

Spatial and compositional structure of European oak urban forests in Kyiv city, Ukraine

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Citation: Matsala M., Bilous A., Feshchenko R., Matiashuk R., Bilous S., Kovbasa Y. (2021): Spatial and compositional structure of European oak urban forests in Kyiv city, Ukraine. J. For. Sci., 67: 143–153.

Abstract: Forest dimensional structure and tree species composition strictly define ecosystem resilience, success of its functioning and development. Spatial structure of forest compartments provides an additional information on the forest stand heterogeneity. The aim of this study is to examine structural patterns (both spatial and non-spatial ones) in European oak (*Quercus robur* L.) urban forests located in Kyiv city, Ukraine. We compared two middle-aged (~ 80 years) and two mature (~ 180 years) oak stands in terms of structural metrics collecting a data from geo-referenced trees on the established permanent sample plots. Younger stands reached similar tree diameter diversity (9.07 and 10.45 vs. 11.42 and 14.05 of Shannon indices), while the compositional diversity was driven by the dominance of either oak or European hornbeam (*Carpinus betulus* L.). We have not found any differences in the species mingling and deadwood distribution indices except a clear occurrence pattern for the stand located near roads. Herewith, the largest distance between the plot and park pathways was an indicator of changed spatial variation and tree dimensional differentiation within one middle-aged stand. We hypothesize that human impacts can alter structural development in urban deciduous forests providing both positive (gap formation, deadwood occurrence and ecosystem complexity) and negative (shifts in compositional and successional trajectories) effects on such forest stands.

Keywords: deadwood management; biodiversity; tree mingling index; dimensional structure

Urban green forested areas sustain local biogeographic and climatic conditions, and provide numerous ecosystem services (e.g., air cooling, soil and water conservation, aesthetic and societal values) for citizens (Escobedo et al. 2019). The structure – in terms of dimensional arrangement of trees and other ecosystem compartments, their species composition and spatial allocation – reflects the forest complexity and resilience (Poldveer et al. 2019). However, as urban (forest) parks are typically designed to provide mainly recreational values for the humans, structural development of such

ecosystems is rather characterized by a homogeneity and dampened biodiversity (Reilly et al. 2015).

On the other hand, several urban green ecosystems can be treated as the prolonged legacies of old-growth forests (Netsvetov et al. 2019). At the last stage of successional development, such forests are typically diverse in terms of structure and composition (Turner et al. 2004; Vacek et al. 2015; Aszalos et al. 2017). Old large trees, presence of large deadwood, high differentiation in diameters at breast height (DBH) and height of trees, diverse composition of trees, shrubs and herbaceous spe-

cies are typical signs of structurally heterogeneous woody communities (Keeton, Franklin 2005; Petritan et al. 2012). These features can be inherited by the forest parks created to protect the remnants of old-growth forests within urban areas (Netsvetov et al. 2018). However, forest managers should consider both the perceptions of local settlers regarding deadwood amounts and the related aesthetic values (e.g., Ebenberger, Arnberger 2019; Pelyukh et al. 2019), and altering risks of pest outbreaks.

Forests composed of European oak (*Quercus robur* L.) are considered having special importance in the continental forest conservation and biodiversity strategies (Vasile et al. 2017; Molder et al. 2019). Capability of the old large oaks to provide microhabitats and structural diversity (e.g., Bouget et al. 2011) is crucial while the typical managed forests in Europe have already been surrounded by the common mid-seral species like Norway spruce (*Picea abies* L.). Oak deadwood is strictly linked to the issues of saproxylic beetles and nesting bird preservation (e.g., Widerberg et al. 2012), while these species are playing a critical role in the ecosystem functioning. Different approaches are applied to either retain or increase deadwood stocks in both managed and urban European forests (Vitkova et al. 2018).

Typically, forest stands are experiencing the structural heterogeneity at the late stages of structural development (Lorimer, Halpin 2014). However, some communities can become structurally and compositionally complex earlier, namely under the specific growth and climatic conditions (Donato et al. 2012). Former old-growth European oak forests in Ukraine are currently represented by either mature and over-mature forest stands within large city parks (e.g., in Kyiv city) or middle-aged communities (Bilous et al. 2019; Yarotskiy et al. 2019). These ecosystems can simultaneously experience both nature protection regime and anthropogenic pressure due to their mainly recreational role (Netsvetov et al. 2019). Human impacts, however, can accelerate structural development through increasing the tree mortality rates, which leads to the dimensional differentiation, gaps and sapling occurrence (Grotti et al. 2019). As well, it facilitates spatial heterogeneity in terms of tree and shrub distribution and spatial mingling (Annighofer et al. 2015; Pommerening, Uria-Diez 2017). Such indicators can reflect credible ecosystem complexity and subsequent resilience even at the middle

stages of forest development (Neumann, Starlinger 2001; von Oheimb et al. 2007).

