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COARSE WOODY DEBRIS IN MATURE OAK STANDS OF UKRAINE: CARBON STOCK AND DECOMPOSITION FEATURES

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Abstract

Forest ecosystems play crucial role in climate changes mitigation, providing the carbon (C) sequestration process. Here we overview increasing ecological importance of mature and over-mature oak forest stands in Ukraine, with strong focus on dead biomass compartment of those. We examined respective national forest inventory data, permanent sample plots, logs' samplings for estimation of decomposition dynamics. Founding out that coarse woody debris (CWD) is insufficiently accounted in forest inventory data, we have estimated potential of this compartment to store 4.5 % of total oak stand biomass C according to empirical data. Mean dead biomass C stock (CWD and fine litter together) is nearly 9.3 % of total biomass stock. Obtained C stock estimations based on field measurements correspond to previous studies in Ukraine. Modelling of oak downed logs decomposition indicates that deadwood may remain in ecosystem for decades, achieving 40–50 kg·m^{-3} wood density at 100 years point after tree death, thus playing substantial role not only as habitat for species, but also as C sink in mid-term perspective. Imperfections in national forest inventory system and local management regimes lead to unrecognized biases in efforts to assess oak deadwood values in Ukraine. Herewith, target consideration of CWD importance in current silvicultural practices is needed for maintaining this important ecosystem component.

Key words: dead biomass, deadwood, litter, logs, snags.

Introduction

To date, carbon (C) sequestration is in a special focus of international society among ecosystem services as an important component of climate changes mitigation efforts (Grassi et al. 2017). Naturally, C is stored in organic matter of aquatic and terrestrial ecosystems, including forest biomass and soils (Bazylevych et al.

1978). C cycle in forests is defined by plants photosynthetic productivity (Bonan 2008), starvation and decomposition processes (Yatskov et al. 2003), impact of natural disturbances (Seidl et al. 2014) and several lateral fluxes (Chen et al. 2014). Knowledge, whether given ecosystem is either a net C sink or source, is a crucial for defining local climate mitigation capacity, together with ecosystem evapotranspiration, surface albedo and land use regime (Schwaab et al. 2015). Hence, Ukraine, signing and ratifying in 2016 Paris Climate Agreement, became responsible for inventory of national C budget, *inter alia*, of forest ecosystems (Shvidenko et al. 2017).

Deadwood, being a crucial component of forest ecosystems, is tended to be strictly considered in national forest, climate and biodiversity maintaining policies worldwide (Franklin et al. 2007). Deadwood in managed forests presented by late-seral species which are defined by low decomposition rates, thus may store C for decades, with moderate emissions until final felling (Harmon et al. 1986). In conservation areas it is an important structural legacy after natural disturbances and plays rather preserving role as a habitat for microbiota, saproxylic and avian fauna (Kuuluvainen 1994, Franklin et al. 2002, Thom et al. 2018, Lakyda et al. 2019). Importantly, coarse woody debris (CWD) must be considered as a key part of larger ecosystem compartment – dead biomass, which includes, *inter alia*, fine litter of branches and leaves, dead branches on the live trees, dead roots, etc. (Bilous et al. 2017a).

Ukrainian forest ecosystems, being located in temperate zone and Mid-Latitude Xeric belt, are rather net C sinks (Sytnyk et al. 2017, Lesiv et al. 2018). Those cover 15.9 % of country area according to last forest accounting at state scale carried out in 2011. Furthermore, forest stands of *Oak* spp. genus together take a significant share (22 % of forested area in Ukraine), being a second the most abundant genus. Common, or European oak (*Quercus robur* L.) is the main deciduous tree species in Ukraine; however, some areas are covered by Downy oak (*Q. pubescens* Willd.), Red oak (*Q. rubra* L.) and Sessile oak (*Q. petraea* (Matt.) Liebl.).

Common oak is a typical temperate late-seral tree species, which prefers well-drained soils with high fertility values and medium moisture regime (Lakyda et al. 2006). There are common oak stands in Forest-Steppe subzone of Ukraine; however, a number of forest patches in Polissya (subzone of mixed forests (i.e. Scots pine (*Pinus sylvestris* L.) with soft-leaved species like Silver birch (*Betula pendula* Roth.) in Northern Ukraine) and Steppe (forestless subzone in Southern Ukraine) are covered by Common oak.

This species in Ukraine is highly abundant in areas where occurrence of these stand-replaceable natural disturbances like intense wildfires or storms is rare. Hence, oak forests can accumulate the substantial stocks of CWD, or deadwood: snags (standing dead trees) and logs (stumps, downed dead stems and large branches). Threshold is mainly defined by management regime, including final felling and salvage loggings. To date, in Ukraine salvage loggings is hitherto used treatment aimed to remove CWD from ecosystem that even was not threatened by insects or diseases and irrespective whether storm of wildfire had occurred before (Pasternak 2011).

A series of studies has been carried out with aim to estimate growth and yield, net primary productivity (NPP), C stocks and some other regulating ecosystem services (oxygen and energy productivity) of oak stands in Ukraine (Lakyda et al. 2006, 2011). However, studies considered deadwood or whole dead biomass compartment as an essential for oak ecosystems, were conducted only on landscape (Bilous et al. 2017a) or regional scale (Pasternak 2011). So, Pasternak and Yarotskii (2013) concluded that CWD in oak stands of North-Eastern Ukraine (Kharkiv region) was mainly presented in patches with clearly defined borders, i.e. under impact of gap-scale natural disturbances (relatively not severe storms, pest outbreaks, disease affections).

A number of studies represent increasing understanding of deadwood importance for ecosystem functioning in Central Europe: natural oak forests in Austrian Alps (Rahman et al. 2008); stands of sessile oak in Hungarian Carpathians (Bölöni et al. 2017), focusing on biodiversity (Ranius 2002, Horak et al. 2014). Natural consideration seems to be a key requirement for sufficient accumulation of deadwood in oak forests: Vandekerkhove et al. (2009) in their review analysis of forest inventories throughout Central and North-Western Europe concluded that only in protected areas logs (i.e. downed CWD) could reach 75 % of oak dead biomass pool. Rahman et al. (2008) reported that CWD had reached 39 % ratio to whole biomass stock in Austria natural oak forests. However, Bölöni et al. (2017) reported that managed Hungarian forests accumulate quite low CWD stocks, and these values were relatively larger only in old-growth, protected oak stands.

While national forest inventories and field sample plots can be a comprehensive tool for estimation of current dead biomass C stocks, studying of decomposition rates for CWD is needed for prediction of deadwood accumulation. Chronosequence method (discussed in a classic study of Harmon et al. 1986) is frequently used worldwide: for boreal forests in Russia (Yatskov et al. 2003); temperate rainforests in Coastal Alaska (Yatskov 2016); in Germany (Herrmann et al. 2015); in natural forests of New Zealand (Garrett et al. 2019). Herewith, decaying patterns are dependent on various factors: moisture, temperature regimes, nutrient availability for decomposing agents (Schowalter et al. 1998, Gora et al. 2018), altitude (Petrillo et al. 2015) and differ among logs components (Shorohova and Kapitsa 2016). To date, data on oak deadwood decomposition in Ukraine is actually lacking.

In this paper we describe our study of dead biomass role in Ukrainian oak forests, with focus on mature and over-mature stands, through: (i) presence and ecosystem distribution (i.e. links to forest type and site index) patterns of CWD in data of national forest inventory; (ii) estimation of C stock in a number of sample plots located in Central and Northern Ukraine with focus on CWD and fine litter; (iii) determination of some features of deadwood decomposition (annual decaying velocity independent on site conditions, relativeness to sampling size and type) using collected oak logs samples.

