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Information technology for studying carbon sink in stemwood of forest ecosystems

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Abstract: An information technology for calculation of carbon sink in stemwood of forest ecosystems on a territorial basis is developed. This information technology involves interpretation of input data of statistical inventory of forest stands using electronic maps of forestry, formation of databases and processing the data by applying a special algorithm for calculating the carbon sink in stemwood and presenting the results in a form of thematic maps. The estimation of the carbon sink in stemwood is done by using a "bottom-up" (wood – sample plots (SP) - forestry) approach applying mathematical models of distributed inventory of the carbon sink that take into account regional specificities of species in the study area and average annual growth of biomass. We estimated carbon sink in stemwood using data from experimental studies conducted on 54 sample plots of forestry "Spaske" of forest enterprise "Broshnivske FE" of Ivano- Frankivsk region. The largest carbon sink occurs in mixed forest ecosystems - 1829 tons/year, the average carbon sink (per ha) is 951 kg/year. The information technology can be applied for estimation of the carbon sink in forest stemwood in any part of Ukraine or another country where necessary input data are available.

Key words: forest ecosystems, mathematical models of carbon sink in forest ecosystems, spatial inventory.

INTRODUCTION

Nowadays, climate change is one of the most important global problems, which is a significant threat to the Earth's environment as well as political and economic development of mankind [4]. One way of coping with the climate change is a system of measures for effective forest management that will reduce the human impact on Earth's atmosphere. Enhanced reproduction of forests and increasing forest productivity will help to increase the absorption of carbon dioxide.

Forests play an important role in the global carbon cycle, removing about a third part of the carbon released from burning fossil fuels. Understanding the role of forests in the carbon cycle is increasingly important today, and countries are encouraged to monitor forests in order to effectively manage forests and report their state to respective international organizations.

Ukraine, as a member of the United Nations Framework Convention on Climate Change and the Kyoto Protocol, has certain obligations on greenhouse gas (GHG) emissions. First of all, Ukraine has to establish a national system for inventory of emissions and removals of GHGs [5, 9, 25]. Successful participation of Ukraine in international processes on climate change and GHG emissions trading depends on availability of accurate control, completeness and accuracy of data reporting [1, 3, 14, 18]. The assessment of carbon dynamics in forest ecosystems is an important part of functioning of the national inventory. Therefore, the investigation of the carbon balance in forest ecosystems is particularly relevant today.

ANALYSIS OF RECENT PUBLICATIONS AND RESEARCH

Today, a lot of attention is paid to research questions on the carbon balance of forest ecosystems.

While investigating the dynamics of carbon in forests, it is necessary to study the size of carbon reservoirs, stocks of carbon, and the impact of environmental factors [26] on the carbon cycle processes.

Many recently published books and journal articles are devoted to temperate and boreal forests [15, 22], the forests of Canada [8], Finland [16], Ukraine [10, 11, 19, 20], and others. To estimate carbon stocks and changes in stocks, a growing number of countries use carbon budget model developed by the Ministry of Natural Resources of Canada [8], known as the carbon budget model of the Canadian forest sector (Carbon Budget Model of the Canadian Forest Sector), or CBM-CFS3. This model simulates the dynamics of all forest carbon stocks as required under the Kyoto Protocol (aboveground biomass, underground biomass, litter, dead wood and soil organic carbon); it allows monitoring carbon stocks in forests and predicting future changes. CBM-CFS3 is being tested by scientists from Australia, China, Korea, Germany, Italy and the United States. Model meets integrating carbon forests. Results of CBM-CFS3 can be used to support ongoing monitoring of carbon stocks in forests. This model can also be used to produce forecasts of future flows of carbon based on forest management, natural disturbances and changes in land use. These predictions can be used to develop forest management strategies that are aimed at mitigating the effects of climate change.

