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Energy potential of main forest-forming species of stands in the Northern Steppe, Ukraine

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Abstract

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The study evaluated the energy potential of Scots pine and black locust stands within the Northern Steppe of Ukraine, in forest plantations subordinated to the State Agency of Forest Resources (Ukraine). This study defined general values of aboveground biomass components per age-class structure in the forest stands. Allocated carbon was calculated using the biomass components by age groups as follows: stem, branches and leaves (needles). Contribution of different age groups to carbon allocation was investigated. A key role of stem wood in the process of carbon allocation in the forest stands was shown. It was found that the maximum carbon budget was accumulated in stands of both forest-forming species aged 41–60 years. The models are made on a dependence of carbon allocation in the different components of aboveground biomass by age. Results of energy content in the aboveground biomass were presented in Scots pine and black locust stands within the surveyed area. The study has shown that the energy potential of carbon accumulated in the biomass of Scots pine stands amounted to 40.31 PJ, and that of black locust stands was 32.04 PJ. Development of forest ecosystems in the Steppe zone of Ukraine can result in the optimization of abiotic conditions on a local level under the influence of the global climate changes.

Keywords: black locust; Scots pine; aboveground biomass; carbon allocation; age structure

Energy security and creation of the internal energy base that uses local alternative energy sources are the parts of the Strategy for Sustainable Development of Ukraine (Breymeyer et al. 1998; Shepashenko et al. 1998; Ritson, Sochacki 2003; Gough et al. 2008; Pan et al. 2011; Woodall et al. 2013; Lindner et al. 2014; Birdsey, Pan 2015).

Annually, about 21 × 10^7 t of fuel equivalent to energy resources are consumed in Ukraine; that is why Ukraine has experienced a shortage of energy supplies (Kudrya et al. 2010). At the same time Ukraine has a considerable potential to use non-traditional and renewable energy sources. Use of such sources is characterized by a positive trend in the energy balance of the country: in 1995 – 0.13%, in 2000 – 5.3% (Makarovskiy 2004; Lakyda, Vasylyshyn 2006; Adamenko et al. 2010).

The abovementioned information calls for an importance to implement systematic national policy and to use renewable energy sources. This kind of sources can be applied in energy saving both on the regional and local levels. Biomass of forest ecosystems is also one of such sources (Makarovskiy 2004; Gruenewald et al. 2007; Timilsina et al. 2014; Cosmo et al. 2016).

The biomass provides primary production of organic matter in the native forest ecosystems amounting to 4–50 $t \cdot ha^{-1} \cdot yr^{-1}$, equivalent to 15–25 × 10^4 $MJ \cdot ha^{-1}$ of stored energy (Tretyak 2014). Tree biomass is one of the few environmentally friendly fuels. It is a renewable source of energy production, the use of which can be managed (Fiorese, Guariso 2013). In Ukraine total amount of carbon allocated by forest stands is equal to

766.4×10^6 tC. According to LAKYDA et al. (2007), forest biomass in Ukraine amounted to 1.24×10^9 t, and the biomass accumulates about 615 MtC.

Recently, a considerable number of complex surveys has been conducted on forest stand bioproductivity with separate biomass components and values of carbon allocated in forest plantations within different climatic and edaphic zones worldwide (YAKYMENKO et al. 2001; DOLMAN et al. 2002; BALBOA-MURIAS et al. 2006; PIETRZYKOWSKI, SOCHA 2011; YÜKSEK 2012; PAUL et al. 2013; VERKERK et al. 2014; WILLIAMS et al. 2016).

However, no work on this issue has been conducted for the forest stands in the Steppe zone of Ukraine. Natural conditions of the Steppe zone are far from optimal criteria for effective implementation of environmental, recreational, soil-protective, and water-protective functions. Enforcement of compliance sustainable development criteria within the region is the primary task of steppe forestry.

Assessment of carbon allocation in stands by forest-forming species of different ages and in the main separate components of their aboveground biomass is a very interesting and relevant issue in environmental conditions of the Northern Steppe. Forest ecosystems perform crucial ecological functions in the Northern Steppe. They accumulate significant volumes of energetic biomass such as fuel wood which is one of the main sources of potential energy in the region.