Data and Methods

Data

According to forest inventory evidence (databases of ‘Ukrainian State Forest Inventory Project’), oak stands of Ukraine grow on 1.8 million ha area and accumulate 377 million m^3 of growing stock volume (GSV), thus they have been used for analysis. Data is represented by 427 thousand inventory units, where stands of all age cohorts (young (1–40 years), middle-aged (41–80), immature (81–100), mature (101–140), over-mature (141+), relative to the lowest allowed final felling (LAFF) age in Ukraine, i.e. 101 years) have been found.

Sample plots were established in 12 mature and over-mature oak stands (101+ years old). These plots present mixed, mostly high-productive (site index I–II) stands within areas owned by State Enterprise ‘Lubny forestry’ (Poltava region, Central Ukraine, plots No 1–10) and of park ‘Feofania’ (Kyiv, Northern Ukraine, plots No 11–12). All plots represent geographical and climatic conditions common for Forest-Steppe subzone. Plots No 1–10 are located in the areas of continental climate subtype with mean temperature for the year 7.6 °C and average precipitation amount for the year 600 mm. Similar climatic conditions are observed for the areas where plots No 11–12 are located: for the year, average temperature and total precipitation are 7.2 °C and 690 mm, respectively (Weatherbase Climate Summary 2019). See Supplementary materials (Appendix 1) for list of geographical coordinates of sample plots, its location is given in Figure 1.

Representing biological productivity, site indexes in Ukrainian forest science range from the most productive stands (I_d–I_a) to the least productive (V_a–V_b) (Ostapenko and Tkach 2002). Forest types represent soil fertility (A – poor sand with the lowest fertility, B – sandy soils, C – loamy soils, D – loamy and clay soils with

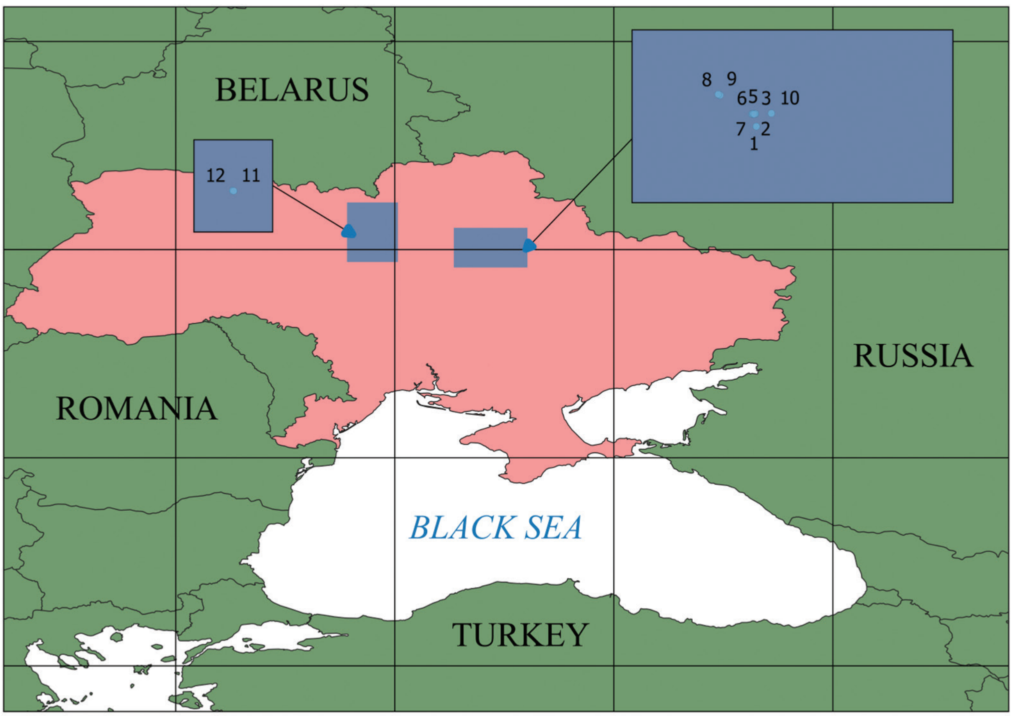


Fig. 1. Location of sample plots: stands No 1–10 belong to Poltava region and are situated in Forest-Steppe subzone that is common for oak, while stands No 11–12 are linked to Kyiv city and the northern edge of Forest-Steppe.

the highest fertility) and soil moisture (0 – extra-dry, 1 – dry, 2 – medium, 3 – wet, 4 – extra-wet, 5 – swampy). Growing with European hornbeam (*Carpinus betulus* L.), Norway maple (*Acer platanoides* L.), Littleleaf linden (*Tilia cordata* Mill.), European ash (*Fraxinus excelsior* L.), insignificant admixtures of European white elm (*Ulmus laevis* Pall.), Black locust (*Robinia pseudoacacia* L.) and Sour cherry (*Cerasus avium* L.) within, all 12 stands (Table 1) have soil and hydrological conditions which correspond to suitable development of Common oak (forest type – D_2). This forest type corresponds to mesic loamy soils, sufficient moisture content and high content of soil nutrients (Ostapenko and Tkach 2002). Typically, there is absence of understory due to the lack of light. Herewith, oak stands without European hornbeam contain understory formed by Common hazel (*Corylus avellana* L.), European spindle (*Euonymus europaeus* L.) and White dogwood (*Cornus alba* L.).

Table 1. Studied oak stands.

No of stand	A, years	D, cm	H, m	Relative stocking	GSV, $m^3 \cdot ha^{-1}$	Site index	Forest type
1	122	40.3	27.2	0.7	545	I	D_2
2	122	37.5	22.7	0.6	304	I	D_2
3	107	42.5	24.5	0.6	445	I	D_2
4	117	43.9	25.1	0.6	464	I	D_2
5	102	44.2	31.1	0.5	518	I	D_2
6	102	60.2	34.1	0.6	506	I	D_2
7	115	58.8	25.5	0.6	480	II	D_2
8	137	40.2	24.0	0.6	273	III	D_2
9	127	51.5	24.6	0.6	462	IV	D_2
10	107	41.8	24.0	0.6	520	I	D_2
11	178	68.2	34.8	0.4	496	II	D_2
12	175	52.0	35.0	0.7	304	II	D_2

Note: Site indexes presented here according to Ukrainian classification are relatively medium.

A number of logs samplings have been gathered for density dynamics estimation. These were collected mainly in the most common for oak growth conditions (D_2) presenting 79 % of the samplings' quantity, while forest types C_2 and D_3 were presented by 12 % and 9 % of total number, respectively. See Supplementary materials (Appendix 2) for detailed description of each sampling.

Thus, 94 logs' samplings with 1–50 years of time since tree death (Table 2) have been collected. Descriptive statistics for two main variables (remained density *Pt* and time since tree death *t*) are given in Table 3.

High values of variation and significant difference between skewness and excess indicate evident absence of normal distribution, because of presence of exponential distribution. We tested normality of distribution of remained wood density for samplings with Shapiro-Wilk test: obtained *p*-value 0.023 is lower than significance level (0.05), so respective null hypothesis must be rejected. Further analysis of model quality has thus been performed using nonparametric tests.

Table 2. Logs' samplings gathered for density dynamics estimation.

Component	Sampling diameter, cm	Time since tree mortality, years					Total
		1–10	11–20	21–30	31–40	41–50	
Stumps	to 20 cm	11	6	4	2	1	24
	over 20 cm	7	4	2	1	1	15
Other logs	to 20 cm	13	9	7	3	3	35
	over 20 cm	10	4	3	2	1	20
Total	–	41	23	16	8	6	94

Table 3. Descriptive statistics for logs' samplings.

Variable	*M*	*Me*	min	max	*v*, %	*Es*	*As*
Remained density, kg·m^{-3}	380	385	87	580	31	-0.89	-0.14
Time since tree death, yr	15	11	1	49	85	-0.57	0.84

Note: *M* – mean value; *Me* – median; *v* – coefficient of variation; *Es* – excess; *As* – skewness.