Here we examined the structural, compositional and spatial development of European oak urban forest communities within Kyiv city in Ukraine. We tested whether middle-aged stands differ substantially from mature oak forests in terms of (i) tree dimensional differentiation, (ii) structural and compositional diversity, and (iii) spatial patterns of deadwood and live trees.

MATERIAL AND METHODS

Study site. We have established four rectangular sample plots in the Feofania park of Kyiv city. Two plots represented middle-aged forest communities (with the age of oak trees ca 80 years), the other two plots were established in mature oak stands (with the age of oak trees ca 180 years). One plot in middle-aged oak forest was located on the hill at a higher elevation (170 m a.s.l.). Plot areas ranged from 0.25 to 0.84 ha.

This park is located in the southern part of Kyiv city (coordinates of central point are 50.34°N, 30.49°E according to the coordinate system EPSG:4326) encompassing the legacies of natural old-growth European oak forests. Elevation in the Feofania park ranges from 75 to 189 m a.s.l.; the local relief is represented by a beam valley with steep slopes. The study site climate is humid continental, with decreasing seasonality patterns (lowering difference between summer and winter seasons over time) during the last decades (Shvidenko et al. 2017). Mean monthly temperature ranges from –5.6 °C (January) to 19.3 °C (July), the annual average is 7.7 °C. Average monthly precipitation ranges from 35 mm (October) to 88 mm (July), while the mean total annual precipitation is 650 mm (Netsvetov et al. 2018). Local soils are mesic clay Podzols, and are not typically subjected to flooding (the level of groundwater table is mostly below 5 m annually, Netsvetov et al. 2019). Forest stands in the park are mainly composed of deciduous tree species: European oak with European hornbeam (*Carpinus betulus* L.), small-leaved lime (*Tilia cordata* Mill.), and Norway maple (*Acer platanoides* L.). Additionally, some trees of European ash (*Fraxinus excelsior* L.), black locust (*Robinia pseudoacacia* L.) and European elm (*Ulmus laevis* Pall.) can be found there. The location of the study area is given in Figure 1 and a more detailed plot quantitative description in Table 1.

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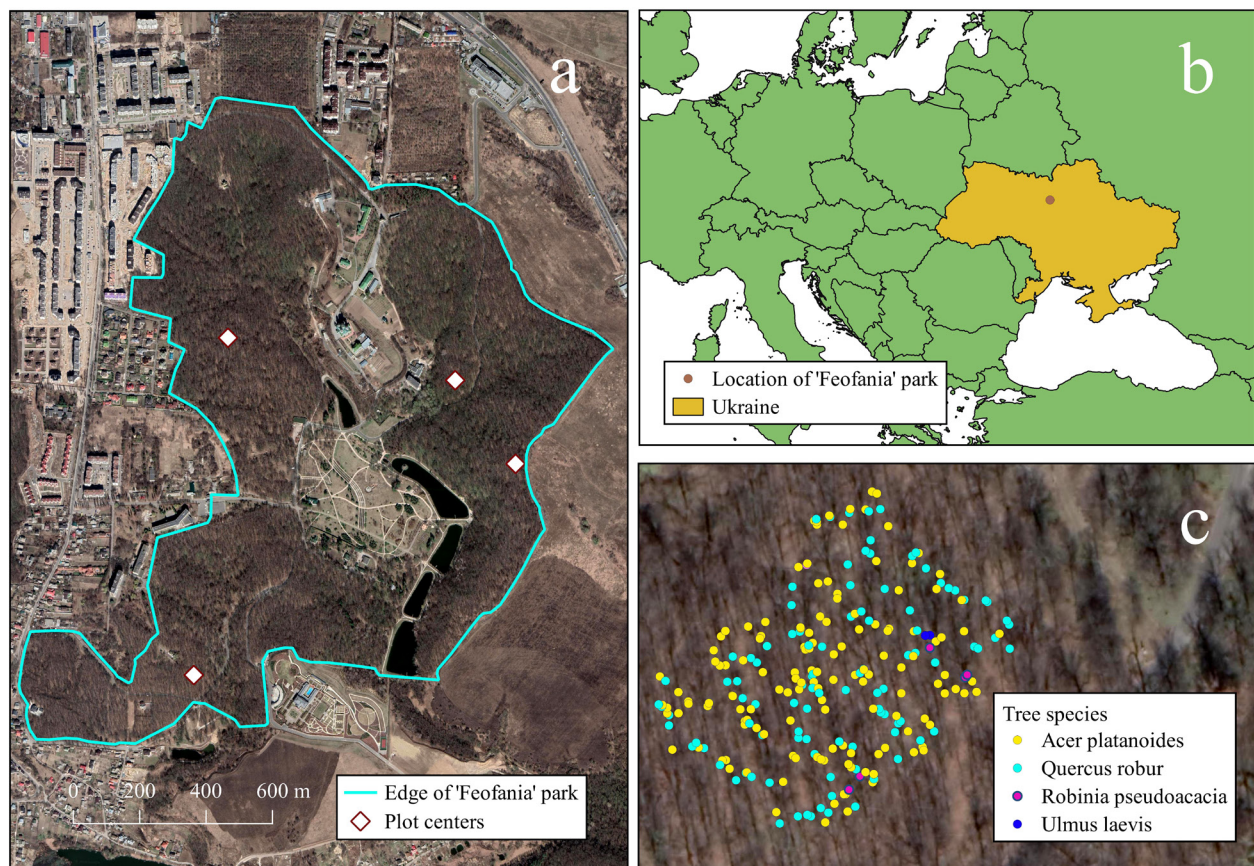


