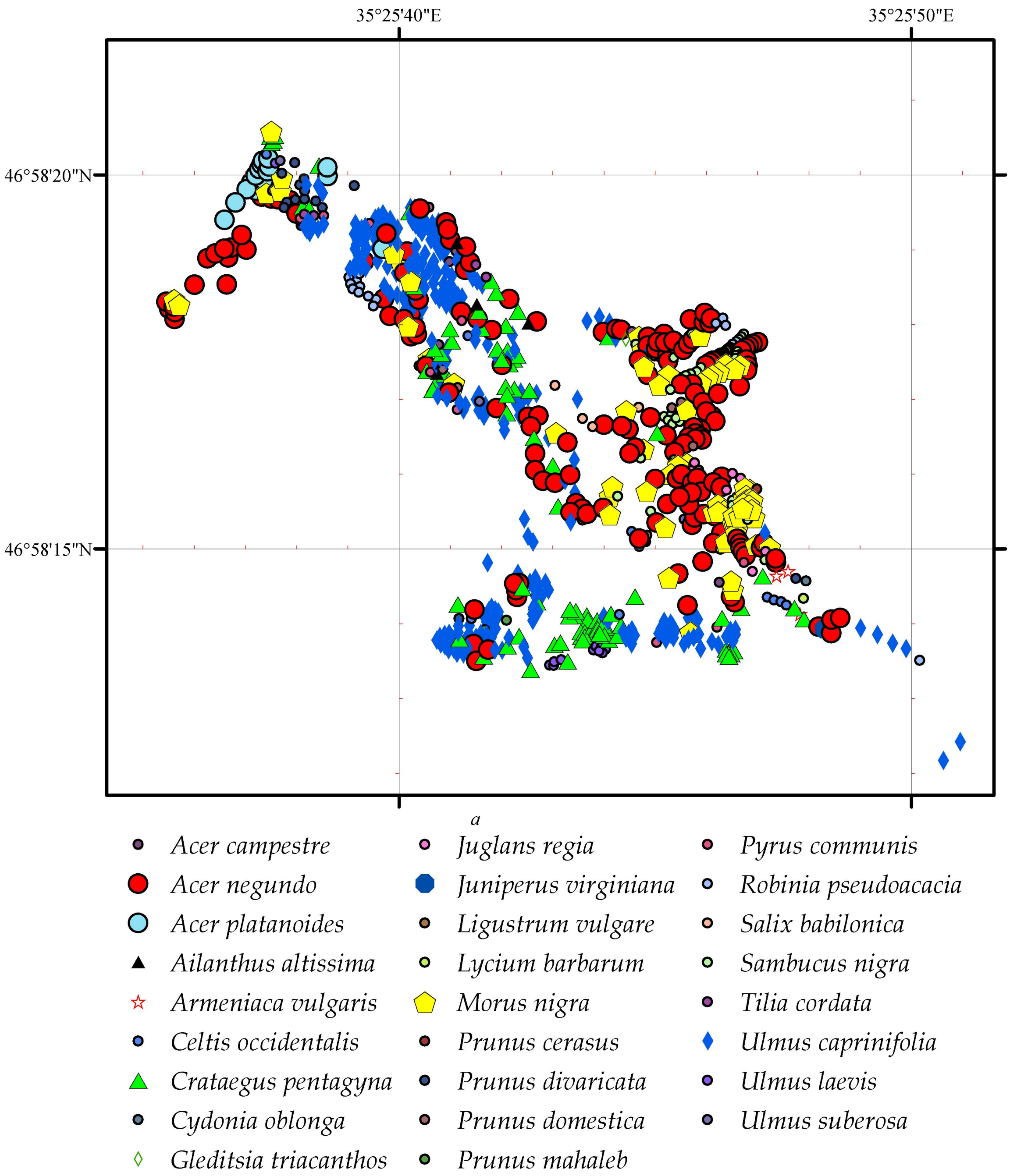

Fig. 1. Position of the park "Healing Springs" and location of tree species within the park.

Table 1. Age, species diversity and ecological groups of trees and shrubs in the park. *Legend:* *: Ph – phanerophytes; nPh – nanophanerophytes; **: MsTr – mesotrophic (plants prefer moderately fertile soils), MgTr – megatrophic (plants prefer highly fertile soils); ***: X – xerophytes (plant adapted to life in a dry habitat), MsX – mesoxerophytes (xerophytes are more demanding to the presence of available moisture), XMs – xeromesophytes (mesophytes, which are able to inhabit more dry conditions), Ms – mesophytes (a plant adapted to life in a moderately humid habitat or, in other words, not adapted to particularly

dry or particularly humid habitats); ****: He – heliophytes (plants of open places, which are located under direct sunlight), ScHe – scyoheliophytes (plants of light forests and shrubs, or tall herbaceous communities; the lower layers are in the shade), HeSc – helioscyophytes (plants of light coniferous and sparsely closed deciduous forests), Sc – scyophytes (plants of typical deciduous forests).