Carbon balance of forests of Ukraine has been studied by P. Lakyda [13], V. Pasternak [19, 20], I. Buksha [19, 20], R. Bun [2], S. Myklush [17]. The approach in [13] is based on the results of forest inventory and regression models of phytomass components of main tree species of Ukraine. It does not take into account changes in soil carbon. The technique of carbon dynamics in forest ecosystems, described in [19], includes all components of the system and is based on the transfer of forestry statistics into carbon units using conversion factors. Another approach to assess carbon dynamics in forest ecosystems [16] is based on the existing forest inventory data as input for statistical models and simulation of the dynamics of biomass litter and soil. This model of terrestrial vegetation needs to be improved: consider different types of forests and assess the carbon in litter and soil carbon by integrating Yasso dynamic model, which simulates the carbon cycle in forest soils. The approach presented in [2] estimates carbon stocks in ecosystems of broadleaf and coniferous forests for individual region and for the whole Ukraine; it involves data of forest inventory using regression and correlation, linking the supply of wood with a mass of absolutely dry matter ground and underground parts of the stand, litter vegetation, and corresponding conversion factors.

Therefore, it is a relevant and not fully researched problem of estimating carbon balance of forest ecosystems, which would take into account the characteristics of different types of carbon reservoirs, national inventory data, conversion factors, environmental factors.

AIM OF THE STUDY

The aim of the study is to create a database of parameters of forest ecosystems and mathematical models to study the carbon balance in forests. To achieve this aim, the following tasks have to be solved: to develop algorithms to determine the biomass accumulation in plants; to develop mathematical models to estimate emissions and carbon sink of forest ecosystems; based on these models and GIS technology to build a software package for spatial inventory of carbon in forests.

METHODOLOGY

The processes of absorption, emission and carbon sequestration in forest ecosystems depend on many factors (e.g. age of plantations, tree species, productivity, natural and anthropogenic disturbances, etc.). Therefore, to assess carbon dynamics in forest ecosystems we need a detailed information on the status of forests, forest parameters, and mathematical models and geoinformation approach that will help to carry out a spatial inventory of absorption and emission of carbon in forests, carbon stocks, and to determine and to display the results on the map.

As a basic methodology for creation of a database "Forest Ecosystems" we took a technique which was used for inventory of Uholsko- Shyrokoluzhanskyi primeval beech forest of the Carpathian Biosphere Reserve [23]; this technique was designed to store, edit and display forest information and to assess dynamics of structure of forest stands of dead wood, natural regeneration, distribution stands for diameter and height, with margin and more. By building queries it is easy to get all necessary information on forest ecosystem (time of measurement, all characteristics of wood, etc.). Mathematical modules were designed for statistical analysis of data, e.g. a choice of models of growth stands and determination of parameters of these models.

The developed database "Forest Ecosystems" is based on the relational data model. This model was selected because of easy data presentation (in tables), a powerful theoretical framework for it and thus tools to create a relational database management systems. The database was created using Microsoft Access (format .mdb), which is a software package of Microsoft Office. Nowadays, Microsoft Access is a well-developed package and can be used for support and maintenance of databases, including forest inventory.

When designing the database structure (a few tables with fields and their interconnections), the method described in [23] was used. All forest inventory, service and reference information contained in the tables are logically linked. Total number of tables is over 60. All tables can be divided into three groups: tables of forest inventory measurements, service tables, and tables of references.

The table named "Trees" contains records of measured diameters of all standing live trees (at a height of 1.3 m), their height and specified azimuth and distance from the centre of the plots, the average age of plantation. The dependence of the height on the diameter is approximated by the expression described in [21].

Based on the calculated height and diameter for each level of thickness of specie, form factor is estimated using formula [7]:

$$f = \frac{1}{1 + e^{(b_1 + b_2 / \ln(d) + b_3 / \ln(h) + b_4 * (h/d))}} , \quad (1)$$

where: d is a diameter of a tree at the high of 1,3 m, cm; h is a tree high, m; $b_1,\ldots,b_4$ are the coefficients of equation.