Figure 1. Location of the Feofania park and established sample plots in Kyiv city (A), European context of study site (B), and an example of sample plot with geo-referenced trees and their species (C); Google Satellite Service is in the background

Forests of the Feofania park (Figure 1, Table 1) have not been treated by sanitary loggings since 2016. However, forest management interventions with the aim to remove dangerous snag trees located near the roads are intensively carried out nowadays (e.g., several large old oaks were cut after having been broken by a severe windstorm in 2018).

Data collection. Sample plots were established in 2016–2017 as permanent study polygons with

the aim to launch the long-term observations of European oak deadwood accumulation. All plots were established within the Forest Observation System, a global network of permanent sample plots (Schepaschenko et al. 2019) designed to facilitate the validation of forest remote sensing products. Data on the basal area and mean height, growing stock volume, and aboveground biomass stocks for the stands represented on these plots are available online on

Table 1. Quantitative description of sample plots

Parameter	No. of stand			
	1	2	3	4
Age (years)	~80	~180	~180	~80
Altitude (m a.s.l.)	159	176	161	173
Plot length and width (m)	85 × 60	120 × 73	80 × 55	80 × 36
Mean DBH (cm)	24.0	30.2	24.4	18.0
Maximum height (m)	34.8	38.9	35.0	25.0
No. of trees	262	315	214	226
Tree aboveground biomass (t·ha ⁻¹)	271.8	391.7	211.9	176.3

<https://forest-observation-system.net>. Within each plot, all trees (which achieved DBH ≥ 1 cm and height ≥ 1.3 m) were recorded, namely their geographical coordinates (latitude and longitude), DBH, tree state (alive, snags, logs, removed), and tree species. Geographical coordinates were recorded with the GPS navigator (eTrex 10; Garmin, USA). Dead trees were considered as snags if they were hitherto standing; if such trees were downed, those were considered as logs (at least 1 cm of diameter and 1.3 m of length). We considered as logs only that deadwood which had a clear sign of being rather a downed young tree (if the diameter was < 10 cm) than a fallen branch of an older tree. Some trees could be removed from the stand during sanitary loggings. In total, we collected data on 998 trees within all four sample plots.

Data analysis. To examine patterns of dimensional differentiation, we built histograms of DBH distributions for each plot. We used both raw and standardized (i.e. scaled to 0.1) distributions. Additionally, we calculated basal area proportions of tree species for each stand, with the aim to estimate this key forest biophysical parameter which is typically used in biomass and carbon stock estimations.

To reveal differences in structural patterns between sample plots, we computed several metrics. To account for non-spatial diversity, we estimated Shannon indices (Shannon 1948) of tree species composition (by basal area proportions) and DBH dimensional structure (by 4-cm DBH classes). The Shannon index was calculated as Equation (1):

$$H' = -\sum_{i=1}^S p_i \ln p_i \quad (1)$$

where:

H' – Shannon diversity;

S – number of samples;

p_i – proportion of each DBH class or tree species of i -class.

As well, we calculated Pielou evenness (Pielou 1975) and Margalef species richness (Margalef 1958) indices (Equations (2) and (3)):

$$J = \frac{H' \ln(10)}{\ln(m)} \quad (2)$$

where:

J – Pielou evenness;

m – number of tree species.

$$S = \frac{m-1}{\ln(n)} \quad (3)$$

where:

S – Margalef species richness;

n – number of trees per hectare.

Spatial indices applied in this study included deadwood distribution and tree species mingling (Pommerening, Stoyan 2006). Deadwood (both snags and logs together) distribution in the space according to the live trees was calculated as Equation (4):

$$D_i = \frac{1}{k} \sum_{j=1}^k v_j \quad (4)$$

where:

D_i – deadwood distribution index;

k – number of nearest neighbours (in this study $k = 4$);

i – reference alive tree;

j – neighbouring tree of reference i -tree;

v_j – either 0 (if neighbouring j -tree is alive) or 1 (if such neighbouring tree is dead).