The objective of the study was to evaluate the potential energy of stands of the main forest-forming species within the Northern Steppe (Ukraine) on the basis of aboveground biomass components and values of carbon allocation. The data obtained allow to conduct a comparative analysis of the main forest-forming species of steppe forests such as black locust (*Robinia pseudoacacia* Linnaeus) and Scots pine (*Pinus sylvestris* Linnaeus) in the context of their age groups, and to identify the dominant biomass component that deposits carbon.

MATERIAL AND METHODS

Site of the study. The study was conducted in monoculture Scots pine and black locust stands in Dnipropetrovsk region, which is located in the Northern Steppe of Ukraine and covers 31,974 km^2. The sites were established in different parts of Dnipropetrovsk region (47–49°N; 33–37°E) (Fig. 1). The climate of the area is temperate continental with mild winter having a small amount of snow, and hot, dry summer with frequent downpours and strong southern winds. Average annual temperature (during the last 25 years) is 10.6°C, and annual total precipitation is 400–490 mm.

The surveyed sites are located in 4 enterprises within the responsibility of the State Agency of Forest Resources: Dnipropertrovskiy – 12 plots, Novomoskovskiy – 9 plots, Vasilkovskiy – 6 plots and Verchnedneprovskiy – 3 plots (Fig. 1). Total number of sample plots was 30 (area 50 × 50 m).

Field surveys and laboratory analyses. As a basis for the study, a modern technique was used for collecting and processing the experimental data, which utilizes advantages of progressive vision in field and laboratory work having a systemic approach and

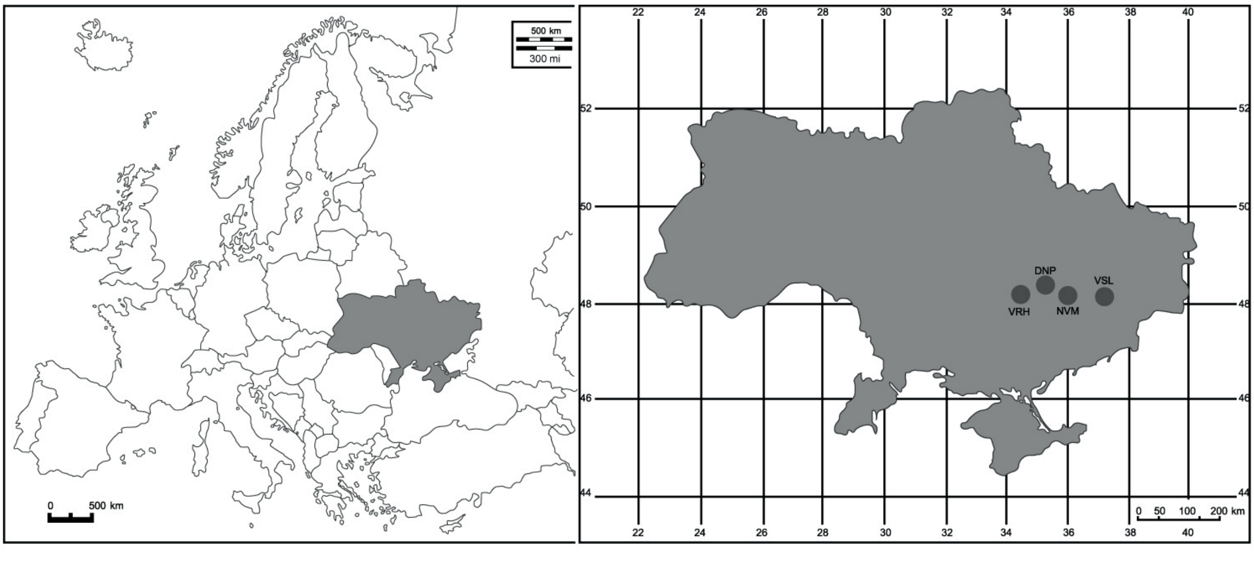

Fig. 1. Location of surveyed sites

DNP – Dnipropertrovskiy, NVM – Novomoskovskiy, VRH – Verchnedneprovskiy, VSL – Vasilkovskiy practical application. The technique successfully combined mensurational and biometric methods, applied theoretical generalizations with statistical and mathematical methods (Lakyda 2002).

The sampled plots were selected in forest stands in the responsibility of the Dnipropetrovsk Administration of Forest and Hunting Management. Temporary sample plots (TSP) were planted in forest types typical of the Northern Steppe zone, having high quality and belonging to different age groups. Number of all trees was counted within the TSP, and diameter and height were measured for each tree; then trees were ranked by their diameters. Selection of 3 sample trees within the TSP was conducted by different diameter of stem.

