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Reserve of Organic Carbon in Forest Soils of Lowlands in Poland

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Abstract

The content of organic carbon is the basic property that characterizes soil. It is the measure of content of humus compounds in soil and one of important factors influencing the soil fertility.

The interest in carbon reserve that is stored by soils has increased in the moment of growing climatic changes. In connection with very important role of carbon reserve in soil as an element of circulation cycle of this element and the lack of data on coal content in deeper levels of soils an attempt was made to designate the size of organic carbon reserve in forest soils of lowlands' stands in Poland and its profile distribution. The purpose of studies was also to designate factors that decide on the size of carbon reserve in soil. For studies purposes were assigned 203 areas representing basic and occupying greatest areas types of forest habitats – boggy stands were not taken into consideration. The areas were located in larger pieces of a given stand type over the whole area of lowland in Poland. Sectional distribution of organic carbon reserve in forest soils indicate necessity of taking into consideration during studies its content in deeper levels – up to 150 cm. Stand's productivity influences carbon supply in small degree – it is humidity that seems to be of more importance. Soil with developed process of podzolization show larger reserve of organic carbon. Its main source is mainly the level of overlay hummus but also accumulation in deeper levels of soil (illuvial level Bh). Large differentiation of carbon reserve was stated in sub-types of soils – it may result from differences in species composition of stands that occur on the same soils subtypes. Here bears testimony small differentiation of organic carbon reserve between trophic categories of stands and clear among wetly categories similar dependencies were stated for vegetation complexes. The above mentioned relations clearly show the need for taking curry of protection of those wet habitants so important in natural protection and sustainable development.

Keywords: forest soil, carbon content, forest habitant

Introduction

The content of organic carbon is the basic property that characterizes soil. It is the measure of content of humus compounds in soil and one of important factors influencing the soil fertility [1]. The interest in carbon reserve that is stored by soils has increased in the moment of growing climatic changes [2-4]. Reserves of carbon in soils are directly connected with its reserves in atmosphere. The content of carbon in atmosphere increases systematically at the cost of its reserve in soil and living organisms and at the cost of geological reserve. Retention of carbon in soils is a very important method of restriction of CO_2 surplus in atmosphere as greenhouse gas. In soils are accumulated

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approximately 2,3 billion tons of C, and more carbon is accumulated only in the oceans (38 billion tons) and in geological deposits (5 billion tons) [5]. Dixon and Turner [6] estimate global reserves of coal in soils at the level of 1,4 to 2,0 billion tons. Those values depend mainly on the type of soil [7], on vegetation type [8] and on vegetation zone [9]. The content of carbon in soil is also influenced by microbiological activity, the size of organic fallout and the method of forest development [10-12]. In forest ecosystems are 82-86% of the global carbon content of terrestrial ecosystems [13-15].

In connection with very important role of carbon reserve in soil as an element of circulation cycle of this element [16] and the lack of data on coal content in deeper levels of soils [5] an attempt was made to designate the size of organic carbon reserve in forest soils of lowlands' stands in Poland and its profile distribution. The purpose of studies was also to designate factors that decide on the size of carbon reserve in soil.

Methodology

For studies purposes were assigned 203 areas representing basic and occupying greatest areas types of forest habitats – boggy stands were not taken into consideration. The areas were located in larger pieces of a given stand type over the whole area of lowland in Poland. Those were areas in stands of older age class (above 60) with species structure of stand and ground cover corresponding to conditions of stands that were chosen for studies. The stand had full or moderate density. On studied areas have been conducted descriptions of soils and samplings. Description of soil was conducted according to traditional system of text characteristics for soil profile according to the Instruction of Forest Arrangement Part II [17] giving thickness of levels, colour, moisture, arrangement and the method of transition to a successive level. Samples of soils for determining organic carbon content with Tiurin's oxidometric method were replenished with samples for determining volumetric density. It allowed computation of obtained results on soil's volume and on 1 hectare area. The samples for determining volumetric density were taken as collective samples with the use of cylinders with volume of: – 100 cm³ – 5 unit samples (from surface levels -organic (Oh, Of, Ofh) and humus and sometimes Ees and Bfe at small thickness of those levels, 250 cm³ – 3 unit samples from the remaining levels – B, BC, C. The samples were taken from the depth of 150 cm. In the samples was marked volumetric density – with the use of dryer-weight method [18].