Methods

Processing of national inventory data

With aim to analyze ecosystem distribution of snags and logs (ratio to GSV in different combinations of site index and forest type), national forest databases were processed and filtered using following restrictions: (i) data with errors (e.g., presence of snags or logs and simultaneous absence of GSV) was excluded; (ii) each given combination of site index and forest type was excluded if its area did not exceed 100 ha; (iii) abnormal ratios (> 100 %) of CWD to GSV were excluded from analysis.

Measurements on sample plots

Permanent rectangular sample plots with area ranged from 0.05 ha to 0.84 ha were established following Lakyda et al. (2011) recommendations. Since studied forest stands had nature protection considerations and felling down of model trees could not be allowed there, for calculating the GSV we used common linear model with basal area, mean height and ratio coefficient as predictors (Svynchuk et al. 2014). Therefore, we conducted total survey of trees on sample plots with measuring of model trees heights via height-meters. Aiming to assess the wood density and mass of live biomass components, information-support materials (Lakyda at al. 2006, 2011) were used.

During sample plots establishment, field data was collected using software and hardware system 'Field-Map' (Buksha et al. 2006). Evidence from range-finder, height-meter and electronic caliper was passing into field computer where sample plot map had been created for further processing.

Dead biomass components on each sample plot were assessed according to common methodology of Harmon et al. (1986) and methods modified for Ukraine (Bilous et al. 2017b). Simultaneously with trees total survey, dead stems (snags) were determined by crown branches presence (I–IV groups) and decomposition state (I–II classes). Downed logs also were examined with length and diameter measuring and classification by decomposition state (I–V classes) and branches presence and wholeness (I–VI groups). This classification was performed with aim to use respective wood density ratios for different decomposition classes (based on Lakyda et al. 2006 data).

Three square plots with area 1 m^2 were established on each sample plot for coarse branches (d > 1 cm) litter and fine litter (including fine branches (d < 1 cm) and leaves litter) examination. Litter of coarse branches was estimated separately according to the method proposed by Bilous et al. (2017b), since this compartment is linked to specific microbiota that also is presented in forest logs and snags and rarely can be found in fine litter. Stock of dead roots was estimated with use of respective root content coefficients (as a ratio to stem live biomass, relating to snag biomass instead), according to Lakyda et al. (2006) data. Dead roots stock was computed in a same way, as a share to snags dead biomass stock. The same assumption was made for estimation of non-stem live biomass compartments (leaves and branches).

Estimation of biomass and C stocks

It was based on empirical and analytic data and was carried out according to Ravindranath and Ostwald (2008), and Intergovernmental Panel on Climate Change (IPCC 2006) recommendations. Carbon stock in every biomass component was estimated as a share of biomass in dry weight. For the stem and branches mass this ratio is 0.5 Mg $C \cdot t^{-1} \cdot m^{-3}$, for the crown leaves in live trees – 0.45 Mg $C \cdot t^{-1} \cdot m^{-3}$, for leaves litter in fine litter biomass component – 0.37 Mg $C \cdot t^{-1} \cdot m^{-3}$ (IPCC 2006). In order to estimate the dead biomass (litter of fine branches, leaves, and coarse branches) in dry weight, samplings were oven-dried until constant mass, then its weight was compared to the fresh one. There is a reference data (Lakyda et al. 2006) used for estimation of dry weight ratio for other biomass compartments (all live biomass compartments, CWD as mentioned above).

Processing of logs' decomposition data

Logs' samplings have been collected due to Harmon et al. (1986) and Yatskov (2016) recommendations in the areas either not linked to sample plots mentioned above (National Natural Park 'Holosiivskiy' and Boyarka Forest Research Station, in Kyiv) or within abovementioned park 'Feofania' in Kyiv. Samplings were collected only within stands where dates of tree mortality (loggings, storms, etc.) could be identified using forest planning materials. Diameters' distribution (to and over 20 cm) was chosen according to Harmon et al. (1986) conclusion that these logs' groups of late-seral tree species differ significantly in its density and decaying patterns. The chronosequence exponential equation by Olson (1963) for logs' density dynamics estimation is defined as (1):

$$P_t = P_0 \cdot e^{-k \cdot t} \quad (1),$$

where: P_t – remained density (kg·m^{-3}) at time t (yr) since tree death; P_0 – basic density (0.57 kg·m^{-3} for Ukrainian oak forests where samplings were collected); k – decomposition rate per year constant (yr^{-1}), computed as ln ($P_t \cdot P_0^{-1} \cdot t^{-1}$).

We tested similarity of distributions for different groups of samplings (stumps and logs with d < and > 20 cm) with non-parametric Kolmogorov-Smirnov test, aiming to examine whether dataset must be separated for further modelling or used whole (if estimated *p*-value for two sample distributions < significance level, i.e. 0.05). Same method was used for testing quality of exponential model, comparing observed and predicted values of wood density.

Results

CWD in mature and over-mature oak stands: analysis of national inventory

From the nearly 40 thousand of inventory units where mature and over-mature stands are formed by oak as main tree species (15.6 % of area), mean GSV has been found out as 280.6 $m^3 \cdot ha^{-1}$, which corresponds to 75.6 Mg $C \cdot ha^{-1}$ of mean C stock. Respective total stem over bark live biomass is 31.8 million t, which corresponds to 15.9 Tg C of sequestered C stock.

Since last state forest accounting in Ukraine (2011), snags (dead standing stems) and logs (downed stems, their huge parts and stumps) were accounted on the quite insignificant areas of oak mature and over-mature stands: 11.2 % and 4.1 % to total inventory unit's quantity, respectively, while any deadwood has not been found in 72.2 % of respective stands total area. Only 3.3 % of those forests had as snags as logs according to forest inventory data. Age cohort structure analysis is given in mean (Fig. 2) and total (Table 4) values.

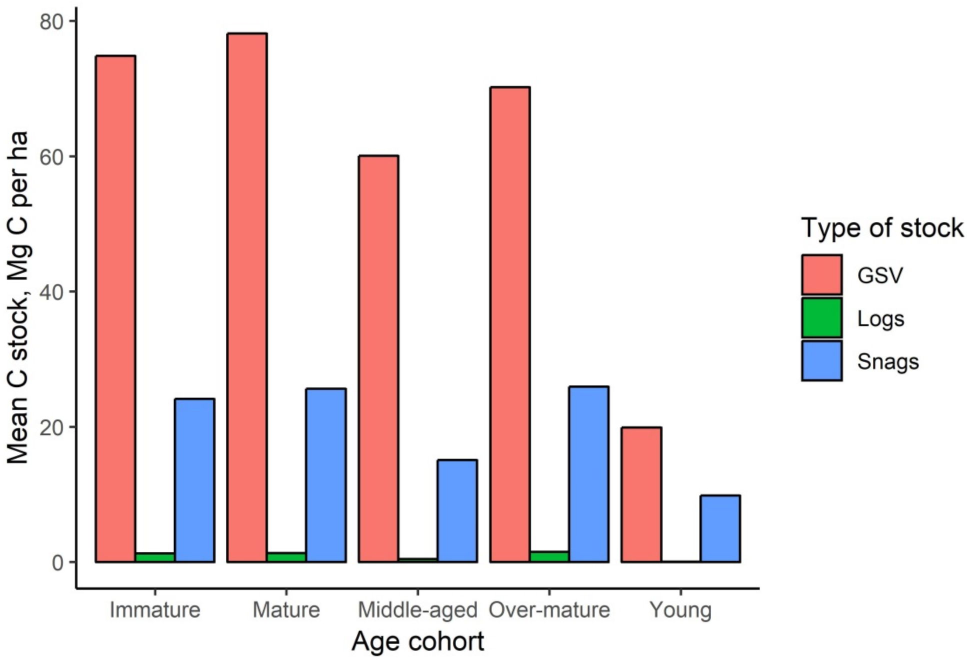


Fig. 2. Age cohort structure of mean C stock in GSV, snag and logs' compartments of oak stands in Ukraine.