The tree species mingling index was calculated as Equation (5):

$$M_i = \frac{1}{k} \sum_{j=1}^k v_j \quad (5)$$

where:

M_i – species mingling index;

v_j – either 0 (if neighbouring j -tree has the same tree species) or 1 (if such neighboring tree has another tree species).

Additionally, we have examined the spatial variance of DBH distribution of live trees and compared it between sample plots. To do that, we calculated an empirical semivariogram as a half of variance in DBH between all pairs within each studied forest stand. For the deadwood location distribution, we calculated respective semivariograms and built respective maps of variance for each sample plot. As well, we compared distances between reference dead trees and the nearest either random live trees or large (DBH > 40 cm) live trees to examine whether dominant European oak trees entail tree mortality under given rich soil (fertility, humidity) conditions.

All data was processed in R environment (R Core Team 2019). Specifically, Shannon diversity and Pielou evenness indices were calculated in the *vegan* package (Oksanen et al. 2019); deadwood distribution and tree species mingling indices were computed in the *spatialsegregation* package; semi-variance graphs and maps were built in the *gstat* package (Pebesma 2004).

<https://doi.org/10.17221/173/2020-JFS>

RESULTS

Diameter and basal area distribution

The most diverse was stand No. 2 which has the age of ca 180 years and several large live European oak trees (with DBH > 60 cm, Figure 2). Scaled dis-

tribution revealed the age of stands No. 1 and 4 (ca 80–90 years, Figure 3) that contain the high proportion of trees with large relative DBH (> 0.5).

The basal area in studied forests is mainly represented by the older live trees of European oak regardless of their number (Figure 4). Herewith, old-

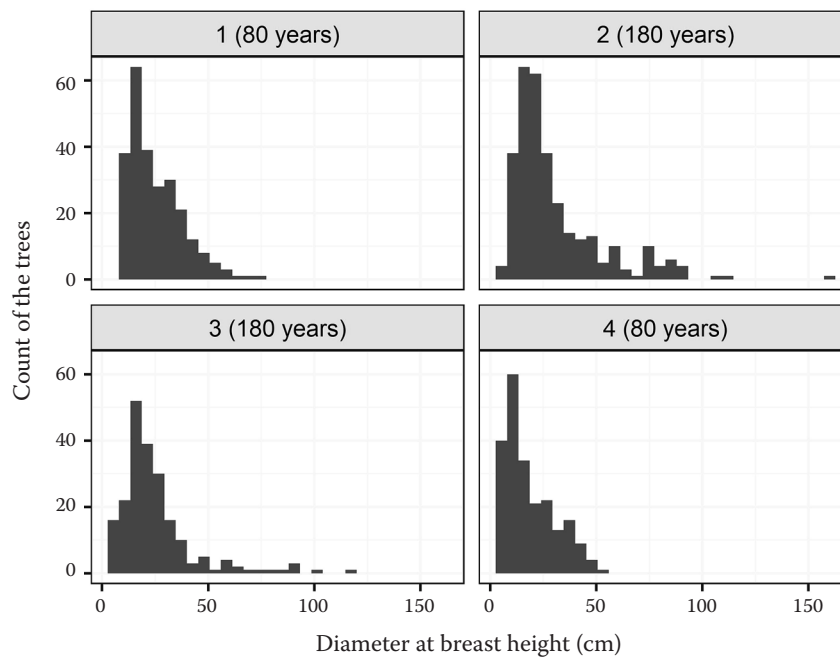


Figure 2. Raw diameters at breast height (DBH) distributions of live trees across studied stands

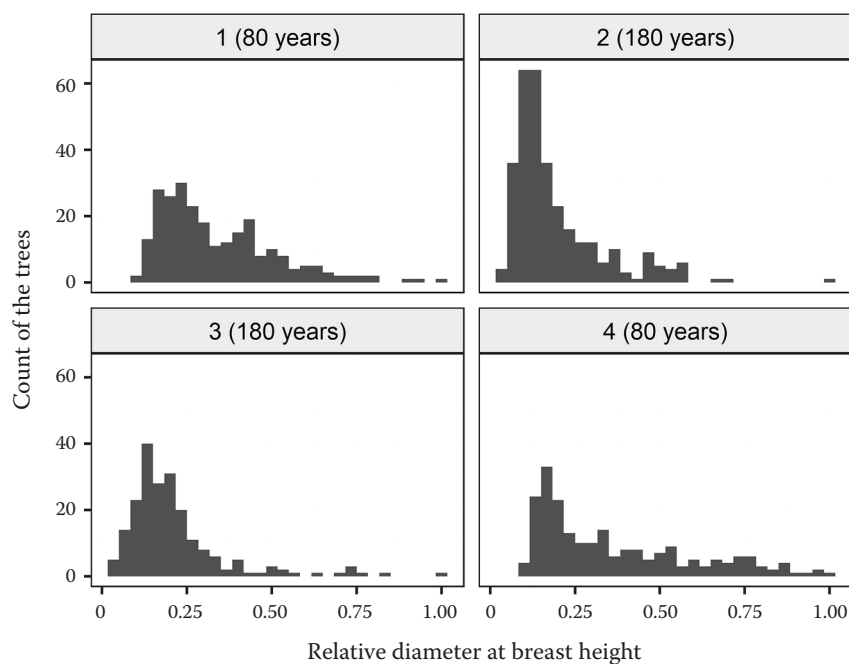


Figure 3. Scaled diameters at breast height (DBH) distributions of live trees across studied stands