Based on values of d, h, f, by using main forest inventory formula below, we determine the volume of each tree:

$$V = g \cdot h \cdot f \ , \quad (2)$$

where: g is a cross sectional area of a tree, m2; f is the form factor.

Growing stock of specie on SP is determined as the sum of volumes of all trees:

$$M_i = \sum_{i=1}^{n} V_i \ , \quad (3)$$

where: M_i is a growing stock of tree specie on a SP, m3; V_i is a volume of a tree, m3.

The total growing stock on a SP is calculated as a sum of growing stock of all trees:

$$M_{total} = \sum_{i=1}^{n} M_i \ . \quad (4)$$

The growing stock per ha is calculated by dividing total growing stock on a sample plot by the plot's area (S):

$$M_{1ha} = \frac{M_{total}}{S} . \quad (5)$$

Mean annual increment of stemwood for species is determined by the following formula:

$$\Delta_{M_i}^{average} = \frac{M_i}{A} , \quad (6)$$

where: $\Delta_{M_i}^{average}$ is a mean annual increment of stemwood of tree species, m3 per year; M_i is a growing stock of a specie at a sample plot, m3; A is an average age of a tree specie on a SP.

Accordingly, the total increment of stemwood per ha for all species is equal to:

$$Z_{M1ha}^{average} = \frac{\sum_{i}^{n} \Delta_{M_i}^{average}}{S} , \quad (7)$$

where: $\Delta_{M_i}^{average}$ is mean annual increment of stemwood of a tree specie, m3 per year; S is an area of a sample plot, m2.

Based on the measurements of azimuth and distances from the plot center to the trees we calculated conditional coordinates x and y:

$$x = \sin\left(radian(\,l\,)\right) \cdot L ,$$

$$y = \cos\left(radian(\,l\,)\right) \cdot L , \quad (8)$$

where: l is an azimuth from centre of a SP to a tree, degrees; L is a distance from center of a SP to a tree in meters.

These coordinates were transferred to conventional coordinate system UTM WGS-84, and then by means of ArcGIS and attribute information of tables, thematic maps were created to visualize the data (Fig. 1).

Additionally, these tables are filled with information for every tree: category of technical suitability, class of Kraft, defoliation, category of sanitary conditions, availability of folked tree, level of tree, trunk form, which are grouped and graphically presented in relative terms (Fig. 1 - 4).

Further results are used to analyze the plantation, its spatial structure, trade and sanitary condition, its vitality and resistance to adverse factors.

To evaluate the flow of carbon into the test plot we used the technique [6] (the Gain-Loss method) and mathematical models of distributed inventory of carbon sink [2, 24], where we took into account regional specificities of the study area [12]. Average annual biomass per ha was calculated based on forest inventory.

Below, an example of the technology for estimating carbon sink in stemwood of forest ecosystems at 54 sample plots of Savior Forestry of "Broshniv LH" with total area of 4143.9 hectares is presented. The whole area was divided into 1km x 1km grid. The results can be obtained in the form of reports on carbon sink in stemwood by species in the Savior Forestry of "Broshivske LH" (Fig. 5) or by the sample plots (Fig. 6), report on overall distribution of carbon sink in stemwood in the investigated area, and digital maps (Fig. 7, 8).

Carbon sink in stemwood varies depending on the category of land, age and breed structure. For the study area the calculated carbon sink in stemwood is presented in Table 1.

The largest amount of carbon sink in stemwood of mixed forest is 1829 t per year, the average sink per ha is 951 kg/year. The largest sinks are observed for the beech forests of age 50, where carbon sink is approximately 2187 kg/ha per year. Average sink of forest is 376 m3/ha, the relative completeness is of 0,87 and the average increase of carbon sink in stemwood accordingly is 7,7 m3/ha per year.