Note: Mean values for GSV are given for all oak stands, irrespective whether those contain (according to inventory data) deadwood or not.

Table 4. Carbon of the stands where deadwood has been found: total values.

Age group	Stands area, thousands ha		Stored carbon, Gg C	
	with snags	with logs	snags	logs
Young	3.1	1.8	7.0	4.0
Middle-aged	148.4	42.3	399.2	102.8
Immature	92.2	31.6	265.1	78.7
Mature	45.7	17.2	152.6	44.5
Over-mature	6.6	2.0	26.3	6.6

Total volume snag stock of mature and over-mature stands has been found out as 0.7 million m^3, logs' volume stock – 0.2 million m^3. The carbon stock of these dead biomass components is 0.2 and 0.05 Tg C, respectively (Table 4). Logs, according to inventory data, start to accumulate only in age close to LAFF for common oak (Fig. 2); however, due to the competition between young trees, snags are presented in forest ecosystem starting actually from canopy closing.

Here is an analysis of spatial distribution given for GSV, snags' and logs' stocks in oak forests (all age cohorts) linked to administrative regions of Ukraine (Fig. 3).

Map in Figure 3 rather focuses on the administrative regions with specific values. Sumy region (1) is located in Polissya subzone, i.e. partially in the zone of mixed forests, and occasionally according to inventory data contains the highest

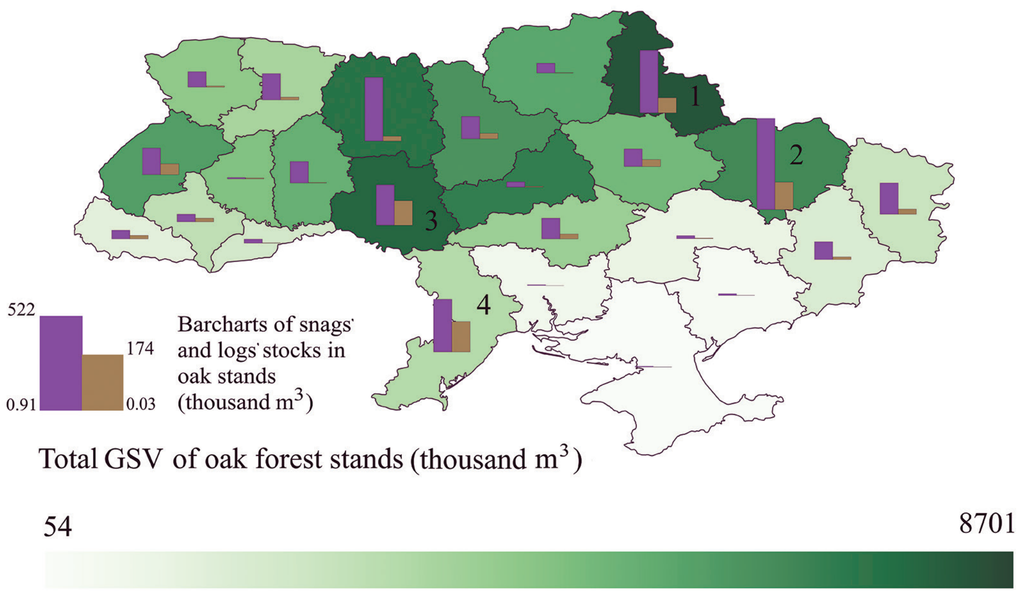


Fig. 3. Spatial distribution of oak GSV (gradient green scale), snags' and logs' stocks in Ukrainian administrative regions.

Note: Ranges of values are presented on legend scales. Regions with specific values here are presented as: 1 – Sumy region, 2 – Kharkiv region, 3 – Vinnytsya region, 4 – Odesa region.

total oak GSV among Ukrainian regions. The highest snags' total stock belongs to Kharkiv region (2) – typical area within Forest-Steppe subzone. The best geographical conditions for growth of oak are linked to Vinnytsya (3) region; however, stands located there contain the highest logs' stock among regions. The north of Odesa (4) region belongs to Forest-Steppe subzone, while coastal regions are relatively forestless. Herewith, this region not only contains the largest oak stands in southern Ukraine, but also accumulates substantial stocks of deadwood.

In order to analyze ecosystem distribution of either snags' or logs' ratio to GSV in mature and over-mature oak forests, we assessed mean values for inventory units (i.e. stands) linked to site indexes and forest types. Assessed composition for all age cohorts for Ukrainian oak forests is given in Supplementary materials (Appendix 3) for comparison. Here compositions for studied age cohorts (mature and over-mature) are given for mean snag ratio (in %) to GSV (Fig. 4) and mean logs' ratio to GSV (Fig. 5).

Figure 4 does not contain site indexes such common for oak in Ukraine: I, Ia, Ib and Ic. Same situation occurred for logs to GSV ratio (Fig. 5). Herewith, extra-dry sites (forest types A) are also not given in these heatmaps. Gaps in graphs and absent combinations indicate that these classes were presented only on the sites with total area < 100 ha.

Data on CWD presence in national inventory databases is however limited. On the other hand, Figure 4 and Figure 5 explicitly explain ecosystem distribution of oak deadwood: higher ratios are given for combinations of drier and especially wetter forest types and stands with low productivity (site indexes 2–4).

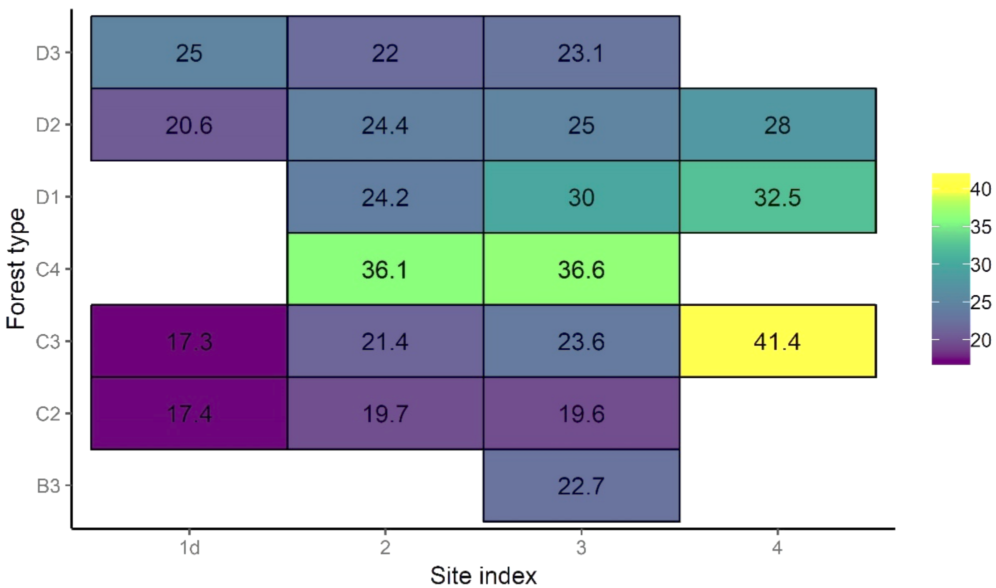


Fig. 4. Heatmap of ecosystem distribution of snag compartment.

Note: Numbers and color of boxes represent gradient scale of mean snag ratio (in %) to GSV. Data was computed explicitly for each oak stand, then mean values were estimated.