Species	Raunkiær plant life-form*	Ecological groups in relation to			Origin	Age, years		
		soil fertility**	soil humidity***	light****		Mean±st. error	Minimum	Maximum
Acer negundo L.	Ph	MsTr	XMs	HeSc	Adventive	44.2±2.17	3	100
Acer campestre L.	Ph	MsTr	XMs	Sc	Autochthonous	24.6±13.88	7	80
Morus nigra L.	Ph	MsTr	XMs	He	Autochthonous, Cultural	28.3±3.19	5	95
Acer platanoides L.	Ph	MgTr	Ms	Sc	Autochthonous	8.1±1.04	6	23
Celtis occidentalis L.	Ph	MsTr	XMs	Sc	Adventive	24.1±5.78	2	90
Crataegus pentagyna Waldst. & Kit. ex Willd.	nPh	MsTr	MsX	ScHe	Autochthonous	41.1±1.32	18	80
Tilia cordata Mill.	Ph	MgTr	XMs	Sc	Autochthonous	40.5±15.65	3	85
Prunus cerasifera Ehrh.	nPh	MsTr	MsX	He	Adventive, Cultural	19.7±1.55	10	30
Prunus domestica A.Sav.	Ph	MsTr	MsX	He	Adventive, Cultural	36.8±4.75	11	85
Pyrus communis Gouan	Ph	MgTr	MsX	Sc	Autochthonous	21.6±0.87	5	90
Ulmus minor Mill.	Ph	MsTr	X	ScHe	Autochthonous	20.9±2.18	13	32
Ulmus laevis Pall.	Ph	MsTr	Ms	Sc	Autochthonous	18.3±1.67	15	20
Ulmus suberosa Moench	Ph	MsTr	MsX	Sc	Autochthonous	11.2±2.60	5	20
Ailanthus altissima (Mill.) Swingle	Ph	MsTr	XMs	ScHe	Adventive	19.8±1.60	10	30
Rosa sp.	nPh	MsTr	XMs	He	Autochthonous	–	–	–
Robinia pseudoacacia L.	Ph	MgTr	MsX	ScHe	Adventive	21.0±4.25	5	70
Styphnolobium japonicum (L.) Schott	Ph	MsTr	XMs	ScHe	Adventive	60.0±20.00	40	80
Sambucus nigra L.	nPh	MgTr	Ms	Sc	Autochthonous	38.4±1.66	20	50
Gleditsia triacanthos L.	nPh	MsTr	MsX	He	Adventive	10.0	10	10
Ligustrum vulgare L.	nPh	MsTr	MsX	Sc	Adventive	20.0	20	20
Salix babylonica L.	nPh	MsTr	Ms	HeSc	Adventive	38.8±8.51	25	60
Juglans regia L.	Ph	MgTr	MsX	He	Adventive	34.6±8.94	12	90
Prunus cerasus L.	Ph	MgTr	XMs	Sc	Cultural	40.0	40	40
Prunus armeniaca L.	Ph	MsTr	MsX	He	Adventive, Cultural	23.3±8.82	10	40
Lycium barbarum L.	nPh	MsTr	MsX	He	Adventive, Cultural	2.0	2	2
Cydonia oblonga Mill.	nPh	MsTr	MsX	He	Adventive, Cultural	25.0	25	25
Juniperus virginiana L.	Ph	MsTr	MsX	ScHe	Adventive	10.0	10	10

Xerophytes were rare (3.7%). The proportion of mesophytes in the community was not high (14.8%). The plant community was dominated by species of marginal ecological groups in the light regime gradient, such as heliophytes (33.3%) and sciophytes (37.0%). The species of transitional ecological groups were less present in the community. The heliophytes accounted for 7.4% of the total number of species in the community, and the sciogeliophytes accounted for 22.2%. Adventive species accounted for 59.3% of the total number of species, and autochthonous species accounted for 40.7%. Cultivated species accounted for 25.9%.

Plant community diversity ranged from 0.05 to 2.85 bits/species (mean 1.44±0.019 bits/species) (Fig. 2). Species differed in the diversity of their surroundings ($F = 7.47$, $p < 0.001$). The lowest diversity of surroundings was found for *Acer campestre* (0.66±0.08 bit/species), *Robinia pseudoacacia* (1.24±0.11 bit/species), *Ulmus caprinifolia* (1.27±0.03 bit/species), *Crataegus pentagyna* (1.36±0.07 bit/species). The highest diversity of surroundings was found for *Ailanthus altissima* (1.80±0.20 bit/species), *Prunus domestica* (1.80±0.10 bit/species), *Ligustrum vulgare* (1.81±0.12 bit/species), *Prunus divaricata* (2.09±0.07 bit/species). There was a negative correlation between diversity and vegetation density ($r = -0.21$, $p < 0.001$). Thus, more dense vegetation cover was more uniform. A positive correlation was found between plant diversity and stem width of *Ulmus caprinifolia* ($r = 0.13$, $p < 0.001$), *Ulmus laevis* ($r = 0.74$, $p < 0.001$), *Sambucus nigra* ($r = 0.39$, $p < 0.001$). A negative correlation was found between diversity of surroundings and trunk width of *Ligustrum vulgare* ($r = -0.57$, $p < 0.001$). No correlation of diversity was found with plant height. The plant community diversity in the surroundings of healthy plants was higher than in the surroundings of damaged plants ($F = 35.9$, $p < 0.001$). The diversity in the surroundings of healthy plants averaged 1.66±0.032 bits/species, and in the surroundings of damaged plants averaged 1.37±0.023 bits/species.

The Gaussian mixture model allowed to estimate the distribution parameters of the three distributions that compose the final distribution of tree ages in the park plantation: age 14.0±4.50 years (48.3% of plants in the community), age 38.2±13.64 years (44.1% of plants in the community), and age 85.5±6.84 years (7.5% of plants in the community) (Fig. 3). The age of plants in the community as a whole was positively correlated with the diversity of vegetation in the surroundings of a particular plant ($r = 0.11$, $p < 0.001$). A correlation of individual plant species age and plant community diversity was found for *Ulmus caprinifolia* ($r = 0.12$, $p = 0.038$), *Ulmus laevis* ($r = 0.70$, $p = 0.025$), *Juglans regia* ($r = 0.83$, $p = 0.020$).

Table 2. Descriptive statistics of morphometric traits of tree and bush species in park plantations.