Methods of Lakyda (2002) were used for the calculation of biomass in Scots pine and black locust stands within the TSP.

As the first step natural and basic density of different components of aboveground biomass was established. After cutting of sample trees within the TSP, dendrometric measurements were carried out when measuring 6 diameters at the root collar, 1.3 m (DBH), and relative height of trees – 0.1, 0.25, 0.50, 0.75. To determine stem and bark natural and basic density of the sample trees, wood cross-sections (of about 2–3 cm in thickness) were cut along the stem. Samples of wood cross-sections were weighed in freshly-cut state, and their volume was calculated as the sum of the volumes of 18 wood cross-sections using some special programs as follows: ZRIZ (Version 2002), PLOT (Version 2002) (Lakyda 2002; Lakyda et al. 2007). The calculation of basic density required drying of the samples at a temperature of 105°C. Basic density was calculated at the oven-dry mass per unit volume. Average natural and basic branch density calculation was the selection of sample branches and determination of the volume using special programs ZRIZ, PLOT. The branch mass was determined by a weighing method.

On completing all the TSP measurements using the special programs PERTA (Version 2002) the number of trees per hectare and wood stock over and under bark on trees in different age groups were calculated.

Stem biomass was calculated by multiplying wood stock (over bark) by average basic density of wood. The total stem biomass was calculated by multiplying stem biomass per hectare by the area covered by the investigated age group.

Branch biomass (B_{branches}) was calculated using Eq. 1:

$$B_{\text{branches}} = \left(V_{\text{small branches}} + V_{\text{big branches}}\right) \times p_{\text{branches}} \tag{1}$$

where:

$V_{\text{small branches}}$ – volume of branches below 1 cm in diameter over bark (m^3),
$V_{\text{big branches}}$ – volume of branches above 1 cm in diameter over bark (m^3),
p_{branches} – average basic branch density ($kg \cdot m^{-3}$).

Biomass of big branches having diameter ≥ 1 cm was obtained using a mathematical relationship knowing the weight of branches and the number of trees on the TSP. Biomass estimation of small branches was obtained by the subtraction of foliage biomass [branches having diameter < 1 cm with leaves (needles)] and biomass of leaves (needles).

Leaf (needle) biomass was calculated by Eqs 2 and 3:

$$\text{LB} = \text{LB}_{\text{share}} \times \text{TB} \times N \times S \tag{2}$$

where:

LB – leaf biomass,
LB_{share} – percentage share of the total weight of the needles for a mean sampled tree in the stand which is equal to the dimensions of mean tree in the experimental plots,
TB – total biomass of mean sampled tree,
N – number of trees per hectare,
S – area covered by the age group.

$$\text{LB}_{\text{share}} = \left(\frac{\text{LB}}{\text{TB}}\right) \times 100 \tag{3}$$

Total aboveground biomass of Scots pine and black locust stands was calculated as the sum of stem biomass, branch biomass and leaf (needle) biomass for every age group.

Carbon allocation in aboveground biomass was estimated by averaged data from scientific literature where the average carbon allocation ratio per 1 t of wood biomass amounted to 0.50, and that of leaves (needles) was 0.45 (Matthews 1993). Energy potential per 1 t of carbon accumulated in aboveground biomass amounted to 35.78 GJ (Matthews 1993). The mathematical models of total carbon allocation to components of aboveground biomass were statistically verified using the program STATISTICA (Version 12.6, 2015).

RESULTS

The analysis of inventory data showed that the total area of Scots pine stands within the Northern Steppe of Ukraine reached 21,427 ha (32.5% of the total area covered with forest vegetation) with the total wood stock of 4,571.1 thousand m^3. Native

Table 1. Ecological potential of Scots pine and black locust stands (aboveground biomass components) in the Northern Steppe of Ukraine