On the basis of volume of particular soil levels, their volumetric density and the content of organic C in those levels was computed the reserve of organic C in Mg/ha in layers of soil of thickness to 150 cm (0-25, 25-50, 50-100, 100-150, 0-50, 0-100 and 0-150).

Results

Organic carbon is accumulated mainly in surface levels of soil, however, in case of forest soils one also has to pay attention to deeper layers. Averagely 65% of carbon reserve that is stored in the whole volume of soil (analysed to the depth of 150 cm) is in the 0-25 cm layer, but the reserve that was accumulated in this layer varied from 35 to 88%. In deeper layers there are less carbon: in 25-50 cm layer – 15% on the average, in 50-100 cm layer – 13%, in 100-150 cm layer – 7%. However, it has to be underlined , that in extreme cases (brown leached soil developed from glacial sands and boulder clays – Sieniawa 5) in 50-100 cm layer may contain even 40% of the total content of carbon from 0-150 cm layer, and in 100-150 cm layer still 26 % (typical lessive soil developed from Pleistocene silt formations – Międzychód 1). Because of that in further analysis

Table 1. Profile distribution of organic carbon reserve in studied forest soils, average values and extreme examples expressed in Mg/ha and as a percentage of a resource accumulated in a layer with 150 cm thickness.

C reserve in a layer of thickness of (in cm)	0-25	25-50	50-100	100-150	0-150 cm
average (n=203)	62,1 65%	14,9 15%	12,1 13%	6,9 7%	96,0 100%
Sieniawa 5	18,6 35%	8,2 15%	21,3 40%	5,5 10%	53,6 100%
Międzychód 1	27,2 45%	13,1 21%	04,6 8%	16,1 26%	61,0 100%

Table 2. Reserve of C in soil layer of 150 cm thickness [Mg/ha] in main habitation types of Polish forests.

Site type	N	Mean	SD	Min.	Max	cv
Bśw	41	83,8	28,1	47,5	187,6	33,52
BMśw	52	97,7	49,6	30,8	273,4	50,74
LMśw	63	89,7	29,5	29,3	172,1	32,87
Lśw	22	90,2	28,5	51,8	166,9	31,59
Bw	2	142,4	13,2	133,1	151,7	9,24
BMw	11	155,7	66,8	79,0	337,1	42,89
LMw	7	114,7	36,2	80,5	173,6	31,52
Lw	4	92,0	22,9	66,9	120,2	24,89
OlJ	1	164,0	0,0	164,0	164,0	-
Total group	203	96,0	41,2	29,3	337,1	42,89

Bśw- fresh coniferous forest, BMśw - fresh mixed coniferous forest, LMśw - fresh mixed broadleaved forest, Lśw - fresh broadleaved forest, Bw - moist coniferous forest, BMw - moist mixed coniferous forest, LMw - moist mixed broadleaved forest, Lw - moist broadleaved forest, OlJ - ash-alder swamp forest

Table 3. Reserve of C in soil layer of 150 cm thickness [Mg/ha] in selected vegetation sets.

Plant community	Stand composition	N	Mean Mg/ha	SD standard deviation
Leucobryo-Pinetum	So	30	89,8	25,6
Peucedano-Pinetum	So	15	83,8	35,5
Molinio-Pinetum	So	4	191,8	97,1
Querco roboris-Pinetum typicum	So+Db	25	117,8	61,7
Querco roboris-Pinetum typicum	So+Db	5	132,7	41,1
Serratulo-Pinetum	Św, So	13	91,5	22,2
Calamagrostio-Quercetum	Dbb	14	100,7	31,1
Fago-Quercetum	Bk, Dbb	5	93,5	13,2
Luzulo pilosae-Fagetum	Bk	8	77,5	48,7
Tilio-Carpinetum typicum	Db, Gb	11	79,5	18,7
Tilio-Carpinetum caricetosum brizoides	Db, Gb	5	114,9	29,2
Tilio-Carpinetum calamagrostietosum	Db, So, Gb	13	85,7	27,0

So-*Pinus silvestris*, Db-*Quercus robur*, Dbb-*Quercus petraea*, Św-*Picea abies*, Bk-*Fagus sylvatica*, Gb-*Carpinus betulus*
N- number of samples, SD- standard deviation, cv-coefficient of variation

was taken into consideration organic carbon accumulated at the depth of 150 cm (Table 1).