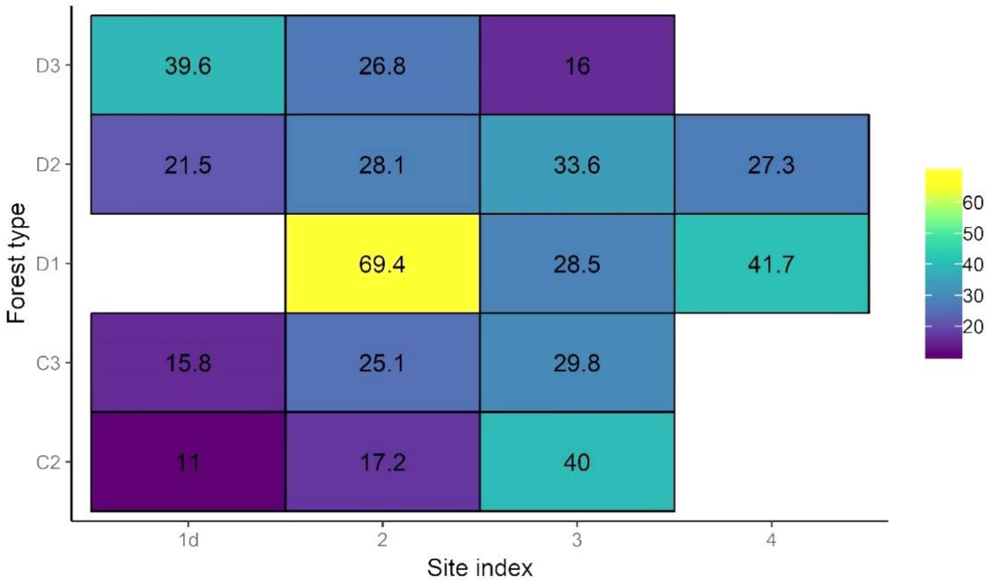


Fig. 5. Heatmap of ecosystem distribution of logs' compartment.

Note: Gaps in the graph correspond to the absence of compartment in the stands with respective combination of site index and forest type or restrictions described in Methods and Materials.

Dead biomass in studied stands

Since only C stock in live stem biomass of oak stands could have been estimated through forest inventory databases, potential carbon share of the rest live biomass compartments (crowns, roots) and dead biomass may be obtained with use of sample data from studied stands. Box-whisker plots with median and mean values for C stock of dead biomass compartments are given in Figure 6. Table with values given for all studied stands see in Supplementary materials.

Hence, mean carbon stock of dead biomass in studied oak stands is 15.6±1.4 Mg C·ha^{-1}. Share of CWD and fine litter is almost equal: 7.5 and 7.6 Mg C·ha^{-1}, respectively, the rest is accounted for under-ground dead biomass (Fig. 6). The carbon stock in live biomass of stems, crowns and roots of studied stands is 153.2±8.7 Mg C·ha^{-1}. Therefore, 168.8±9.2 Mg C·ha^{-1} is sequestered in total stand biomass of studied oak forests, while dead biomass takes 9.3 % share within.

Logs wood density dynamics

Statistical difference between samplings that represent logs and stumps with *d* more and less 20 cm was tested using Kolmogorov-Smirnov λ-test. *D*-statistics (supremum function of difference between two sample distributions, empirical and predicted ones, i.e. core value of λ-test) for all tested combinations (logs with *d* less and more 20 cm, stumps with *d* less and more 20 cm, all logs and all stumps, all sampling with $d < 20$ cm and with $d > 20$ cm) were given as 0.2, 0.13, 0.16 and 0.11, respectively, and all estimated *p*-values were higher than significance

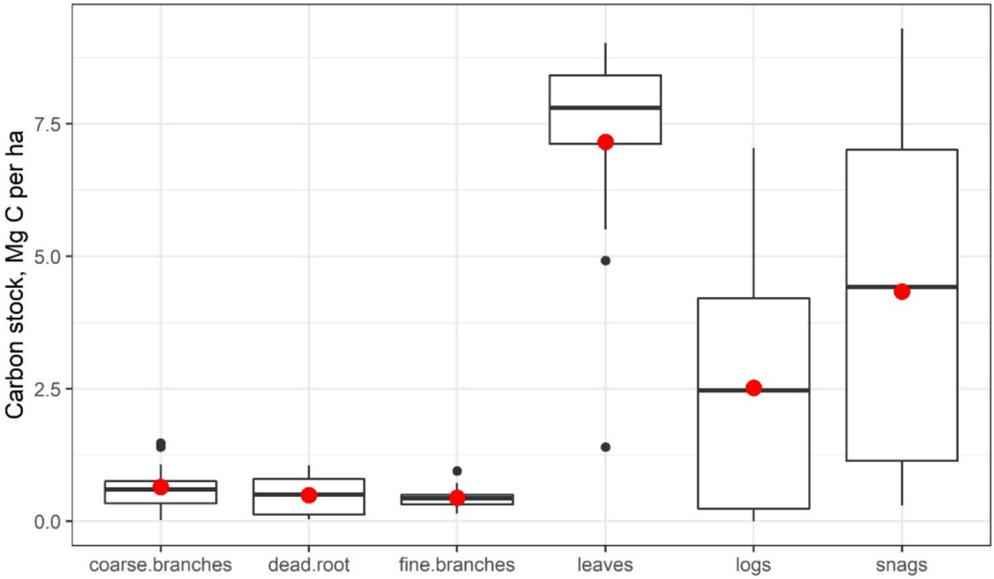


Fig. 6. Box and whisker plots of C stock among 12 sample oak stands.

Note: Horizontal line in each box is a median, while box represents 0.25–0.75 quantiles. Whiskers indicate to full range of compartment C stock. Red points are the respective mean values.

level (0.05): 0.69, 0.97, 0.58, 0.96. Result of this test has thus shown that no difference between samplings relative to its diameter or type (either log or stump) exists. As no statistical difference between diameter groups was found, model of oak logs decomposition was built basing on all 94 logs' samplings (Fig. 7).

Regression (Fig. 7a) shows next exponential-based model (2):

$$P_t = 514.5 \cdot e^{-0.023 \cdot t} \quad (2)$$

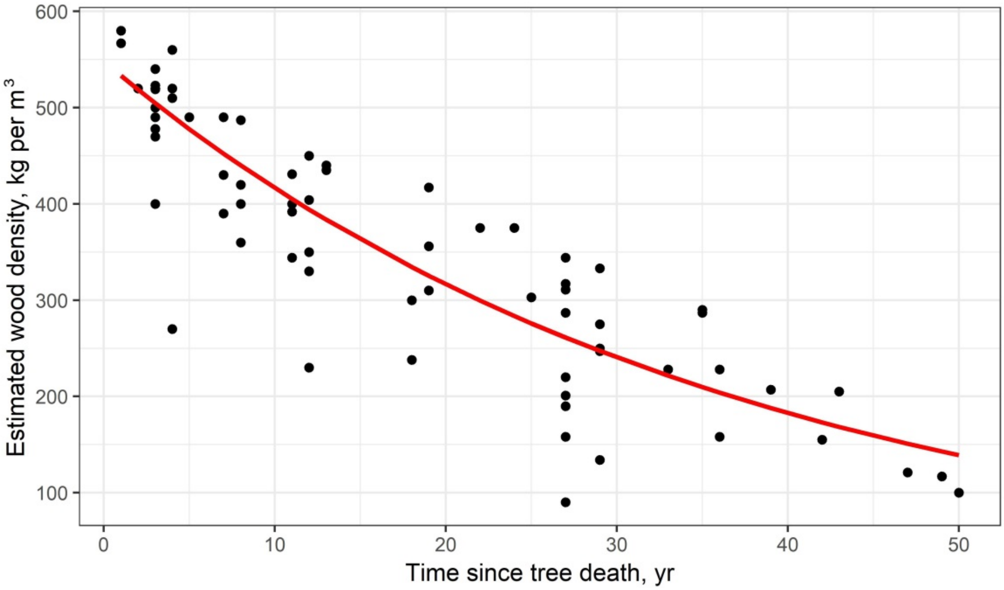
Coefficient of determination (R^2) is 0.75. Observed and predicted by model (2) values are agreed quite well, being adequately distributed along 1:1 reference line on the graph (Fig. 7b). Residuals of the model are randomly distributed, irrespective to sampling diameter (Fig. 8).