Groups (yr)	Species	Area (ha)	Dry organic matter (thousand t)					Carbon allocation (thousand t)				
			trunk		branches	needles/ leaves	total	trunk		branches	needles/ leaves	total
			wood	bark				wood	bark			
1–20	Scots pine	1,329	1.56	0.36	0.28	1.98	4.18	0.78	0.18	0.14	0.89	1.99
	black locust	1,329.8	1.86	0.32	1.05	0.86	4.09	0.91	0.16	0.52	0.43	2.02
21–40	Scots pine	5,512.6	511.82	29.82	47.68	32.91	622.23	255.91	14.91	23.84	14.81	309.47
	black locust	3,710.2	226.40	48.71	72.31	12.28	359.70	110.94	23.87	35.43	5.53	175.77
41–60	Scots pine	9,363.9	820.18	116.35	53.75	29.50	1,019.78	410.09	58.17	26.87	13.27	508.40
	black locust	11,911.8	924.00	212.51	202.98	41.81	1,381.30	452.76	104.13	99.46	18.81	675.16
61–80	Scots pine	404.8	450.74	47.81	33.22	16.0	547.77	225.37	23.91	16.61	7.20	273.09
	black locust	731.8	59.62	14.40	13.22	1.84	89.08	29.21	7.06	6.48	0.83	43.58
81–100	Scots pine	785.3	67.36	6.39	6.31	2.56	82.62	33.68	3.20	3.16	1.15	41.19
Total	Scots pine	21,427.0	1,851.66	200.73	141.24	82.95	2,276.58	925.83	100.37	70.62	37.32	1,134.14
	black locust	17,683.6	1,211.88	275.94	289.56	56.79	1,834.17	593.82	135.22	141.89	25.60	896.53

pine stands take up the area of 3,694 ha (17.2% of the total area of pine stands), while artificial pine forest stands were located on 17,779 ha (82.8%, respectively). Forest stands with black locust perform reclamation, soil-protective and environment-forming functions, and occupy an area of 17,683.6 ha (26.9% of the total area covered with forest vegetation) with the total wood stock of 2.624 × 10^6 m^3 (Lovinska, Sytnyk 2016).

At the first stage of the study the values of forest vegetation biomass were calculated by component composition and age groups of both investigated species. Results of calculations of the ecological potential of Scots pine and black locust stands for numerous aboveground biomass parameters are presented in Table 1.

Surveyed forest stands within the Northern Steppe of Ukraine have accumulated 4.11 × 10^6 t of total aboveground biomass, among which the stands of Scots pine shared 2.277 × 10^6 t, and the stands of black locust accounted for 1.834 × 10^6 t. In regard to distribution of aboveground biomass by the age structure, it should be noted that the stands aged 41–60 years predominate in both Scots pine and black locust stands. This specified age range for Scots pine corresponds to middle-aged forest stands, whereas for black locust it corresponds to overmature forest stands. Total biomass values of 41–60 aged trees are 1.381 × 10^6 t (black locust) and 1.020 × 10^6 t (Scots pine) (Fig. 2).

Total stock of carbon allocation in aboveground biomass of forest stands makes 1.134 × 10^6 t in Scots pine stands, and 0.898 × 10^6 t in black locust stands. Distribution of carbon allocated by age groups showed that its main values were observed in stands with Scots pine and black locust aged 41–60 years which accumulated 0.508 and 0.675 × 10^6 t, respectively. These values are almost half of the total stock of carbon allocation by the studied forest stands. A minimum share of carbon was allocated in stands of the youngest group (1–20 years old), primarily due to their very small area and low aboveground biomass formed.

Relative distribution of carbon allocation by the component structure of aboveground biomass demonstrated that this index was highest in fractions of trunk wood: 4/5 from the total stock in Scots pine stands and 2/3 in black locust stands (Fig. 3).