The smallest average wealth of organic carbon in 150 cm layer for the category of soils sub-types was stated in podzolised arenosols (Arb) where it totalled 49,2 Mg/ha. The greatest wealth of carbon equal to 173,6 Mg/ha was characteristic for ground gley muck soil sub-type (Gm) (Table 4.). Respective soils sub-types show differential variability of organic C reserve. Maximum values for variability coefficient was stated for typical gley-podzolic soils (58,04%) and typical podzolic soils (46,09%). For the remaining sub-types this variability coefficient most often takes values from the range of 20-40%. Values of variability coefficients seem to be dependable on sample size in a limited extend as its maximal values were stated for n = 10 and 28. In case of typical arenosols at the greatest trial (n = 52) this variability coefficients took the value of 26,63%. The soils where organic O level is present in shape of raw humus Ofh, peat humus Ot, muck humus OM or mucky-like humus are characterized by the greatest reserve of organic carbon. In majority of podzolic soils sub-types (Blw, Bgw, Bgms, Bgts, Blggw), in soils with marked process of podzolisation (BRb), in black mucky soils (CZms), in ground-gley soils (Gts, Gm) and in mucky soils (MRms) it is higher than 120 Mg/ha (Table 3).

Reserve of carbon of 150 cm thickness was taking values from the range from 29,3 to 337,1 Mg/ha. Minimal value was stated in typical red-coloured soil constituting LMśw stand and maximum in typical gley-podzolic soil in BMw habitat. Average values for trophic categories of new habitats did not differ statistically in a significant way and they amounted to 83,8 – Bśw, 97,7 – BMśw, 89,7 – LMśw and 90,2 – Lśw. Majority of humid habitats Bw, BMw, LMw and OlJ was characterized by the higher average reserve of organic carbon, that amounted respectively: 142,4, 155,7, 114,7 and 164,0 Mg/ha. Only in soils of Lw habitats was stated a reserve of size that was close to noted down in new sites equal to 92,0 Mg/ha. Reserve of organic carbon is characterized by high variability. Variability coefficient of this property in most forest sites types assumes the value from the range of approximately 30 to 50%. Only in Lw site it is significantly lower and equal to 9%, but it may result from small trial size for this site type (n = 2) and from the lack in studied material soils with muck humus that are typical for strongly humid variant (Lw2). The highest value of variability coefficient was stated in BMśw site where it was equal to 50.74% (Table 2).

In the study was analysed the reserve of organic carbon in soils of different vegetation sets but it was limited only to those complexes which appeared on at least four research stands (Table 3). Results that were obtained give evidence, that the size of accumulated in soil organic carbon is to higher extend influenced by moisturisation of site and in this way of soil, than the type of species that constitutes the stand. Represented in studied material soils and fresh sites settled by qualitatively differentiated vegetation collections (fresh pine tree forest sites – *Leucobryo-Pinetum, Peucedano-Pinetum*, sub-boreal mixed forest site with numerous spruce *Serratulo-Pinetum*, acidophilic leafy beech forests – *Luzulo pilosae-Fagetum*, beech and oak *Fago-Quercetum*, or oakwood *Calamagrostio-Quercetum*; typical and poorer elements of sub-continental oak-hornbeam wood *Tilio-Carpinetum typicum, Tilio-Carpinetum calamagrostietosum*) characterize with near reserve of organic carbon in a layer up to 150 cm, mounting 78-100 Mg/ha. Higher reserve of studied element characterizes soils of

Table 4. Reserve of C in soil layer of 150 cm thickness [Mg/ha] in types and subtypes of soils.