Species	Total (N, mean ± st. error)			Healthy tree (N, mean ± st. error)			Tree with signs of pathology (N, mean ± st. error)		
	N	H, meters	D, cm	N	H, meters	D, cm	N	H, meters	D, cm
A. negundo	170	8.48 ± 0.29	25.86 ± 1.21	100	8.50 ± 0.39	30.36 ± 1.65	70	8.44 ± 0.43	19.43 ± 1.45
A. campestre	5	5.10 ± 1.27	14.33 ± 5.83	2	4.00 ± 1.00	6.37 ± 1.27	3	5.83 ± 2.09	19.64 ± 8.81
M. nigra	71	6.75 ± 0.51	18.02 ± 1.83	19	9.42 ± 1.28	33.57 ± 4.64	52	5.77 ± 0.46	12.33 ± 1.06
A. platanoides	17	5.50 ± 0.53	8.39 ± 0.70	8	4.75 ± 0.53	8.28 ± 0.99	9	6.17 ± 0.86	8.49 ± 1.03
C. occidentalis	15	5.82 ± 0.96	14.67 ± 3.62	3	7.17 ± 3.42	28.87 ± 14.24	12	5.48 ± 0.94	11.12 ± 2.43
C. pentagyna	90	5.06 ± 0.25	12.86 ± 0.59	22	5.39 ± 0.71	16.06 ± 1.65	68	4.96 ± 0.23	11.82 ± 0.52
T. cordata	6	7.90 ± 2.70	25.47 ± 9.48	3	10.43 ± 3.92	35.77 ± 13.99	3	5.37 ± 3.82	15.16 ± 12.16
P. cerasifera	16	4.66 ± 0.18	9.89 ± 0.97	4	5.00 ± 0.21	14.89 ± 0.68	12	4.54 ± 0.23	8.22 ± 0.82
P. domestica	12	5.13 ± 0.74	11.73 ± 1.74	5	4.20 ± 1.46	13.25 ± 4.02	7	5.79 ± 0.72	10.65 ± 1.18
P. communis	16	7.64 ± 0.85	19.61 ± 2.79	5	8.40 ± 1.75	27.26 ± 6.25	11	7.29 ± 0.99	16.13 ± 2.45

U. minor	285	6.71 ± 0.21	12.74 ± 0.47	25	5.76 ± 0.94	17.62 ± 2.91	260	6.80 ± 0.21	12.27 ± 0.43
U. laevis	11	9.77 ± 0.77	16.68 ± 1.49	5	9.50 ± 1.79	19.11 ± 3.02	6	10.00 ± 0.35	14.65 ± 0.45
U. suberosa	3	3.67 ± 0.67	9.77 ± 1.66	–	–	–	3	3.67 ± 0.67	9.77 ± 1.66
A. altissima	5	5.40 ± 0.87	9.55 ± 1.65	2	7.00 ± 1.00	13.06 ± 1.27	3	4.33 ± 0.88	7.22 ± 1.29
Rosa sp.	1	2.00	1.00	–	–	–	1	2.00	1.00
R. pseudoacacia	19	5.65 ± 0.67	10.66 ± 1.87	5	6.80 ± 1.74	19.04 ± 5.19	14	5.24 ± 0.68	7.67 ± 0.99
S. japonicum	2	11.00 ± 1.00	30.57 ± 8.92	–	–	–	2	11.00 ± 1.00	30.57 ± 8.92
S. nigra	36	2.81 ± 0.10	11.78 ± 0.72	13	2.58 ± 0.22	15.73 ± 1.03	23	2.95 ± 0.09	9.55 ± 0.58
G. triacanthos	1	3.50	6.37	–	–	–	1	3.50	6.37
L. vulgare	14	2.71 ± 0.10	2.93 ± 0.05	6	2.33 ± 0.11	2.83 ± 0.11	8	3.00 ± 0.08	3.00 ± 0.07
S. babylonica	4	15.50 ± 2.99	50.62 ± 14.62	2	20.00 ± 2.00	71.94 ± 6.69	2	11.00 ± 3.00	29.30 ± 18.15
J. regia	8	5.70 ± 1.20	15.84 ± 3.92	3	6.33 ± 2.85	21.44 ± 10.04	5	5.32 ± 1.22	12.48 ± 2.29
P. cerasus	1	9.00	26.11	–	–	–	1	9.00	26.11
P. armeniaca	3	5.00 ± 2.00	16.24 ± 5.79	1	3.00 ±	15.92 ±	2	6.00 ± 3.00	16.40 ± 10.03
L. barbarum	1	1.20	1.00	–	–	–	1	1.20	1.00
C. oblonga	1	3.00	9.55	–	–	–	1	3.00	9.55
J. virginiana	1	3.00	7.96	–	–	–	1	3.00	7.96
Total	814	6.58 ± 0.13	16.07 ± 0.44	233	7.20 ± 0.29	24.31 ± 1.11	581	6.36 ± 0.14	12.76 ± 0.34

As the radius of the sample site increases, the density raster generalizes, but the value of stand density decreases (Fig. 4). A regression relationship was found between the radius of the sample site and the average density of the stand:

$$Y = 7.2 \text{ x } X^{-0.73} \ (R^2 = 0.99),$$

where Y is the mean density of the stand, ex./100 m^2, X is the radius of the sampling site, m.

A regression relationship between the radius of the sample site and the maximum density of the stand was found:

$$Y = 58.7 \text{ x } X^{-1.0067} \ (R^2 = 0.99),$$

where Y is the maximum of the stand density, ex./100 m^2, X is the radius of the sampling site, m.

About 74.1% of the trees were found to have the signs of pathological damage. The plant species that were rarely found in the plantation had signs of damage in 100% of cases. For the rest plants, there was a tendency for the degree of damage to increase with increasing presence in the community. A positive correlation ($r = 0.69$, $p < 0.001$) was found between the level of damage of a particular species and its abundance in the community. *A. negundo* was an exception to this trend. This species was second in the community in terms of dominance, but its damage rate was relatively low (41.2%). The best model to explain tree damage was a model that included as predictors plant species, its age, the diversity of the surrounding stand, and its density estimated from a 7-m radius sampling site (Table 4). As the age and density of the stand increases, the probability of pathological plant damage increases. The diversity of the stand around a given plant reduces the probability of plant damage.

Table 3. Descriptive statistics of height to diameter ratio (HDR) and allometric coefficient of tree and bush species in park plantations. *Note:* a^* – allometric coefficient derived from the equitation $H = a D^b$ where H – tree height, D – tree diameter, b=2/3.