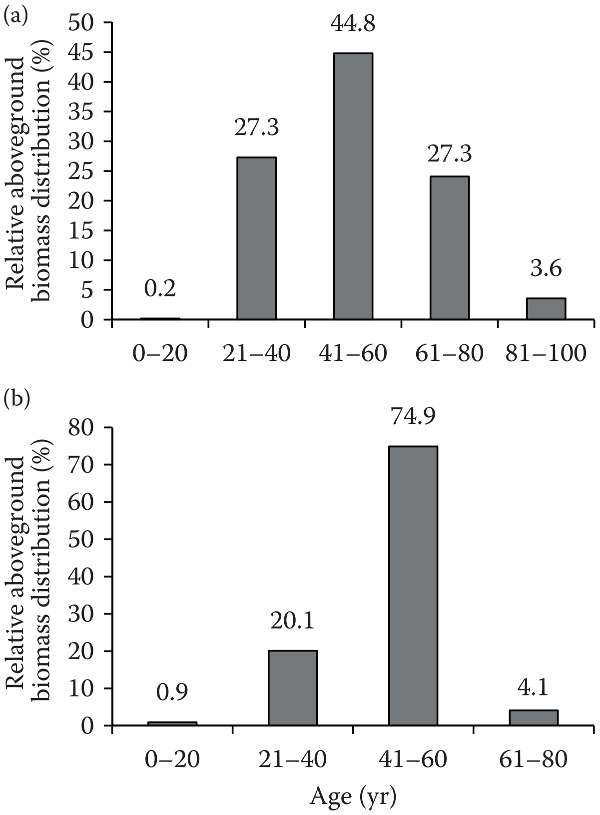

Fig. 2. Relative distribution of aboveground biomass in Scots pine (a) and black locust (b) stands by age

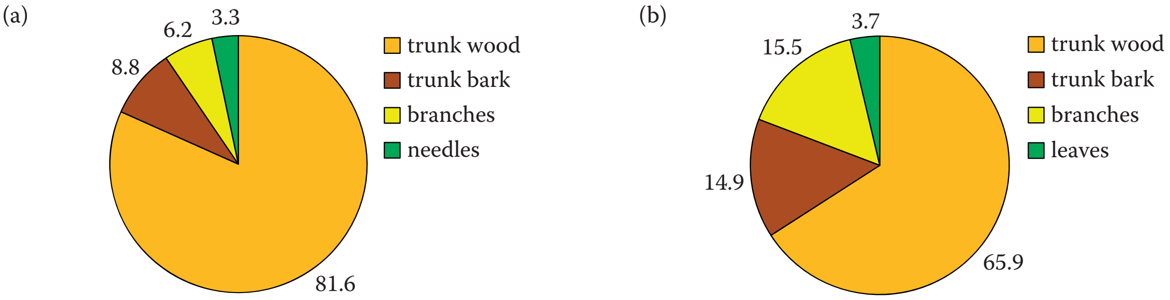

Fig. 3. Relative distribution of carbon allocation (%) by components of aboveground biomass in Scots pine (a) and black locust (b) stands

It should be noticed that a share of carbon allocation in black locust stands in the fractions of trunk and branches over bark was twice larger than in these fractions of Scots pine stands. Maximum concentration of organic carbon was allocated in the biomass of trunk wood, and minimum was deposited in pine needles and black locust leaves.

Comparative analysis of aboveground biomass, carbon allocation in the different age groups and biomass components of the stands of both species calculated per unit area (ha) is shown in Tables 2–4.

The revealed values show that the maximum amount of carbon per unit area was contained in the biomass of Scots pine stands aged from 61 to 80 years. In the same age group, carbon allocation per hectare in the black locust plantation was lower by 12%. In the oldest age group of Scots pine stands (81–100 years), a decrease of carbon amount per unit area was observed relatively to the previous age group up to 22.4%.

Energy potential was also calculated. According to MATTHEWS (1993), 1 tC is equal to 35.78 GJ. The revealed trends for carbon allocation are retained in determining the energy potential of aboveground biomass in the two species studied (Table 4).

Equations are calculated depending on carbon allocation in the relative age structure of the stands of both investigated species, and the models reflecting the studied parameters in different components of aboveground biomass were selected (Table 5).

An algorithm for the calculation of total energy potential in aboveground biomass of Scots pine and black locust stands was implemented depending on the age and component structure of aboveground biomass (Table 6). This calculation was done for the land area covered by Scots pine and black locust within Northern Steppe of Ukraine.

Both investigated species show typical trends of energy increase in aboveground biomass with growing age, when the maximum energy values were concentrated at 41–60 years of age. These values reached 75.0% of the total energy accumu-

Table 2. Aboveground biomass (t·ha^{-1}) of Scots pine and black locust stands in the Northern Steppe of Ukraine

Age group (yr)	Species	Trunk wood	Trunk bark	Branches	Needles/ leaves
1–20	Scots pine	1.02	0.24	0.18	0.002
	black locust	1.39	0.24	0.79	0.65
21–40	Scots pine	92.84	5.41	8.65	5.97
	black locust	61.02	13.13	19.49	3.31
41–60	Scots pine	87.59	12.43	5.74	3.15
	black locust	77.57	17.84	17.04	3.51
61–80	Scots pine	111.51	11.83	8.22	3.96
	black locust	81.47	19.67	18.07	2.51
81–100	Scots pine	85.79	8.14	8.04	3.26