We tested model quality using non-parametric Kolmogorov-Smirnov λ-test. Estimated value of *D*-statistics is 0.13, and estimated *p*-value is 0.43 (with significance level 0.05). Since estimated *p*-value is higher than significance level, null hypothesis of distributions similarity between observed and predicted wood density with given model cannot be rejected, indicating to adequacy of mentioned exponential model.

Discussion

Empirical and inventory data on CWD

CWD thus has been found more in studied stands than considered in forest inventory databases. According to that evidence, actually only 1.4 % C as a ratio to live biomass sink is sequestered in CWD (coarse branches litter is not considered). In studied oak stands, CWD share in C stock



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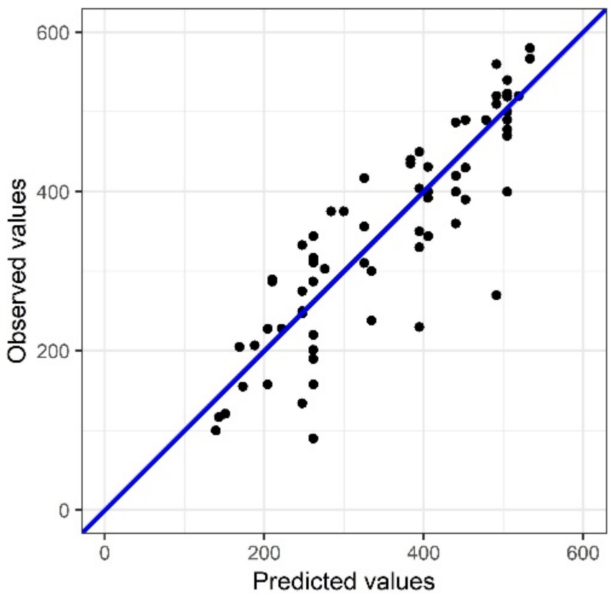

b

Fig. 7. Pattern of Common oak logs' decomposition: a) exponential model is drawn for empirical data; b) agreement between observed (empirical) and predicted (modelled) values of basic wood density at time unit since tree death.

Note: Blue line represents 1:1 line.

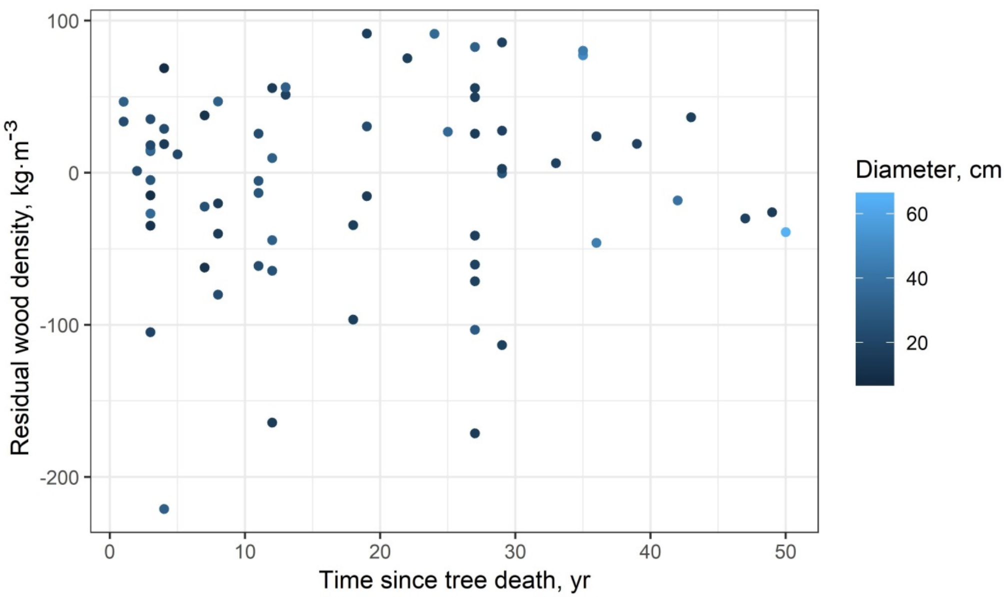

Fig. 8. Residuals of predicted wood density for oak logs' samplings are coloured by samplings' diameter.

structure is much higher – 6.0 %. Such insignificant CWD stocks in mature oak forests of Ukraine accounted in forest inventory data can be explained by the fact that dead stems (snags) and/or downed logs are only started to be accounted by inventory officers if they evaluate its presence at level 5 $m^3 \cdot ha^{-1}$ or more (Matsala and Bilous 2017).

Actually, there is still common to take out these dead biomass components from the forest during the silviculture activities in many state forest authorities with stands without nature considerations or protection regime. Moreover, as studied oak stands are concentrated in areas with high nature value, even there CWD stocks must be higher, especially after gap-scale natural disturbances (wildfires, storms, pest and diseases affection). Herewith, massive salvage loggings in the forest with nature concern (like sample stands in 'Lubny forestry', Poltava region) or in the park located within the capital city (like sample stands in 'Feofania', Kyiv), are still common practices with aim to prevent fast pest spreading after outbreaks occurrence or to provide humans safety, respectively (Pasternak 2011).

Fine litter remains a main dead biomass compartment in oak stands until achieving maturity. Further, CWD accumulates higher C stocks, simultaneously leading to increasing C emissions from deadwood through decomposition, but being a key ecosystem component related to biodiversity preservation. This pattern can be seen comparing fine litter ratio in studied stands (49 % of dead biomass C stock) to Bilous et al. (2017a) data (43 % ratio in over-mature stand), while this ratio in middle-aged (75 years) exceeded 73 %.

Reliability of plot and inventory data

Pasternak (2011) found out that oak stands of North-Eastern Ukraine had had 1.3 % snags' ratio to GSV (forest type – D_2) in mature stands and 9.2 % ratio in over-mature forests (state on 2006). Snags' and logs' carbon stock (in the stands of all age cohort groups) also was estimated, for D_2 forest type in particular. Resulted mean C stocks are 2.5 Mg C·ha^{-1} for snags and 2.1 Mg C·ha^{-1} for logs, which are less with 41 % and 16 % than C of these dead biomass components from studied stands presented in this study, respectively. Such difference might be explained by the fact that Pasternak took into account stands of all age cohorts (with no data separated by these cohorts) while we focused on mature and over-mature forests.