Species	Total (N, mean ± st. error)			Healthy tree (N, mean ± st. error)			Tree with signs of pathology (N, mean ± st. error)		
	N	HDR	*a**	N	HDR	*a*	N	HDR	*a*
A. negundo	170	2.97±0.08	0.93±0.03	100	3.52±0.09	1.04±0.04	70	2.19±0.09	0.77±0.04
A. campestre	5	2.55±0.42	0.62±0.16	2	1.61±0.08	0.38±0.05	3	3.18±0.30	0.78±0.23
M. nigra	71	2.51±0.09	0.71±0.05	19	3.56±0.11	1.10±0.11	52	2.13±0.04	0.57±0.03
A. platanoides	17	1.56±0.05	0.45±0.02	8	1.74±0.06	0.45±0.03	9	1.40±0.04	0.46±0.04
C. occidentalis	15	2.39±0.27	0.62±0.10	3	4.00±0.35	0.99±0.33	12	1.99±0.19	0.52±0.08
C. pentagyna	90	2.62±0.06	0.60±0.02	22	3.16±0.11	0.69±0.05	68	2.45±0.06	0.57±0.02
T. cordata	6	2.83±0.29	0.87±0.25	3	3.36±0.10	1.15±0.34	3	2.30±0.37	0.58±0.35
P. cerasifera	16	2.10±0.17	0.50±0.03	4	2.98±0.14	0.67±0.02	12	1.81±0.14	0.45±0.03
P. communis	16	2.53±0.17	0.78±0.07	5	3.27±0.20	0.98±0.15	11	2.20±0.14	0.69±0.07
U. minor	285	1.99±0.04	0.58±0.01	25	3.25±0.12	0.71±0.07	260	1.87±0.03	0.57±0.01
U. laevis	11	1.78±0.14	0.72±0.04	5	2.16±0.20	0.78±0.09	6	1.46±0.05	0.66±0.01
U. suberosa	3	2.69±0.26	0.50±0.06	–	–	–	3	2.69±0.26	0.50±0.06
A. altissima	5	1.76±0.06	0.49±0.06	2	1.88±0.09	0.62±0.04	3	1.68±0.05	0.41±0.05
P. domestica	12	2.46±0.24	0.56±0.05	5	3.26±0.26	0.60±0.12	7	1.89±0.13	0.53±0.04
Rosa sp.	1	0.50	0.11	–	–	–	1	0.50	0.11
R. pseudoacacia	19	1.82±0.14	0.51±0.06	5	2.73±0.13	0.77±0.14	14	1.49±0.08	0.42±0.04
S. japonicum	2	2.73±0.56	1.08±0.21	–	–	–	2	2.73±0.56	1.08±0.21
S. nigra	36	4.37±0.31	0.57±0.02	13	6.36±0.40	0.69±0.03	23	3.24±0.18	0.50±0.02
G. triacanthos	1	1.82	0.38	–	–	–	1	1.82	0.38
L. vulgare	14	1.09±0.03	0.23±0.00	6	1.22±0.01	0.22±0.01	8	1.00±0.04	0.23±0.03
S. babylonica	4	3.00±0.54	1.46±0.33	2	3.60±0.03	1.92±0.12	2	2.39±1.00	1.01±0.45
J. regia	8	2.77±0.18	0.68±0.10	3	3.33±0.08	0.82±0.26	5	2.43±0.11	0.59±0.07
P. cerasus	1	2.90	0.98	–	–	–	1	2.90	0.98
P. armeniaca	3	3.46±0.96	0.69±0.17	1	5.31	0.70	2	2.53±0.41	0.68±0.30
L. barbarum	1	0.83	0.11	–	–	–	1	0.83	0.11
C. oblonga	1	3.18±	0.50	–	–	–	1	3.18	0.50
J. virginiana	1	2.65	0.44	–	–	–	1	2.65	0.44
Total	814	2.44±0.04	0.67±0.01	233	3.41±0.08	0.88±0.03	581	2.05±0.03	0.58±0.01

The GLM approach allowed to reveal that 83% of tree height variation can be explained by the information on tree and shrub species, plant condition (healthy plant or damaged one), its diameter and stand density (Table 5, 6). The width of the tree trunk was the most informative predictor of height. Other predictors should be considered as the factors that deviate the biologically determined dependence from the ideal form. The pathologic states of trees and shrubs resulted in an average 10.3% reduction in the tree height at a given diameter (F = 3656.3, p = 0.001) (Table 5). The effect of damage on the height of trees and shrubs depended on the species. For *Ailanthus altissima* and *Acer campestre* species, the individuals with signs of pathology were more elongated compared to healthy ones. For other species, healthy individuals were more elongated. This trend was greatest for *Sambucus nigra*, *Celtis occidentalis*, and *Acer negundo*. The calculation of the degree of height reduction for the lowest weighted estimates of the mean indicated a value of 29.1%. The estimation of the role of stand density to explain the variation in tree height depended on the radius of the sample site size. The stand density and the square of this index were found to be statistically significant predictors if the density was calculated for a sample area with a radius of 7 meters. The density quadrant was a significant predictor if the density was calculated for sampling areas with a radius of 5 meters. The stand densities were not statistically significant predictors if the measurements were made for 3-meter and 10-meter radius sampling areas. A quadratic form of the dependence indicates the presence of the maximum of the function. In natural units, the regression coefficients take values of 0.1164 for the linear term and –0.00623 for the quadratic term. The calculations showed that the first derivative of the quadratic function is equal to zero at a density of 9.3 individuals in a sample area with a radius of 7 meters, or 3.0 plants per 100 meters^2. Accordingly, the plant height reaches the maximum at these values. When density deviates upward or downward, the plant height at a given diameter decreases. The predictor that indicated the interaction of species and stand density factor was not statistically significant. Therefore, the above optimal value of park stand density, at which the greatest plant growth can be expected, should be recognized as applicable for all the species studied.