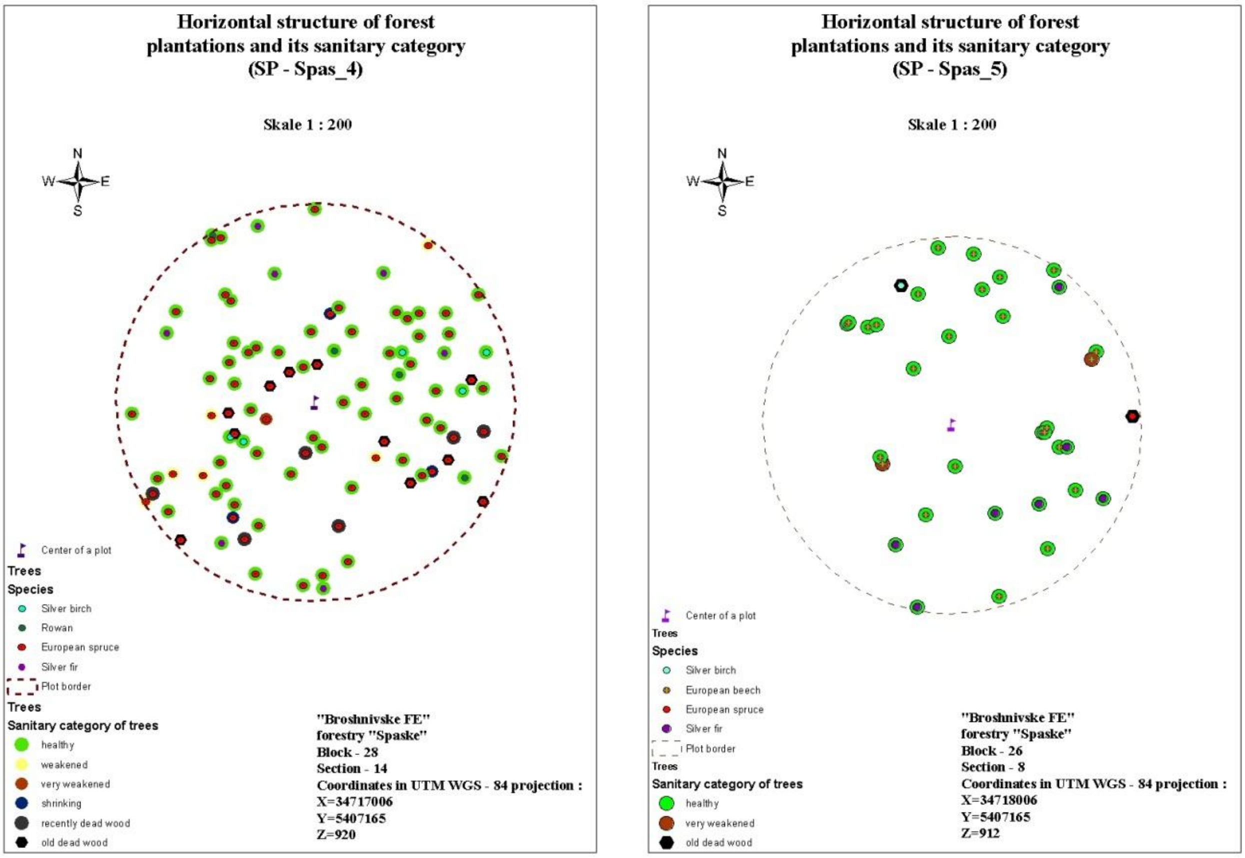

Fig. 1. The horizontal wood structure and sanitary category of planted trees

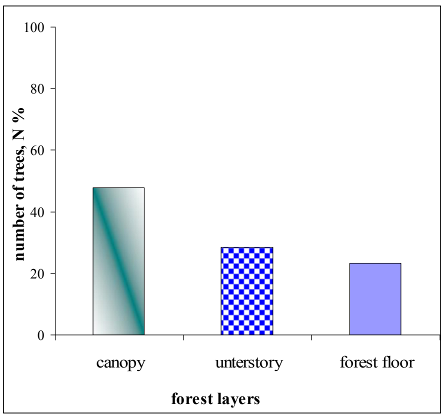

Fig. 2. Distribution of trees by levels

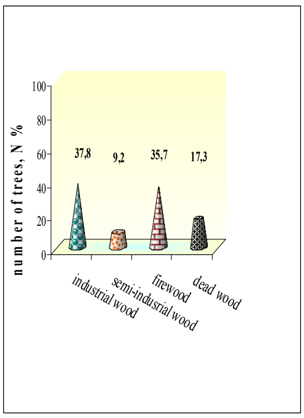

Fig. 3. Distribution of trees by category of technical suitability

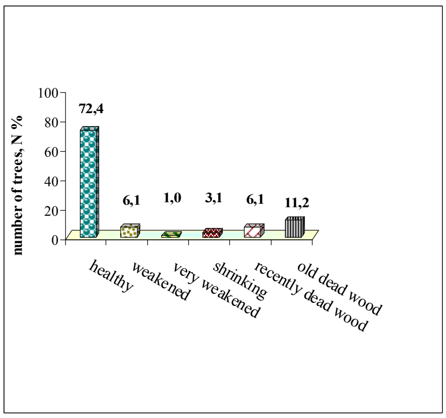

Fig. 4. Distribution of trees by category of sanitary condition

tree species	No.	number of trees	area, ha	growing stock, m3	mean annual increment, m3/year	mean annual increment, m3/ha per year	area covered by tree species, ha	carbon sink, t/year
European beech		427	,4687	321,7977	4,5675	4,9862	1204,67	1676,94
	5	26	,0371	27,1472	,2951	5,9016		
	6	33	,0330	41,7462	,5091	10,1820		
	11	11	,0081	23,5390	,2308	4,6155		
	12	24	,0255	19,5973	,4170	8,3393		
	13	7	,0130	5,6861	,0693	1,3868		
	17	31	,0352	17,9884	,3271	6,5412		
	18	11	,0204	12,3993	,1216	2,4312		
	19	5	,0048	,9467	,1183	2,3666		
	20	5	,0063	3,2041	,0605	1,2091		
	22	39	,0300	18,1459	,3558	7,1161		
	23	1	,0013	,1299	,0027	,0541		
	24	8	,0111	3,2437	,0601	1,2014		
	25	13	,0155	2,9801	,0621	1,2417		