Comparison of stem over bark live biomass carbon with Lakyda et al. (2006) data from Podillya oak woods (South-Western Ukraine) has shown 17.5±3.5 % deviation (Fig. 9), taking into account four 102–107 years old stands (site index I, forest type D_2) that are the most similar to our studied data. Such comparison was needed because of high dependence of different compartments presented in this study (crown and root live biomass, dead roots) on stem over bark stock. Deviation mentioned above could be explained by difference in precipitation and temperature regimes, soil conditions, with regard that plots in our studied stands were established actually in central and northern part of Ukraine, where continental climate

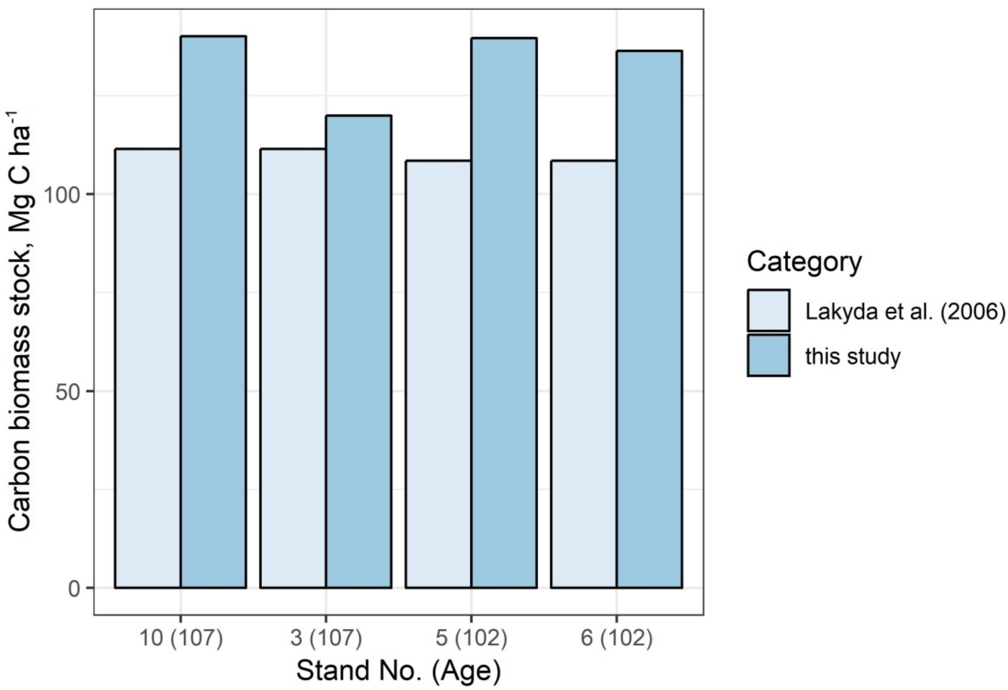

Fig. 9. Comparison of sample plot data from this study and Lakyda et al. (2006) data (stem live biomass C).

Note: Stand numbers are given according to Table 1.

defines local forest growth and yield more explicitly (Bilous et al. 2017a).

Herewith, apparent biases in accounting of CWD in Ukrainian forest inventory data aggregated in 2011 still exist. This study focuses on mature and over-mature oak stands, and for these two age cohorts the share of inventory units with odd values (absent data on GSV or snags'/logs' stocks that exceed GSV for given stand) is relatively low – 1.6 %. However, if all age cohorts are taken into account, this share will achieve 14.7 % level. Such biases create discrepancies in efforts to examine CWD accumulation patterns along oak forest life cycle in a robust way.

Carbon stock in CWD according to ecosystem distribution

The highest CWD ratio relatively to stem live biomass is observed in conditions not suitable for oak successful growth: too dry or too wet, soils with limited amount of nutrients (Figs 4 and 5), which corresponds to less productivity of those stands. Larger stocks of CWD there might be explained by higher natural mortality rate and worse resistance to the insect outbreaks, disease affections and even storm damage. Another explanation could be that less productive oak stands and forests which have been grown in very dry or wet conditions occur mostly in nature reserves, so CWD is not used to being removed from there during silvicultural activities (Bilous et al. 2017b). Furthermore, such mature stands are often not felled for a long time and become over-mature, so have possibility to store more carbon exactly in CWD (Bölöni et al. 2017).

Heatmaps (Figs 4 and 5) actually do not contain data on less fertile forest types (A and B), because of insignificant areas covered by such oak stands. On the other hand, CWD accumulated there can achieve relatively high ratios to GSV (70–90 %). Herewith, this feature may correspond to the errors in national forest inventory data mentioned above. Another feature is that the most common site indexes for managed oak forests in Ukraine (i.e. I, Ia, Ib, Ic), which simultaneously correspond to high biological productivity there, are absent in given heatmaps. We can explain this by management regime been typical in Ukraine: high-productive oak forests due to high timber prices are commonly cut with final felling in the age of 101–110 years, while the 'worse' in economic sense stands (site indexes II–V) can be retained: rarely – for tree species diversity and other natural concerns, more often – with aim to reduce financial loss if such stands would be felled (Pasternak and Yarotskii 2013).

Figure 4 shows typical CWD composition among the oak stands with different range of nature-protection regimes. To date, one forest owners linked to state authorities retain logs and snags as the significant ecosystem component while others prefer to remove those in order to minimize wildfire, pest and diseases spreading risk, aiming to keep high-value wood in mature stands safe and even despite the fact that those stands had natural provenance and were characterized by sustainable growth (Pasternak 2011). On the other hand, coarse branches litter does not fluctuate so much like compartments of snags or logs. Downed branches with d > 1 cm but those are relatively thinner than 'logs' (which thus can be removed from forest during salvage logging or other silvicultural activity), is the crucial component of oak dead biomass, being a specific habitat for microbiota and subsequently positively influencing on forest soil fertility (Holaka al. 2017).

Logs density dynamics

Regression equation used by Yatskov et al. (2003) shows reliable chronosequence of logs' decomposition process. Results correspond to Harmon et al. (1986) evidence about potential of CWD in late-seral forests to store C until full decomposition for decades. No statistically significant difference in remained wood density between diameter groups has been found in contrast to coniferous species in north-western part of USA studied by Harmon et al. (1986), which have apparently other biological features and conditions than common oak in continental Europe. Herewith, stumps also have not shown any difference in decomposition pattern with the logs, although these are used to having larger contact surface with soil (and consequently with its microbiota). Yatskov et al. (2003) indicated that moisture is the main factor that drives CWD decaying, while high mean annual temperatures also cause substantial impact on decomposition, amplifying this process. Therefore, low influence of CWD size on its decaying can be explained by the fact that relatively dry continental regime in Ukraine along all seasons does not actually support decomposers activity, thus keeping decomposition process stable irrespective of logs size. Same situation was found by Bölöni et al. (2017): dry-mesic sites create conditions that decrease decomposition velocity.

However, Herrmann et al. (2015) estimated that with increasing of logs' diameter decomposition velocity is dampening: comparing groups with $d < 20$ cm and $d > 40$ cm, respective rates for European beech (*Fagus sylvatica* L.) and Scots pine (*Pinus sylvestris* L.) decreased twice. Herewith, no significant difference was found for Norway spruce (*Picea abies* L.). Study sites from Herrmann et al. (2015) research were located in Northern Germany, i.e. on the same latitude with Ukraine, however climate there is relatively more humid. Another suggestion why this study has not found difference for diameter groups in oak CWD decomposition could be in biophysical parameters of oak stemwood.

Exponential modelling shows that logs can decompose until 40–50 $kg \cdot m^{-3}$ remained wood density for 100 years, which proves CWD potential to store C so long in temperate latitudes. Therefore, oak deadwood in Ukraine is crucial not only as a habitat and preservation source for species diversity in forest ecosystem, but also as mid-term C sink with relatively low decomposition rates and consequently – C emissions back to atmosphere. This fact thus opens new evidence for preserving CWD in managed forests and keeping old-growth oak stands intact.

Conclusions

By accumulating carbon for decades, dead biomass plays significant role in mature and over-mature oak forest ecosystems of Ukraine. Hoverer this pool is smaller in Ukrainian oak forest compare to natural and protected oak forest in other European countries. Insignificant dead biomass stock in oak stands might be explained by high economic demand on wood taken off during the management activities aiming to reduce the risk of insects' and fungi's outbreaks.

On the other hand, coarse woody debris pool is underestimated by Ukrainian forest inventory. CWD takes a special place as an effective C sink in mid-term perspective according to low decomposition rate: carbon in deadwood may be stored during 100 years until actually total biomass decaying. This fact is quite important for efforts to maintain the forest biodiversity and mitigate climate changes.