Discussion

The studied park plant community has a high level of taxonomic diversity. It includes both autochthonous and adventive species. The adventive species are widely used in the design of park plantings (Blinkova, 2017; Burda & Koniakin, 2019). These species are often marked by an aesthetic attraction and a high ecological stability (Andrea et al., 2020). However, the acclimation of non-native species in botanical gardens and parks has its own negative consequences. Many adventive species, which are now weeds, were acclimatized to botanical gardens as exotic ornamental plants (Mayer et al., 2017). Despite the diversity of geographical sources of the flora of the park plantation, the plant species are highly ecologically similar. This similarity can be explained by the action of the ecological filter, which creates conditions for the normal existence only for species that are adapted to the conditions presented in the park environment (Duflot et al., 2014). The main factor determining the successful introduction of alien species into resident plant communities is ecological filtration, which is expressed in a similar distribution of ecological traits (Zhukov et al., 2017; Divíšek et al., 2018). Such similarity is also the basis for considering plant species as indicators of environmental properties.

Herbaceous plants play a special role in phytoindication of environmental conditions (Zhukov et al., 2018, 2019;Zhukova et al., 2020). Trees have a special role in the typology of forest vegetation (Belgard, 1950; Nazarenko, 2016). The forest type is considered as a combination of trophic and moisture conditions of the ecotope. Trees are considered to be more sensitive to the trophic conditions, while herbaceous plants are more sensitive to the moisture conditions (Zhukov & Shatalin, 2016; Yorkina et al., 2020). These assumptions apply to the natural forests in the steppe zone, but our results confirm this conclusion for artificial park plantations as well (Zhukov et al., 2021). The community is dominated by plants that are very sensitive to the soil fertility. The Calcic chernozem, on which the studied park is formed, is known to have a high level of fertility (Yakovenko, 2017). The positive effect of artificial tree plantations on the fertility of this soil type was also recorded (Gorban et al., 2020). At the same time, ecological groups in relation to the moisture conditions are represented by a wide range from xerophiles to mesophiles. This suggests that the trophic conditions of the ecotope that are the limiting factor that acts as an ecological filter for the selection of species capable of existing in the community. In this connection, a hypothesis can be formulated that species whose ecological optimum deviates from the typical ecotope ecological regimes will be confirmed to be at greater risk of damage.

Naturalization is the process of transforming urban forests into a state compositionally, structurally, and functionally similar to the natural forests that are in the proximity of the city (Maltsev et al., 2017; Kunakh et al., 2020). The positive correlation between the age of plants and the diversity of their environment can be explained by the processes of community development and naturalization. The different-aged plants were found to be represented in the community. The probability of occurrence of younger plants of another species in the surrounding increases with the age of the focal plant (Moreira et al., 2017). Neighboring plants can decrease or increase the likelihood of damage to each other through associative resistance or susceptibility, respectively (Kim, 2017). This suggests an alternative interpretation, which is that in a more diverse community, the probability of surviving to a greater age is higher. This assumption is supported by the fact that the number of healthy plants is higher in more diverse communities.

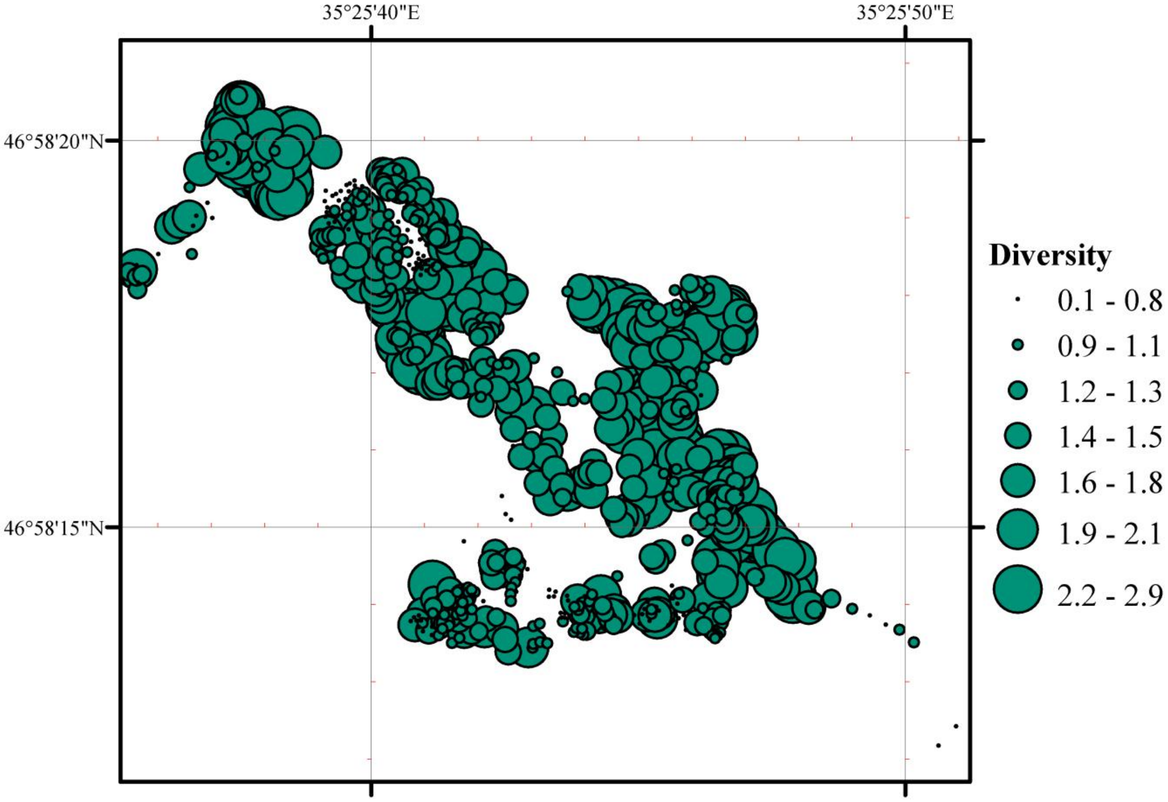

Fig. 2. Shannon diversity of the stand within 10 meters of the focal tree.