Table 3. Carbon concentration (tC·ha^{-1}) in the different components of aboveground biomass

Age group (yr)	Species	Trunk wood	Trunk bark	Branches	Needles/ leaves
1–20	Scots pine	0.51	0.12	0.09	0.001
	black locust	0.68	0.12	0.40	0.29
21–40	Scots pine	46.00	2.70	4.32	2.68
	black locust	29.82	6.43	9.60	1.49
41–60	Scots pine	43.79	6.21	2.87	1.42
	black locust	38.00	8.74	8.35	1.60
61–80	Scots pine	55.76	5.92	4.11	1.78
	black locust	39.91	9.68	8.85	1.13
81–100	Scots pine	42.89	4.07	4.02	1.46

Table 4. Energy potential (GJ·ha^{-1}) in the different components of aboveground biomass

Age group (yr)	Species	Trunk wood	Trunk bark	Branches	Needles/ leaves
1–20	Scots pine	18.25	4.29	3.22	0.04
	black locust	24.33	4.29	14.31	10.38
21–40	Scots pine	1,645.88	96.61	154.60	95.89
	black locust	1,066.96	230.07	343.49	53.31
41–60	Scots pine	1,566.80	222.19	102.68	50.81
	black locust	1,359.64	312.71	297.93	57.25
61–80	Scots pine	1,995.09	211.81	147.06	63.69
	black locust	1,427.98	346.35	316.65	40.43
81–100	Scots pine	1,534.60	145.62	143.83	52.24

Table 5. Models of carbon allocation in the aboveground biomass

	Coefficient of determination
***Pinus sylvestris* Linnaeus**	
$C_{\text{trunk wood}} = 5.482 \times a^{0.512}$	0.78
$C_{\text{trunk bark}} = 0.410 \times a^{0.588}$	0.76
$C_{\text{branches}} = 0.448 \times a^{0.510}$	0.75
$C_{\text{needles}} = 0.305 \times a^{0.447}$	0.55
***Robinia pseudoacacia* Linnaeus**	
$C_{\text{trunk wood}} = 1.666 \times a^{0.772}$	0.91
$C_{\text{trunk bark}} = 0.295 \times a^{0.841}$	0.94
$C_{\text{branches}} = 1.295 \times a^{0.479}$	0.79
$C_{\text{leaves}} = 2.508 \times a^{0.152}$	0.78

a – sample tree age

lated in black locust stands and 44.8% in Scots pine stands. Energy potential of the studied forest-forming species was slowly decreasing with the age of the stands from 60 years of age and older.

DISCUSSION

The analysis of aboveground biomass in the Steppe zone is important because forests are intrazonal ecosystems of artificial origin, and they play a crucial role in the supply of unconventional renewable energy resources to the region.

Lakyda et al. (2013) reported that the positive trend of biomass deposits was observed in Ukrainian forests. The specific volume of total biomass has increased up to 17.8% for the last 10-year period. It is the evidence about forests maintaining stability that has a positive environmental influence and resource potential of this field. It was established that the total biomass of forests of Ukraine amounted to about 1,524 Mt of dry organic matter (159.1 t·ha^{-1}). This forest biomass contains about 758 MtC (79.3 tC·ha^{-1}).

The analysis and distribution of the main tree species by components of total biomass and age groups were presented by Lakyda et al. (2013). In Scots pine, the total aboveground biomass amounted to 414.8 Mt. According to our data, the contribution of the total aboveground biomass of Scots pine stands growing within the Steppe zone of Dnipropetrovsk region amounted to 2.28 Mt. This value was 1.84 Mt in surveyed stands with black locust within the Northern Steppe zone.

Lakyda et al. (2013) noted that the share of trunk wood biomass in Scots pine stands contributed 87.7%. By comparison, the share of Scots pine trunk wood was 81.4% according to our estimates. For another investigated species – black locust, the share of trunk wood was lower and averaged 65.9%.