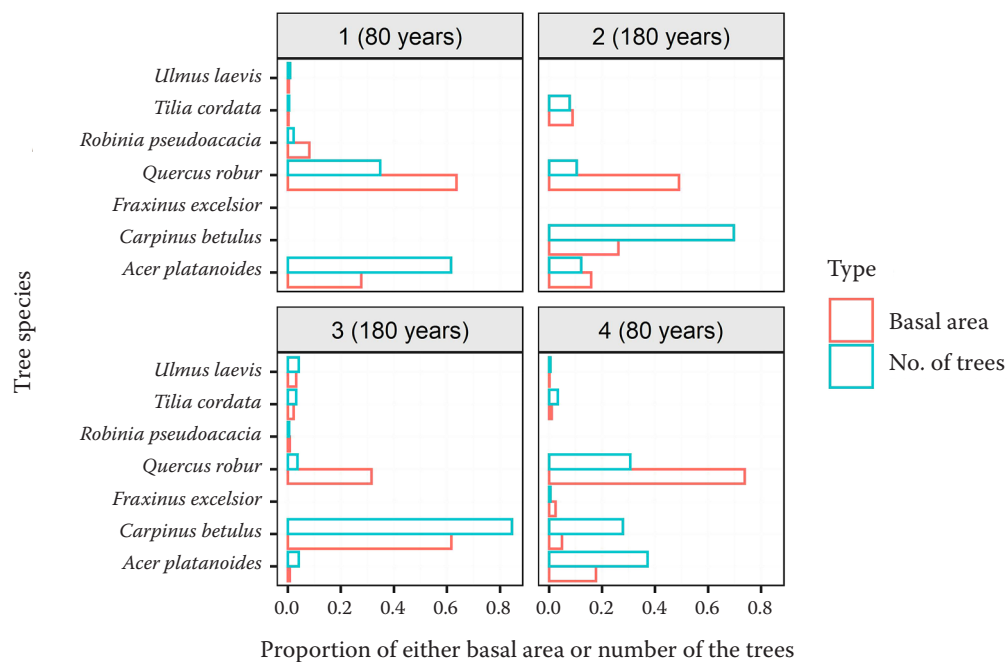


Figure 4. Basal area and tree number proportions across studied stands

growth stand No. 3 is dominated by an extremely large number of European hornbeam trees, which simultaneously outperform European oak in terms of the basal area. The lowest basal area proportion of Norway maple amongst all sample plots can be observed exactly in the stand where European hornbeam dominates. Admixtures of invasive species (of black locust in this case) were found in the oak stands regardless of their age.

Structural diversity

Middle-aged studied stands (No. 1 and No. 4, Table 2) did not achieve such diversity values (in terms of DBH structure and tree species composition) as older oak communities (stands No. 2 and 3).

Herewith, the hyperdominance of European hornbeam trees has entailed substantially lower values of the Shannon index (stand No. 3) compared to stand No. 2 where the oak basal area proportion was higher (Figure 4) and some Norway maple trees were present. Almost all stands experienced similar species evenness, while the net difference in basal area between European oak and European hornbeam in stand No. 2 resulted in a higher value of the Pielou index. Old-growth forest in stand No. 3 can be characterized by the highest Margalef species richness index because of the maximum tree species representation compared to the other plots. The lowest structural diversity can be observed in stand No. 4 located on the top of the hill.

Table 2. Indices of structural and spatial diversity of studied stands

Indicator	No. of stand			
	1	2	3	4
Age (years)	~80	~180	~180	~80
Shannon DBH diversity	10.45	14.05	11.42	9.07
Shannon species diversity	2.30	3.24	2.50	2.26
Pielou evenness	1.43	2.34	1.39	1.26
Margalef species richness	0.72	0.52	0.94	0.93
Species mingling	0.73	0.70	0.77	0.79
Deadwood distribution	0.43	0.53	0.50	0.53

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Relatively similar species mingling index values for all stands (Table 2) indicate that trees of different species are mixed randomly across the sample plots and large groups of one specific tree species are rather rare. A similar situation was revealed for deadwood distribution: however, middle-aged stand No. 1 has a substantially lower value of this index.