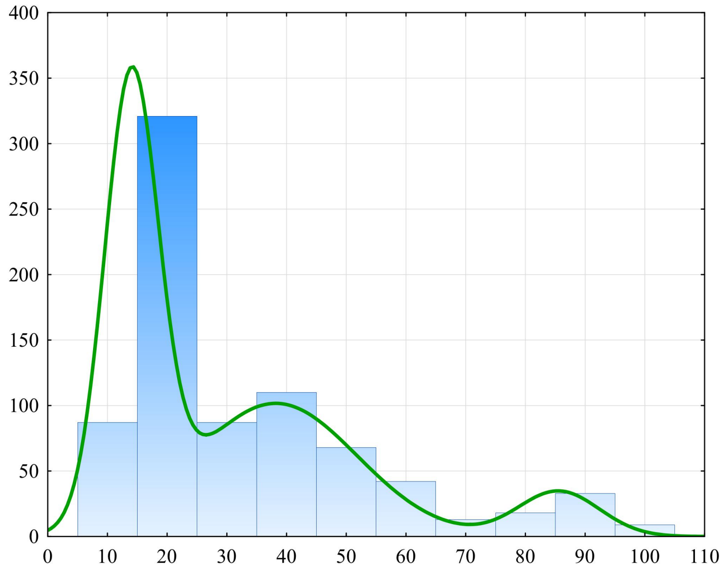

Fig. 3. Age distribution of tree and shrub plants in the park plantation. The abscissa axis is the age of trees, years; the ordinate axis is the number of trees. The green line denotes the hypothetical mixture of the three distributions. Gaussian mixture model revealed parameters of the three distribution: age 14.0±4.50 years (48.3% of plants in the community), age 38.2±13.64 years (44.1% of plants in the community), and age 85.5±6.84 years (7.5% of plants in the community).

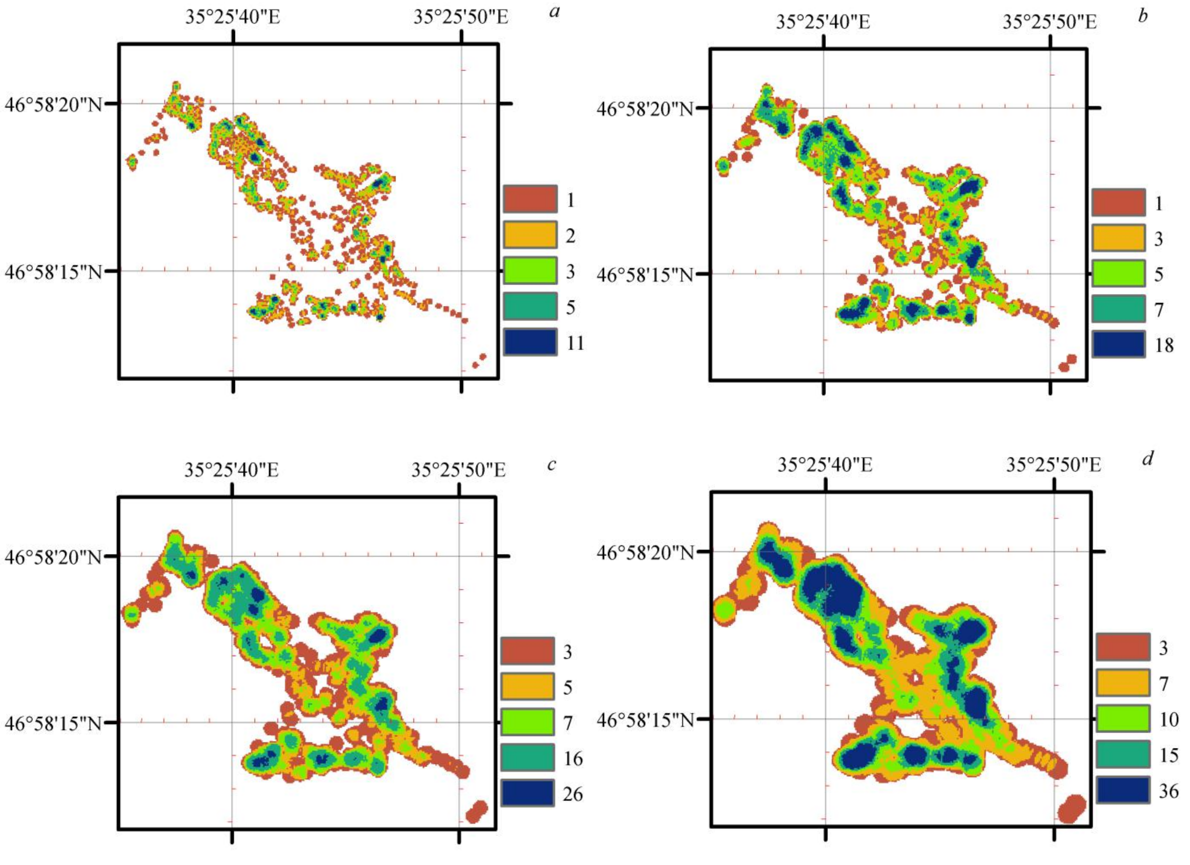

Fig. 4. Tree stand densities in the park plantation at the different radius of the neighboring space: *a* – radius of 3 meters, *b* – radius of 5 meters, *c* – radius of 7 meters, *d* – 10 meters.