	26	12	,0146	17,5522	,1439	2,8774		

Fig. 5. Total carbon sink in stemwood in the forestry “Spaske” of forest enterprise "Broshnivske FE"

No.	tree species	number of trees	area, ha	growing stock, m3	mean annual increment, m3/year	mean annual increment, m3/ha per year	carbon sink, t/year
4		98	,0500	16,9939	,3332	4,5124	,0382
	Rowan	4	,0020	,4421	,0087	,1734	
	Silver birch	5	,0026	1,9679	,0386	,7717	
	Silver fir	7	,0036	1,0646	,0209	,4175	
	European spruc	82	,0418	13,5193	,2651	5,3017	
5		35	,0500	28,7773	,3217	4,4049	,0614
	European beech	26	,0371	27,1472	,2951	5,9016	
	European spruc	1	,0014	,8460	,0092	,1839	
	Silver birch	1	,0014	,6332	,0158	,3166	
	Silver fir	7	,0100	,1508	,0016	,0328	
6		50	,0500	42,2640	,5154	6,7399	,0940
	European beech	33	,0330	41,7462	,5091	10,1820	
	European spruc	1	,0010	,2816	,0034	,0687	
	Silver fir	16	,0160	,2363	,0029	,0576	
7		60	,0500	13,9102	,2440	3,9083	,0330
	European spruc	56	,0467	11,7822	,2067	4,1341	
	Silver fir	4	,0033	2,1280	,0373	,7467	

Fig. 6. Carbon sink in stemwood on the sample plots of the forestry “Spaske” of forest enterprise "Broshnivske FE"