Soil subtype WRB	Soil subtype KGL	Mean Mg/ha	N	SD	Min.	Max	cv %
Podzolic arenosol Proto-Albic Arenosols	ARb	49,2	2	1,6	48,1	50,4	3,28
Black soil Rendzina Mollic Leptosols	Rc	66,9	1	0,0	66,9	66,9	-
Pararendzinas typical Calcaric Regosols	PRw	102,0	1	0,0	102,0	102,0	-
Black muck-like soil Saprihistic Gleysols	CZms	164,0	1	0,0	164,0	164,0	-
Brown typical Eutric Cambisols	BRw	87,0	2	24,7	69,6	104,5	28,40
Brown acid Eutric Cambisols	BRk	100,7	6	19,5	72,0	123,8	19,33
Brown leached Endo-Eutric Cambisols	BRwy	93,4	6	32,3	53,6	149,4	34,59
Brown podzolic Albi-Dystric Cambisols	BRb	137,3	2	41,5	108,0	166,7	30,18
Lessives typical Haplic Luvisols	Pw	86,7	6	29,8	57,7	124,1	34,40
Lessives typical Haplic Luvisols	Pbr	90,4	6	32,2	51,8	143,2	35,58
Lessives pseudogley Haplic Luvisols	Pog	73,4	1	0,0	73,4	73,4	-
Lessives typical Haplic Luvisols	RDw	72,2	52	19,2	29,3	115,3	26,63
Arenosol Hypocambic Arenosols	RDbr	93,1	16	25,8	66,4	172,1	27,75
Arenosol Albic Arenosols	RDb	92,6	26	35,1	30,8	187,6	37,88
Podzolic typical Haplic Podzols	Bw	113,7	28	52,4	60,8	273,4	46,09
Podzolic typical Haplic Podzols (Rustic)	Blw	153,9	1	0,0	153,9	153,9	-
Gley-podzolic typical Gleyic Podzols	Bgw	140,1	10	81,3	57,7	337,1	58,04
Gley-podzolic mucky-like Saprihisti-Gleyic Podzols	Bgms	166,7	2	5,7	162,7	170,8	3,44
Gley-podzolic peat-like Fibrihisti- Gleyic Podzols	Bgts	123,1	1	0,0	123,1	123,1	-
Gley-podzolic typical Gleyic Podzols (Rustic)	Blgw	133,1	1	0,0	133,1	133,1	-
Ground podzolic typical Haplic Gleysols	Gw	78,4	6	16,5	53,6	105,4	21,09
Ground-gley peat soil Fibrihistic Gleysols	Gt	102,5	2	33,3	79,0	126,1	32,48
Ground-gley peat-like soil Fibrihistic Gleysols	Gts	138,9	1	0,0	138,9	138,9	-
Ground-gley muck-like soil Saprihistic Gleysols	Gm	173,6	1	0,0	173,6	173,6	-
Ground-gley muck-like soil Umbric Gleysols	Gms	111,7	2	29,5	90,8	132,5	26,40
Pseudogley typical Stagni-Haplic Gleysols	OGw	95,8	10	39,6	31,2	166,9	41,35
Pseudogley podzolized Stagni-Arenic Gleysols	OGb	97,7	1	0,0	97,7	97,7	-
Amfigley Stagni Eutric Gleysols	OGam	108,8	7	36,0	62,8	163,3	33,11
Mucky-like soil Humic Gleysols	MRms	145,1	2	0,5	144,8	145,4	0,32
	Total group	96,0	203	41,2	29,3	337,1	42,89

N- number of samples, SD- standard deviation, cv-coefficient of variation

"more wetly" subgroup that occupy wet soils and sites. It is visible in composition of subgroups with similar qualitative composition of stand occupying wetly differentiated soils namely: wet pine forest site (*Molinio-Pinetum*) in relation to fresh pine forest sites (*Leucobryo-Pinetum* and *Peucedano-Pinetum*) contains in soil on the average two times more of organic carbon. Similarly variant with *Molinia caerules* of continental pine-oak mixed forest site (*Querco roboris-Pinetum molinietosum*) in comparison to its typical variant shows carbon reserve larger by approximately 12%. Wet subgroup of sub continental *Tilio-Carpinetum caricetosum brizoides* in reference to typical subgroup of *Tilio-Carpinetum typicum* is also characterized by higher by approximately 45% reserve of carbon.