Table 4. Model comparison results for mixed-effects models evaluating the effect of plant species, age, and stand density on pathological damage to trees in a park stand. *Legend:* * – *k* is the number of estimated parameters for the model; log(L_i) is natural logarithm of maximum likelihood for model *i*; AIC_i is the Akaike information criterion value for model *i*; Δ_i is AIC differences, relative to the smallest AIC value for given models; $w_i(AIC_c)$ is the rounded Akaike weights.

i	Model	k_i*	log(L_i)	AIC_i	Δ_i	exp(−1/2*Δ_i)	$w_i(AIC_c)$
1	Species	1	–401.1	834.2	140.1	0.000	0.000
2	Species+Age	2	–351.1	736.1	42.0	0.000	0.000
3	Species+Age+Diversity	3	–343.9	723.8	29.7	0.000	0.000
4	Species+Age+Diversity+$Density_3$	4	–334.3	706.6	12.5	0.002	0.001
5	Species+Age+Diversity+$Density_3$+D_3^2	5	–333.7	707.4	13.3	0.001	0.001
6	Species+Age+Diversity+$Density_5$	4	–331.5	701.0	6.9	0.032	0.015
7	Species+Age+Diversity+$Density_5$+D_5^2	5	–330.9	701.8	7.7	0.021	0.010
8	Species+Age+Diversity+$Density_7$	4	–328.1	694.1	0.0	1.000	0.484
9	Species+Age+Diversity+$Density_7$+D_7^2	5	–327.4	694.9	0.8	0.670	0.324
10	Species+Age+Diversity+$Density_{10}$	4	–330.1	698.2	4.1	0.129	0.062
11	Species+Age+Diversity+$Density_{10}$+D_{10}^2	5	–328.6	697.2	3.1	0.212	0.103

Table 5. GLM of the effects of tree species, condition and diameter, and density of the tree stand on tree height (*N* = 788). *Legend*: * – tree condition: healthy tree or dangerous tree.

Predictor	**Estimation of stand density with different test site radii**							
	3 m radius, R_{adj}^2 = 0.83, F = 200.1, P < 0.001		**5 m radius, R_{adj}^2 = 0.83, F = 111.9, P < 0.001**		**7 m radius, R_{adj}^2 = 0.83, F = 113.3, P < 0.001**		**10 m radius, R_{adj}^2 = 0.83, F = 110.9, P < 0.001**	
	***F*-ratio**	***P*-level**	***F*-ratio**	***P*-level**	***F*-ratio**	***P*-level**	***F*-ratio**	***P*-level**
Intercept	7.2	0.01	11.6	0.001	15.6	0.001	6.5	0.01
Species (*S*)	6.4	0.001	5.1	0.001	6.4	0.001	5.7	0.001
State (*St*)*	250.0	0.001	252.2	0.001	247.7	0.001	244.2	0.001
S x *St*	94.7	0.001	95.5	0.001	100.3	0.001	99.5	0.001
$Diameter^{2/3}$	2707.3	0.001	2793.3	0.001	2785.7	0.001	2793.9	0.001
Stand density (D)	0.5	0.50	1.4	0.23	3.8	0.05	0.1	0.81
D^2	0.1	0.73	5.2	0.02	6.2	0.01	0.9	0.34
S x D	0.7	0.75	0.6	0.88	0.9	0.55	0.9	0.54

Our results are in agreement with findings indicating that more diverse communities have higher and more stable ecosystem functioning over time than less diverse communities (Allan et al., 2011; Bussotti et al., 2018; Turner - Skoff & Cavender, 2019; Budakova et al., 2021). The forest health depends on the ecosystem processes and the sustainability of the ecosystem (Raffa et al., 2009; Domnich et al., 2021). There is a fundamental difference between tree health and forest health, especially when forest health is viewed through the lens of ecosystem management.

Tree defoliation and crown dieback, tree mortality and pathogenic damage are the main aspects considered when assessing tree health. The health of an individual tree depends on the diversity of neighboring trees (Bussotti et al., 2018). Healthy forests include not only healthy trees, but also include diseased, injured, and non-viable individual trees (Manion, 2003; Sniezko & Koch, 2017). The diversity reflects the qualitative aspect of the plant surroundings, and the vegetation density reflects the quantitative aspect. Both of these indicators are scale-dependent (Zymaroieva et al., 2021).

Increasing the radius of the sampling area increases the diversity of the plant community in the plant environment and this indicator tends for all plant species to the diversity of the community as a whole. Thus, as the sampling area radius increases, the specificity of the estimate of plant community diversity at each point in the space, decreases. As the size of the sampling radius increases, the estimate of vegetation density decreases as more and more plant-free space is included in the area calculation. In an infinitely large plant community, density with increasing sampling radius will tend toward the average density of the entire community. For an island plant community, the density will tend toward zero. Obviously, of interest is the scale dependence in the radius range, which corresponds to the spatial coverage of possible interactions between individual plants. The high values of HDR indicate the trees are growing in a crowded stand with the reciprocal support of adjacent trees (Valinger & Fridman, 1997). Absence of competition in an extremely open stand can be indicated by the high HDR values (Wonn & O'Hara, 2001; Valinger & Fridman, 2011). A smaller value of HDR indicates greater crown length, greater crown projection area, better developed root system, lower position of the center of gravity, and higher mechanical stability of trees. HDR is a characteristic of tree and stand stability and their sensitivity to natural disasters (Nykänen et al., 1997; Jiao-jun et al., 2003; Castedo-Dorado et al., 2009).

Table 6. Regression coefficients derived from GLM-procedure of the effects of tree species, condition and diameter, and density of the tree stand on tree height (*N* = 788).

Effect	Level of effect	T–value	P–level	β-regression coefficient		
				mean ± st. error	–95%	+95%
Species	*Acer negundo*	–1.46	0.14	–0.065 ± 0.045	–0.15	0.02
	A. campestre	0.09	0.93	0.004 ± 0.041	–0.08	0.08
	A. platanoides	2.16	0.03	0.103 ± 0.048	0.01	0.20
	Morus nigra	–1.49	0.14	–0.063 ± 0.043	–0.15	0.02
	Celtis occidentalis	–2.13	0.03	–0.083 ± 0.039	–0.16	–0.01
	Crataegus pentagyna	–3.29	0.001	–0.129 ± 0.039	–0.21	–0.05
	Prunus divaricata	–0.71	0.48	–0.032 ± 0.045	–0.12	0.06
	Pyrus communis	–0.21	0.83	–0.008 ± 0.036	–0.08	0.06
	Ulmus caprinifolia	2.80	0.01	0.137 ± 0.049	0.04	0.23
	U. laevis	4.35	0.001	0.161 ± 0.037	0.09	0.23
	Ailanthus altissima	1.16	0.25	0.055 ± 0.047	–0.04	0.15
	Prunus domestica	0.18	0.86	0.009 ± 0.047	–0.08	0.10
	Robinia pseudoacacia	0.62	0.53	0.028 ± 0.044	–0.06	0.12
	Sambucus nigra	–4.71	0.001	–0.199 ± 0.042	–0.28	–0.12
	Ligustrum vulgare	0.98	0.33	0.096 ± 0.098	–0.10	0.29