Many authors used the parameter of mean carbon allocation in aboveground biomass to estimate an energy potential in forest ecosystems (Krebs 1994; Shepashenko et al. 1998; Brown 2002; Ritson, Sochacki 2003; Gough et al. 2008; Pan et al. 2011; Woodall et al. 2013; Birdsey, Pan 2015; Williams et al. 2016). The values of this parameter obtained for the studied forest-forming species within the Steppe zone are as follows: Scots pine stands 36 tC·ha^{-1} and black locust 42 tC·ha^{-1}. Mean carbon allocation in Ukrainian forests was 79 tC·ha^{-1} (Lakyda et al. 2013). According to the data of Harmon et al. (1986), mean carbon allocation was low in forests (tC·ha^{-1}): Russia – 45, Finland – 38, Italy – 31. The forest ecosystems of Germany, Poland and France were more productive than Ukrainian forests with mean carbon allocation 130, 110 and 80 tC·ha^{-1}, respectively.

In Matthews's (1993) analysis, the rate of carbon allocation increased in middle-aged stands and then it has an establishment phase during their full-vigour stage till the age of about 90 years, when stands reach the mature stage and then become

Table 6. Energy potential (PJ) of forest stands in the Northern Steppe, Ukraine

Age group (yr)	Species	Trunk		Branches	Needles/leaves	Total
		wood	bark			
1–20	Scots pine	0.03	0.01	0.01	0.01	0.06
	black locust	0.03	0.01	0.02	0.14	0.20
21–40	Scots pine	9.07	0.38	0.85	0.53	10.83
	black locust	3.96	0.85	1.27	0.20	6.28
41–60	Scots pine	14.67	2.08	0.96	0.48	18.19
	black locust	16.20	3.72	3.55	0.68	24.15
61–80	Scots pine	8.06	0.86	0.59	0.26	9.77
	black locust	1.04	0.25	0.23	0.03	1.55
81–100	Scots pine	1.2	0.11	0.11	0.04	1.46
Total	Scots pine	33.03	3.44	2.52	1.32	40.31
	black locust	21.23	4.69	5.07	1.05	32.04

overmature. When the stands reach the overmature stage, they lose carbon due to mortality and destruction of trees. Our results show a similar tendency with maximization of aboveground biomass accumulation and of relative carbon allocation at the age from 41 to 80 years for Scots pine and black locust stands. After 80 years of age for Scots pine, a decrease of carbon allocation was observed. In our opinion, the energy potential of the surveyed forest stands can provide the Steppe zone with significant environmental and economic benefits to the interregional distribution of quota system on the emissions of greenhouse gases.

CONCLUSIONS

At present and for the foreseeable future, stands of the main forest-forming species in the Northern Steppe of Ukraine have a considerable resource potential: the forest stands make 4.111 × 10^6 t of aboveground biomass, out of which the Scots pine stands come to 2,276.58 thousand t, and black locust stands reach 1.834 × 10^6 t. Distribution of aboveground biomass by age showed its prevalent accumulation in forest stands of both species aged 41–60 years.

The sum of pools on the investigated age range of the forest stands demonstrated that the total budget of carbon in stands within the Northern Steppe was 1.134 × 10^6 t in Scots pine stands and 0.897 × 10^6 t in black locust stands. For both species, forest stands aged 41–60 years were the main carbon sources. Among all other components of wood structure, stem wood makes the most significant contribution to total carbon allocation.

The energy potentials of forest biomass on Scotch pine and black locust were 40.31 and 32.04 PJ, respectively. At present, middle-aged Scots pine stands and overmature black locust stands are the most effective within the total age range.

The results of a quantitative estimation of aboveground biomass components, carbon allocation and energy accumulated in both species forest stands within the Ukrainian Northern Steppe reflected current values of their ecological and energy potential. By these indexes, the investigated forest stands could become dominant elements in a system of measures on ecological optimization of the natural environment within the region. To ensure the rational use of the energy potential of aboveground biomass, it is necessary to develop the regional programs on the fuel wood usage as an energy resource.

Estimation of forest biomass structure and carbon allocation in the Steppe zone of Ukraine depending on the age of stands causes the interest of scientists both in Ukraine and in other countries. This is due to the increasingly growing demand of the society for energy supply by renewable resources of energy and ecology sustainability in the context of global climate changes. Potentially, Ukraine is an important reserve of renewable energy sources for the future development of social community. The Steppe zone of Ukraine has a region-wide forest deficit. Development of forest ecosystems can result in optimization of abiotic conditions on a local level under the influence of global climate changes.

In our opinion, the practical solutions should be planting of young stands under conditions of the Steppe zone of Ukraine; forest management has to be focused on improvement cutting of overmature plantings and on the creation of new forest plantings.

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