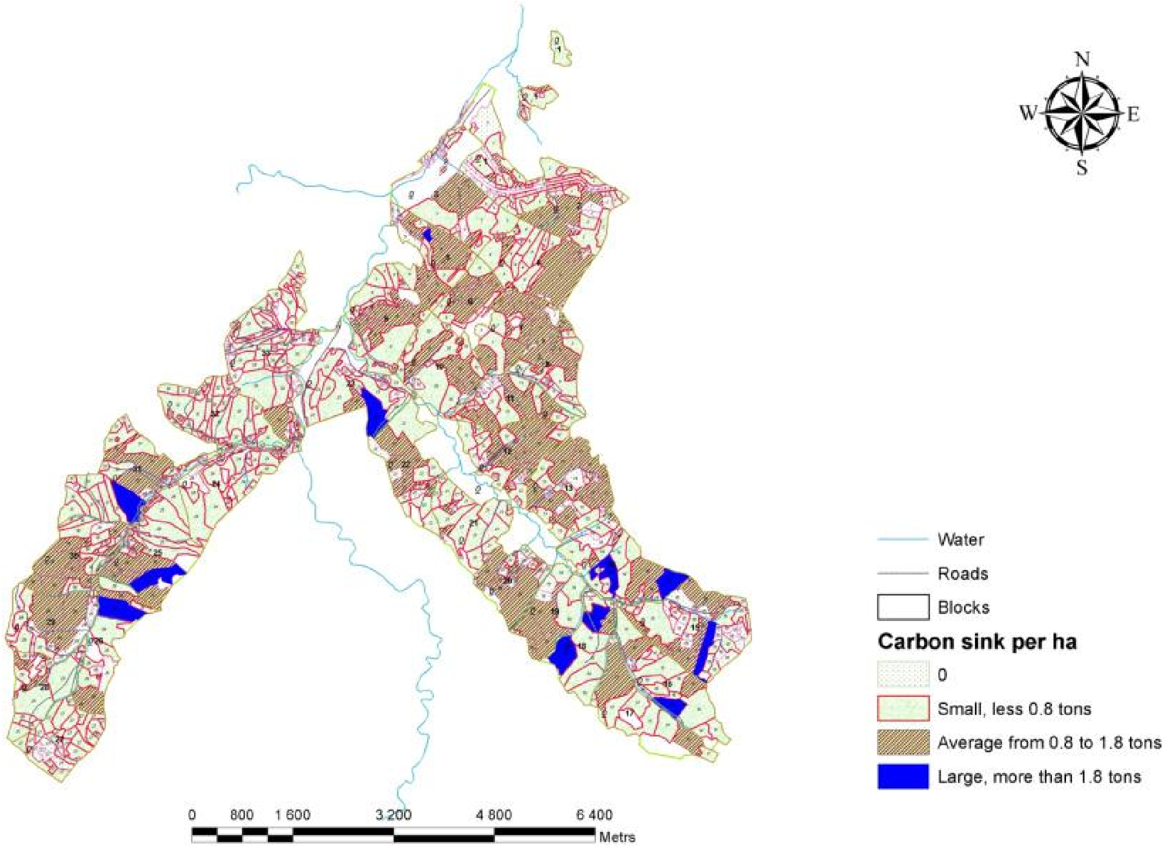

Fig. 7. Distribution of the carbon sink in stemwood for the study area (t ha-1)