Spatial variation

The smallest spatial DBH variation of live trees was found for plot No. 1 (middle-aged oak stand, Figure 5). Within this plot, semivariance did not increase to the small distances up to 10 m. Such a situation is typical if the pairs of older and larger oak trees and smaller trees of other species are distributed across the stand in a homogeneous manner. Other stands are characterized by a rapid increase of spatial DBH variance to the distances up to 20 m which can reflect the uneven distribution of large oak trees. A small number per stand of such extremely large trees (if compared with substantially smaller but numerous plants of European hornbeam) is precisely illustrated by the semivariogram for plot No. 3.

Mature (age of ca 180 years) oak forest stands represented by plots No. 2 and 3 are illustrated (deeper purple colour) by more homogeneous and low spatial variation in deadwood allocation (Figure 6). That is, dead trees are almost absent within the stand and are clumped into several groups. Lighter gradient (in stands No. 1 and 4) indicates the more regular deadwood spatial distribution. However, some larger clusters of variation are visible near the borders of sample plots revealing the typical edge effects and anthropogenic influence. Such human impact is more profound in stand No. 1 which has the lowest deadwood distribution index (Table 2) while the clusters of variation are linked to the pathways located nearby.

There are no spatial patterns in distances between dead trees and live trees depending on their DBH (Figure 7): typically, a distance to the old oak or hornbeam tree is larger than to the tree with random diameter.

DISCUSSION

In this paper we have examined whether European oak forest stands within urban green areas experiencing human impact can achieve high structural diversity and heterogeneity at the different succes-

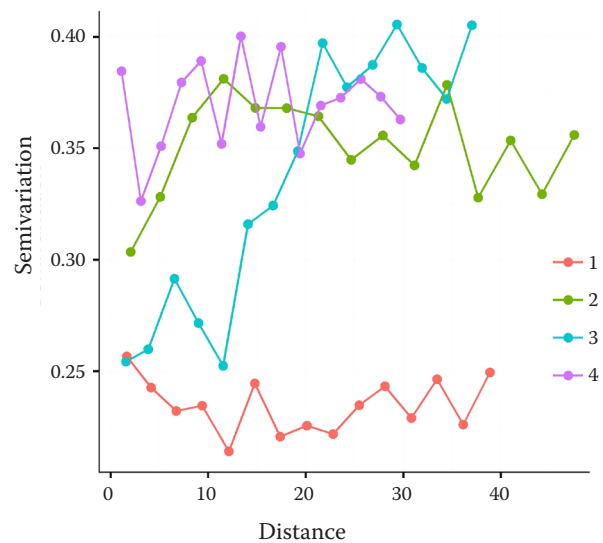


Figure 5. Empirical semivariograms of diameters at breast height (DBH) distributions for live trees across sample plots

sional stages. Old-growth and middle-aged (like in this study) oak stands are typically mixed (e.g., Vasile et al. 2017) being characterized by the larger and less numerous oak trees and multiple plants of either Norway maple or European hornbeam. That is, regardless of the current successional stage, large European oak trees will create respective niches in the ecosystem providing dimensional differentiation and structural diversity (Thom, Keeton 2019). Herewith, we revealed that oak trees in middle-aged stands less differentiate from other tree species in terms of DBH distribution. Norway maple and European hornbeam having faster growth trajectories are successful in competition with dominating oak trees. It promotes the deadwood occurrence, but it can lead to the dominance of these admixtures (as happened in hornbeam-dominated stand No. 3) even in terms of basal area. Additionally, some invasive tree species (e.g., black locust) can appear in the stand composition. Oak regeneration under the main canopy layer is thus threatened by such shifts and possible human impact if being located within the urban areas (Annighofer et al. 2015).

We found some structural homogeneity (Shannon DBH diversity and distribution) in stand No. 4 characterized by the higher elevation compared to other sample plots and larger distances to the pathways used by the park visitors. In such case, there is a possible situation when the anthropogenic impact does not lead to the additional tree mortality