Hopefully, following the comprehension of role of forests and dead biomass in particular as a strong source of different ecosystem services and due to commitments taken in climate change and biodiversity issues on international level, conditions for CWD accounting and preservation in oak forests of Ukraine will occur soon.

Acknowledgements

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Appendix 1

Table A1. Geographical coordinates of sample plots.

No of stand	Age cohort	Latitude (N), °	Longitude (E), °
1	Over-mature	32.999	49.990
2	Over-mature	32.977	50.059
3	Mature	32.981	50.060
4	Mature	32.982	50.060
5	Mature	32.994	50.059
6	Mature	32.993	50.060
7	Mature	32.987	50.058
8	Over-mature	32.809	50.162
9	Over-mature	32.800	50.167
10	Mature	33.078	50.062
11	Over-mature	30.484	50.344
12	Over-mature	30.496	50.341

Appendix 2

Table A2. Description of oak logs' samplings collected for decomposition analysis.

No of sampling	*Pt*, $kg·m^{-3}$	*t*, yr since death	D, cm	Group
1	450	12	16	logs
2	250	29	18	logs
3	560	4	10	logs
4	121	47	19	logs
5	117	49	16	logs
6	490	7	12	logs
7	430	7	16	logs
8	330	12	13	logs
9	190	27	19	logs
10	540	3	12	logs
11	520	3	14	logs
12	400	11	16	logs
13	333	29	19	logs
14	567	1	10	logs
15	580	1	8	logs
16	228	36	19	logs
17	440	13	16	logs
18	311	27	18	logs
19	510	4	8	logs
20	500	3	12	logs
21	431	11	14	logs
22	417	19	18	logs
23	420	8	16	logs
24	300	18	18	logs
25	400	8	12	logs
26	390	7	12	logs
27	375	22	18	logs
28	435	13	16	logs
29	317	27	18	logs
30	500	3	12	logs
31	490	3	16	logs
32	207	39	19	logs
33	205	43	18	logs
34	287	27	16	logs
35	275	29	19	logs
36	520	4	24	logs
37	500	3	28	logs
38	404	12	32	logs
39	392	11	28	logs
40	360	8	24	logs

No of sampling	***Pt*, kg·m^{-3}**	***t*, yr since death**	**D, cm**	**Group**
41	287	35	50	logs
42	430	7	26	logs
43	290	35	44	logs
44	350	12	32	logs
45	344	27	32	logs
46	523	3	22	logs
47	519	3	26	logs
48	344	11	24	logs
49	520	2	24	logs
50	155	42	40	logs
51	487	8	32	logs
52	375	24	36	logs
53	440	13	28	logs
54	303	25	36	logs
55	490	5	22	logs
56	230	12	16	stumps
57	90	27	16	stumps
58	540	3	10	stumps
59	520	3	12	stumps
60	400	11	16	stumps
61	134	29	18	stumps
62	567	1	18	stumps
63	580	1	12	stumps
64	228	33	19	stumps
65	440	13	18	stumps
66	201	27	19	stumps
67	510	4	16	stumps
68	400	3	20	stumps
69	431	11	16	stumps
70	310	19	16	stumps
71	420	8	16	stumps
72	238	18	18	stumps
73	400	8	16	stumps
74	390	7	12	stumps
75	375	22	18	stumps
76	435	13	19	stumps
77	220	27	18	stumps
78	470	3	12	stumps
79	490	3	10	stumps
80	330	12	26	stumps
81	158	27	30	stumps
82	540	3	24	stumps

No of sampling	***Pt*, kg·m^{-3}**	***t*, yr since death**	**D, cm**	**Group**
83	520	3	36	stumps
84	400	11	28	stumps
85	247	29	28	stumps
86	567	1	24	stumps
87	580	1	32	stumps
88	158	36	45	stumps
89	440	13	32	stumps
90	100	50	65	stumps
91	270	4	32	stumps
92	478	3	36	stumps
93	431	11	24	stumps
94	356	19	24	stumps

Appendix 3

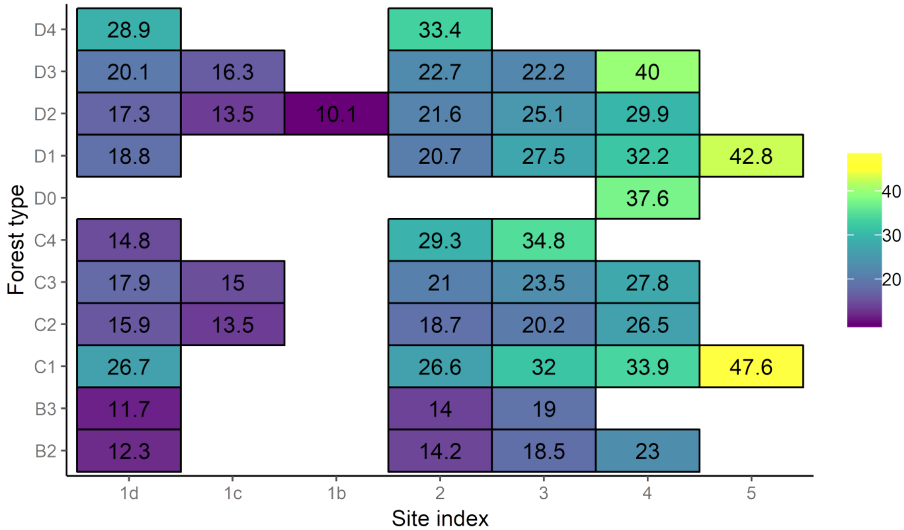

Fig. A3-1. Heatmap of ecosystem distribution of snag compartment in oak stands of all age cohorts.

Note: Numbers and colour of boxes represent gradient scale of mean snag ratio (in %) to GSV. Data was computed explicitly for each oak stand, then mean values were estimated.

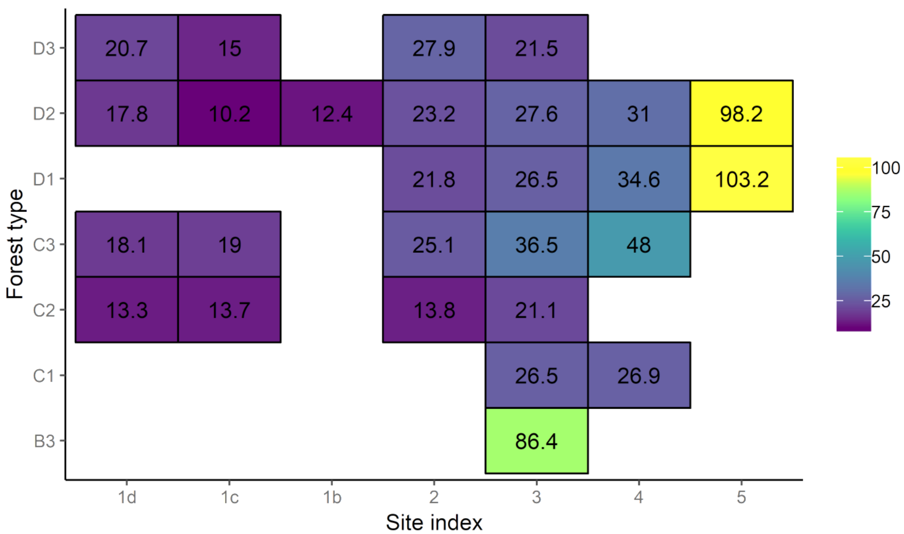

Fig. A3-2. Heatmap of ecosystem distribution of logs' compartment in oak stands of all age cohorts.

Note: Gaps in the graph correspond to the absence of compartment in the stands with respective combination of site index and forest type or restrictions described in Methods and Materials.