In sites of fresh mixed forest sites with the share o oak (*Querco roboris-Pinetum typicum*) was stated a tendency to higher reserve of organic carbon (117,8 Mg/ha) than in sites of fresh forest sites, where the stand is build only of coniferous species (*Leucobryo-Pinetum, Peucedano-Pinetum, Serratulo-Pinetum*) (83-91,5 Mg/ha). In the group of studied aggregations the site of sub continental oak-hornbeam forest (*Tilio-Carpinetum typicum*) showed one of the lowest accumulations of carbon (79,5 Mg/ha). Similarly low accumulation – 77,5 Mg/ha characterized soils of lowland acid beech (*Luzulo pilosae-Fagetum*).

Discussion

The acquired results are close to those ones that are quoted by another authors. However, one has to pay attention on methodology problems in comparing absolute values. Presented studies concerned soil layers of 150 cm thickness whereas in the other studies emerge those with 100 cm [19, 20], 80 cm [21] or even 10 cm thicknesses [22, 23]. Reserve of carbon accumulated in the level of overlay hummus is most often jointly considered with reserve accumulated in a mineral part of soil although these values are sometimes considered separately [23]. The methods of taking samples for analyses differed as well. In Degórski's studies [19, 24] they were taken from genetic levels, and in Wójcik's studies [21] from the layers with depths such as 0-5, 5-10, 10-20, 20-40, 40-80 cm. The reserve of carbon is sometimes related to geographical position for example in the scale of Europe – physical and geographical units according to Kondracki [19] or Poland - units of natural and forest regionalisation [21]. It is also related with types of soil [19, 24] or with types of forest sites [21] Kondracki [19].

In studies of Degórski [19] the average reserve of organic carbon determined for pedons that contain organic level and mineral levels up to the depth of 100 cm was equal in case of podzolic soil to 138 Mg/ha, and in podzolic and arenosols only 54 Mg/ha. In own studies on Poland's lowland the similar tendency was stated, the arenosols contain less carbon so i.e. 92,6 Mg/ha than proper podzolic soils – 113,7 Mg/ha (Table 3). Comparing the total reserve of organic carbon in lessive soils of selected objects of the National Park in Białowieża it was stated, that it is almost two times smaller than that one in arenosols [24]. However, it seems, that such a great difference is not connected with type of soil but originates from differences in type of vegetation. The arenosols that were studied were covered with spruce mixed forest sites whereas lessive soils with oak-hornbeam forest. Generally one points out to spruce as this species that induces significant growth of carbon reserve in soil [21, 22]. In presented studies, where dominated stands with a proportion of pine such significant differences were not stated and to the contrary arenosols showed slightly smaller reserve of carbon so i.e. 72,2 Mg/ha than podzolic soils – 86,7 Mg/ha (Table 3).

Wójcik [21] in his studies conducted on 45 areas linked with naturalistic and forest lands, habitation type of forest and species dominating in a stand brings forward large variation of organic carbon reserve in the soils of specific stands. The reserve of carbon accumulated in soils of fresh forest site (Bśw) was contained within the range from 73 Mg to 133 Mg. The soils of fresh mixed forest sites stands (BMśw) accumulated more carbon than the soils of Bśw stands and contained from 89 Mg C to 131 Mg. C per hectare, Carbon reserves accumulated in soils under stands growing in stands of fresh mixed forest sites (LMśw) did not exceed 100 Mg odf C per hectare and as a rule were smaller than supplies of BMśw. Similarly in own studies in lowlands of Poland among fresh stands the largest reserve of carbon was stated in soils of mixed forest site stand and the differences between particular stands' categories were small at the high differentiation within categories (variation coefficient v from 31-50%) (Table 2). Also other authors [20] point out to high values of variation coefficient for organic C content in soils of stands with different species composition. In spruce, pine and beech stands of eastern Germany this coefficient in organic levels adopted values from the range from 42 to 73%, and in mineral levels was lower and was about 20%. Larger accumulation of carbon in organic levels of soils under the stands with mixed composition of species were pointed out in the studies of Koch and Makeschin [23]. Mixed pine-beech stands accumulated in this layer 55 Mg/ha and pine-beech-oakwood stands 69,2 Mg/ha while in pine monoculture it was 47,2 Mg/ha, in beechwood 51,8 Mg/ha, and under beech-oakwood stand 60,4 Mg/ha).

In literature is underlined big role of boggy stands soils in accumulation of organic C [16]. Conducted studies indicate, that damp stands are characterized by higher accumulation of carbon. Therefore, it seems that for preservation of carbon supplies is vital not only the care for marshy but also for damp stands and prevention of their de-watering and over-drying.