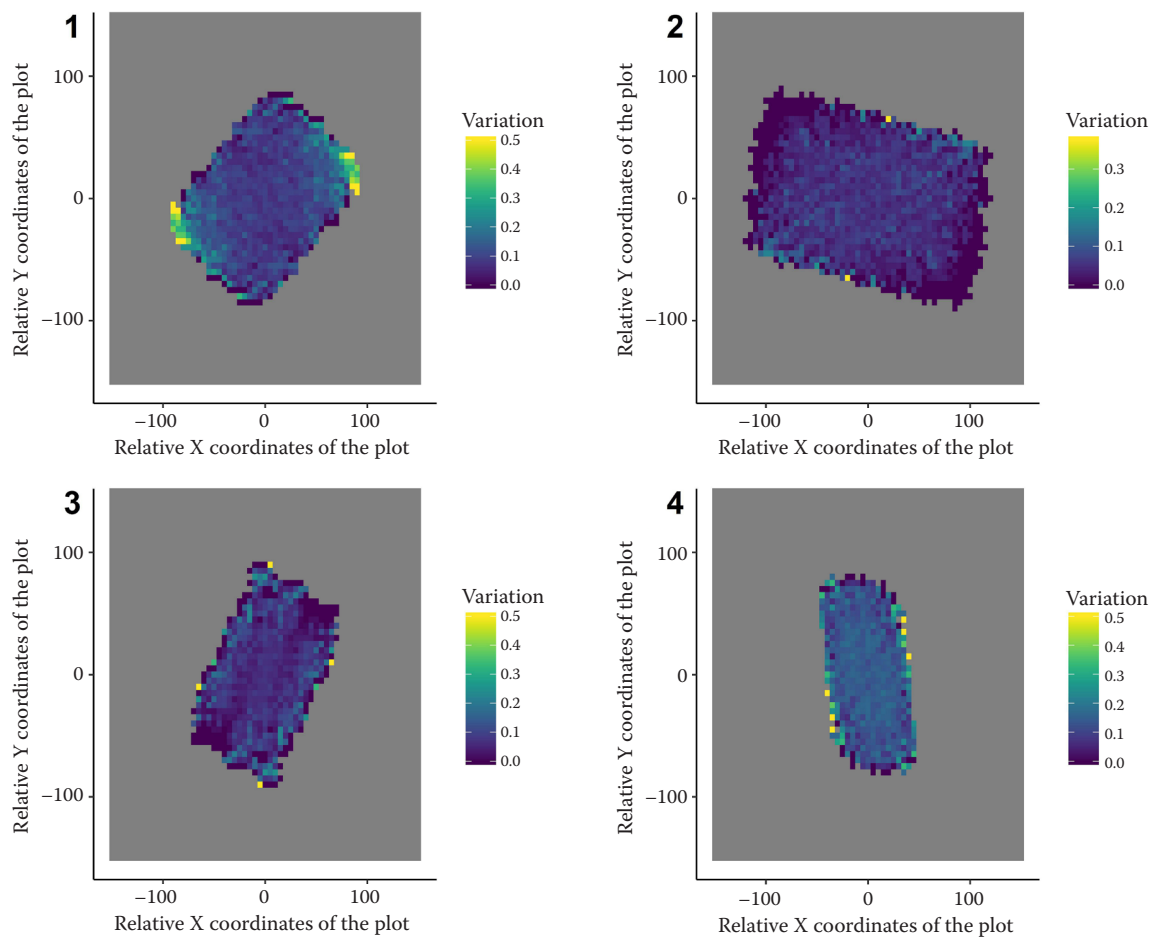


Figure 6. Variation maps of deadwood distribution within the sample plots

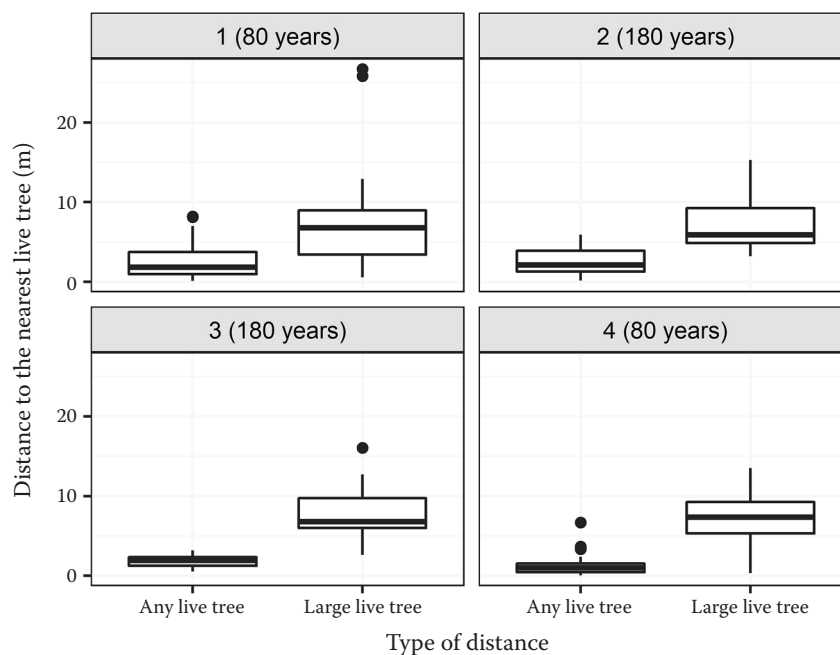


Figure 7. Distances from dead trees to the nearest live trees of any species

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of all species and thus dimensional differentiation through understorey formation. That is, the human influence can result in the additional driving of structural development acceleration while the forest is middle-aged (Donato et al. 2012; Aszalos et al. 2017). There is a common situation when mid-seral (like European hornbeam in this study) tree species are experiencing higher decaying rates and thus they cannot fully provide the sufficient deadwood stocks in their ecosystems (e.g., situation with beech-spruce forest described by Vacek et al. 2015). Here we suggest that the deadwood of European oak should be treated with higher park managers' involvement than considering snags of European hornbeam or other admixtures occurred due to the self-thinning processes.