State	Tree with signs of pathology	–15.74	0.001	–0.276 ± 0.018	–0.31	–0.24
Diameter$^{2/3}$	–	52.78	0.001	0.969 ± 0.018	0.93	1.01
Stand density (*D*)	–	1.95	0.05	0.134 ± 0.069	0.00	0.27
D^2	–	–2.49	0.01	–0.154 ± 0.062	–0.28	–0.03

A decrease in stand density increases the risk of windfalls (Wallentin & Nilsson, 2014). Trees with a large HDR are susceptible to uprooting by wind and breakage by wind (Urata et al., 2012). Tree species and stand height are the most important risk factors for storm damage. Stand density, soil and site condition, and topographic variables are important in explaining susceptibility to storm damage (Albrecht et al., 2012). Tree height-to-diameter ratio or time since last thinning were not significant predictors of vulnerability of forest stands to storms (Schütz et al., 2006). Mixture and aspect combined with gradient are reliable predictors of stand sensitivity to extreme weather events (hurricane). An admixture of 10% or more broadleaved trees or wind-resistant conifers significantly reduced the vulnerability of spruce stands (more than threefold). On wind-exposed slopes, damage was more than twice the average. Tree height-to-diameter ratio or time since last thinning were not significant predictors (Schmidt et al., 2010). The trees with a large HDR may not be adapted to the conditions of increased mechanical disturbance (Moore, 2000; Bošeľa et al., 2014). The mechanical properties of the trunk wood can be evaluated with HDR, e.g., trees with small HDR may have higher bending movements than trees with large HDR of similar height (Peltola, 2006). The maximum bending resistance moment correlates most significantly and positively with the diameter at breast height and tree height (Peltola et al., 2000).

Tree mortality is an important ecological process that alters the structure and function of the forest and influences forest management decisions. Tree mortality is considered as a general process that includes all the forms of tree mortality, from tree parts to large-scale disturbances. Multiple processes can lead to mortality, each with its own set of controls (Harmon & Bell, 2020). The mortality of trees is the result of density-dependent and density-independent processes (Larson et al., 2015; Gendreau-Berthiaume et al., 2016). The density-dependent mortality is caused when trees lose the competition for growing space (Bottero et al., 2017). A density-dependent mortality is a process in which the resources available for plant life are limited and mortality must occur for stand development (Hamilton et al., 1995). The mechanism of density-dependent mortality is believed to be primarily related to competition for light (Weiskittel et al., 2009), as opposed to competition for nutrients (Gafta & Crişan, 2010). However, mortality associated with causes other than competition was reported to be density-dependent as well, especially in mixed species stands (McCarthy-Neumann & Kobe, 2008; Piao et al., 2014). The probability of plant damage is species-specific, proportional to age and density, and inversely proportional to density. The nonlinear dependence of damage risks on density is not excluded, which indicates the possible existence of the extreme density of vegetation, at which the probability of damage will be the highest. The role of vegetation density as a damage risk factor is greatest when sampling with a radius of 7 meters. As the radius size increases or decreases, the role of density in the variation of plant damage probability decreases. The damage and mortality of plants may be independent of density. A density-independent mortality is a species-specific death of a stand due to processes that are unrelated to natural mortality during succession or stand maturation (Lintz et al., 2016). The density-independent mortality of trees in stable forests is caused by disturbance and physical damage, which makes trees more susceptible to other disturbance agents, resulting in tree mortality (Franklin et al., 1987). The management of risks to the safety of people and structures is a high priority in urban forest landscapes (Suchocka & Kimic, 2019; Wolf et al., 2020).

A methodological simplification in our work was the estimation of age based on allometric dependence. The direct determination of age is especially important in natural forests, where trees of different ages are represented and the tree size strongly depends on intra-ecosystem interactions. In park stands in the steppe zone, the artificial stands are not of great age, and the age of a stand is determined by the time of stand formation. Therefore, allometric dependences only for artificial plantations can give an acceptable approximation of tree age. It should be taken into account that the age category in our study has a largely allometric component. The direct measurements of tree age are a prospect for further research.

The plant damage affects the allometric dependence of plant height and trunk width. The leading predictor of plant height is trunk width (Greenhill, 1881; Norberg, 1988; O'Brien et al., 1995), but other predictors also influence the overall pattern. The damaged plants have a relatively lower height for a given trunk width. GLM revealed that the HDR of undamaged trees is 47.6% higher than that of damaged trees if plant species and trunk diameter are taken as covariates ($F = 235.5$, $p < 0.001$). Obviously, the damage of different nature negatively affects the rate of increase in plant height. This pattern seems to apply to all community species. The rate of plant growth is density-dependent. The greatest value as a predictor is density, which is estimated using a sampling area with a radius of 7 meters and this dependence is non-linear. Non-linear form of dependence leads to existence of optimal value of plant community density at which the plant growth will be the highest. Obviously, this density contributes to the formation of a healthy park plantation, which has the greatest functional and aesthetic value.

Conclusion

The probability of tree damage in a park plantation increases with plant age and stand density, but decreases as the diversity of the plant community increases. The allometric dependence of height on tree diameter depends on plant damage and stand density. The damaged plants have a lower height for a given trunk diameter. The dependence on density is scale-dependent. The effect of stand density on the allometric dependence is greatest at the density accounting radius, which is 7 meters. The optimal stand density in park stands in the southern steppe zone of Ukraine, which forms the best conditions for the growth of trees, is 3.0 plants per 100 meters^2.

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