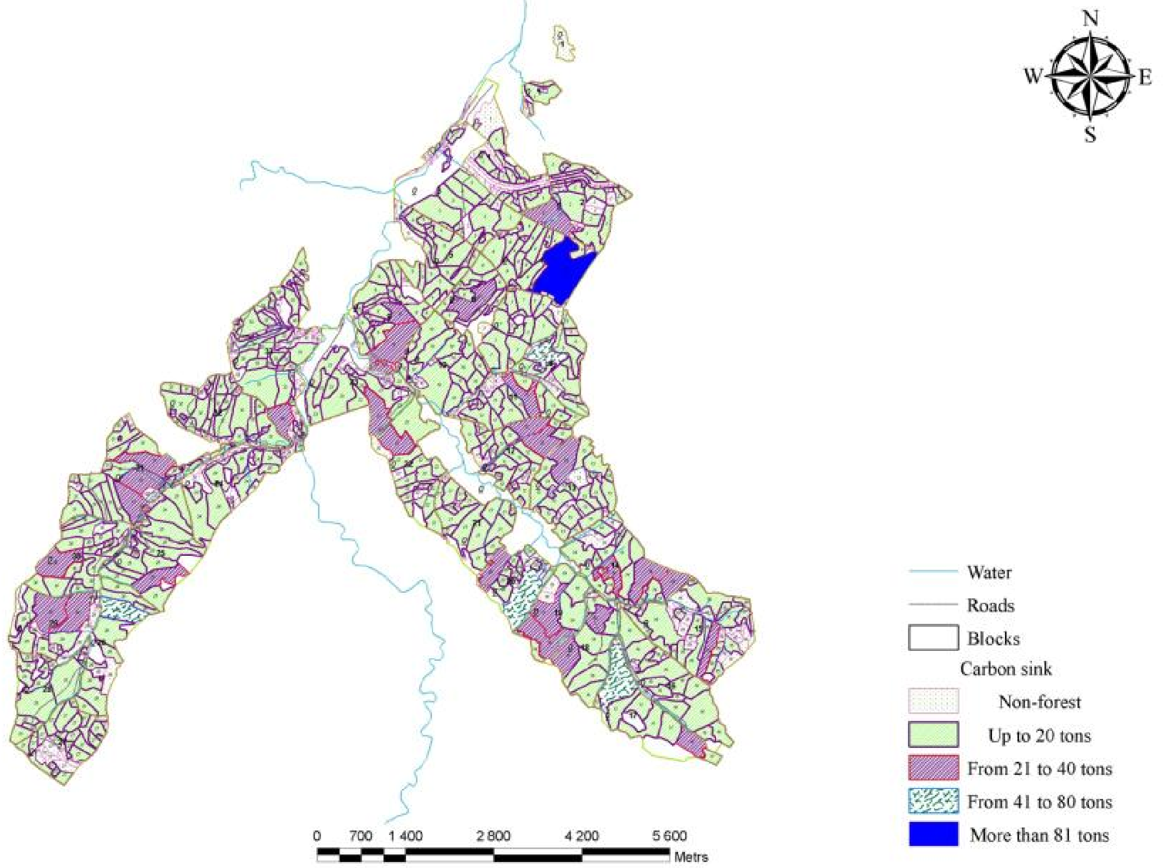

Fig. 8. Overall distribution of carbon sink in stemwood in the investigated area (t)

Table 1. The distribution of carbon sink in stemwood for different categories of the study area

Land category	Area, S, ha	Overall carbon sink, C, t/year	Average carbon sink per ha, C, t/year
Non-forest areas	95,1	0,000	0,000
Open trees	193,2	3,774	0,020
Coniferous forest	1222,8	876,202	0,717
Mixed forest	1922,1	1828,793	0,951
Broadleaf forest	710,7	809,792	1,139
Total	**4143,9**	**3518,6**	**0,849**

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CONCLUSIONS

The paper presents the mathematical model of spatial inventory of carbon sink of individual trees and describes the characteristics of their practical implementation. We developed a database on forest inventory characteristics of trees with visualization of the results on a map. The sample plots in the forestry "Spaske" of forest enterprise "Broshnivske FE" demonstrates the usefulness of spatial inventory of carbon sink by "bottom-up" method (from one tree to a forest area). We calculated carbon sink in stemwood by species in the investigated area. The largest carbon sink occurs in mixed forests and is 1829 tons/year, the average per hectare is 951 kg / year. In our calculations we did not consider underground part of wood, as well as all the above-ground phytomass (only stem phytomass). In the future, we will complement this model in order to assess full wood phytomass for any forest and to estimate carbon sink that will be useful for decision-making on forest management.

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