Spatial patterns, as a rule, provide deeper understanding of underlying structural mechanisms in late-seral temperate forests than the respective non-spatial structural metrics (Grotti et al. 2019). We did not find any differences in species mingling between mature and middle-aged stands. That is, the species occurrence in pairs of European oak and admixtures is similar at the different stages of stand development. Such situation of random spatial distribution is widely observed in the forests of similar growth and bioclimatic conditions [e.g., European beech (*Fagus sylvatica* L.) forests described in von Oheimb et al. (2007); oak coppice forests studied in Vacek et al. (2018)]. The same pattern can be observed in deadwood spatial distribution, with some apparent edge effects and profound anthropogenic influence near the plot borders. There was no relationship between dead tree occurrence and the nearest live tree in terms of the size of such live tree. As large trees (DBH > 40 cm) are mainly European oaks, they can suppress the establishment rates of the new understorey (Tinya et al. 2018). Therefore, the random distribution of deadwood regarding any live trees is thus a result of self-thinning processes among younger trees that occurred to the long distances from the dominant old oaks. Such patterns can be explained by semivariance in the spatial distribution of tree DBH (Figure 5): larger crowns of older trees entail that younger trees are not clumping in their functioning zones.

Deeper understanding of the ecosystem resilience of urban European oak forest stands driven by structural diversity must become an important instrument to protect remnants of old-growth forests. Human impacts can facilitate gap-scale tree

dimensional differentiation, deadwood occurrence and biodiversity promotion, but they will threaten late-seral forest communities within large cities in the longer run (Netsvetov et al. 2019). Considering this study site it is to note that no traditional thinnings typically carried out to shape the forest park structure were performed in Feofania. Park managers planned only the removal of dangerous dead trees located near the roads. However, more profound understanding of key structural and spatial processes is needed to meet efficiency in natural stand development. E.g., removal of large trees can promote the space and light availability for the tree recruitment (Molder et al. 2019), but it is not an option for the urban parks, especially when such important trees are represented by the main tree species – European oak. Dampened ecosystem resilience of oak forest ecosystems in Eastern Europe (and Ukraine in particular) due to altered climatic and natural disturbance regimes is a crucial issue for policy makers and urban green area conservationists (Shvidenko et al. 2017). Herewith, the knowledge of spatial and structural functioning at a stand and gap scale can provide reasonable suggestions for planning obligatory sanitary treatments following various disasters.

Based on our study, there is a variety of pathways how to retain both structural and biological diversity in urban protected forests. This issue has been intensively discussed in numerous studies (e.g., Petritan et al. 2012) in the last decades since it is rather unclear how to keep the balance between functional traits, ecosystem stability and societal demands of park visitors and local inhabitants. While anthropogenic impacts can result in the additional tree mortality and structural heterogeneity, it is important to facilitate such differentiation and to promote diversity in the urban park areas located remotely from the main pathways or recreation spots. Such measures may not only include the retaining of dangerous snag trees (e.g., they were growing near the specific roads, were cut and then left in the stand as downed logs), but also artificial deadwood creation (e.g., through tree girdling, Vitkova et al. 2018). Regarding our case study, such new deadwood can be created through the killing of some trees of invasive, non-native species (like black locust, Figure 4). However, such practices should consider the microhabitat and biodiversity issues (Bouget et al. 2011), and the humans' attitude while discussing the necessity of deadwood in

the managed (Pelyukh et al. 2019) or semi-natural urban forests (Korhonen et al. 2020). Respective trade-offs between the aesthetics of the intensively anthropogenically utilized forests and ecosystem resilience should be addressed in long-term forest planning and strategies.

CONCLUSION

We have empirically revealed that middle-aged (age ~ 80 years) forest stands of European oak can reach similar structural heterogeneity like older (with age ~ 180 years) stands. Herewith, tree species composition is rather defined by local successional trajectories and it is more diverse in mature oak forests. We have found that spatial patterns are strongly driven by direct (absence of silvicultural treatments except the removal of dangerous trees) and indirect (location near roads and human recreation-related pressure) human impacts.

Successful natural regeneration, understorey layer formation and microhabitat formation strongly depend on the spatial and non-spatial forest attributes. We recommend providing more robust and active deadwood management in the urban forests, simultaneously considering microhabitat creation, regeneration promotion, and societal demands of the people linked to such parks. Thus, deeper understanding of key structural processes and functioning in important deciduous urban forests is crucial due to the emerging risks that threaten forest ecosystems at the eastern frontier of the European continent.

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Received: October 16, 2020

Accepted: December 8, 2020