Conclusions

Sectional distribution of organic carbon reserve in forest soils indicate necessity of taking into consideration during studies its content in deeper levels - up to 150 cm. Stand's productivity influences carbon supply in small degree - it is humidity that seems to be of more importance. Here bears testimony small differentiation of organic carbon reserve between trophic categories of stands (B, BM, LM and L) and clear among wetly categories (fresh, wet) - similar dependencies were stated for vegetation complexes. Soil with developed process of podzolization show larger reserve of organic carbon. Its main source is mainly the level of overlay hummus but also accumulation in deeper levels of soil (illuvial level Bh). Large differentiation of carbon reserve was stated in sub-types of soils - it may result from differences in species composition of stands that occur on the same soils subtypes. The above mentioned relations clearly show the need for taking curry of protection of those wet habitants so important in natural protection and sustainable development.

References

1. BROŻEK S., ZWYDAK M., Atlas gleb leśnych Polski. CILP Warszawa, **2003**.
2. VUCETICH, J. A., REED, D. D., BREYMEYER, A., DEGÓRSKI, M., MROZ, G. D., SOLON, J., ROO-ZIELINSKA, E., NOBLE, R., Carbon pools and ecosystem properties along a latitudinal gradient in northern Scots pine (Pinus sylvestris) forests. Forest Ecology and Management **136**, 135-145, **2000**.
3. DE VRIES, W., REINDS, G.J., POSCH, M., SANZ, M., KRAUSE, G., CALATYUD, V., DUPOUEY, J., STERBA, H., GUNDERSEN, P., VOOGD, J., VEL, E., Intensive Monitoring of Forest Ecosystems in Europe. Tech. Rep., EC. UN/ECE, Brussels, **2003**.
4. JANDL R., LINDNER M., VESTERDAL L., BAUWENS B., BARITZ R., HAGEDORN F., JOHNSON D. W., MINKKINEN K., BYRNE K. A., How strongly can forest namagement influence soil carbon sequestration? Geoderma **137**, 253-268, **2007**.
5. LAL R., Węgiel glebowy i nasilenie efektu cieplarnianego. Rolnictwo polskie i ochrona jakości wody. Zeszty Edukacyjne, **6**, 22-36, **2000**.
6. DIXON R. K., TURNER D. P., The global carbon cycle and climate change: responses and feedbacks from belowground systems. Env. Pollut. **73**, 245-262, **1991**.
7. BURINGH P., Organic carbon in soils of the world. In: Woodwell GM (ed) The role of terrestrial vegetation in the global carbon cycle, SCOPE vol. 23. John Wiley, New York, pp. 91-109, **1984**.
8. SCHLESINGER W. H., Soil organic matter: a source of atmospheric CO2. In: Woodwell GM (ed) The role of terrestrial vegetation in the global carbon cycle: measurement by remote sensing. John Wiley, New York, **1984**.
9. POST W. M., EMANUEL W. R., ZINKE P. J., STANGEN-BERGER A. G., Soil carbon pools and world life zones. Nature **298**, 156-159, **1982**.
10. BOUWMAN A. F., LEEMANS R., The role of forest soils in the global carbon cycle. In: McFee WW, Kelly JM (eds) Carbon forms and functions in forest soils. Soil Science Society of America, Madison, **1995**.
11. FEARNSIDE P. M., BARBOSA R. I., Soil carbon changes from conversion of forest pasture in Brazilian Amazonia. For. Ecol. Manage. **108** (1-2),147-167, **1998**.
12. GUNAPALA N., VENETTE R. C., FERRIS H., SCOW K. M., Effects of soil management history on the rate of organic matter decomposition. Soil. Biol. Biochem. **30** (14), 1917-1927, **1998**.
13. SEDJO R. A., Temperate forest ecosystems in the global carbon cycle. Ambio **21**, 274-277, **1992**.
14. DIXON R. K., BROWN R. A., HOUGHTON R. A., SOLOMON A. M., TREXLER M. C., WISINIEWSKY J., Carbon pools and flux of global forest ecosystems. Science **239**, 185-90, **1994**.
15. HOUGHTON J. T., DING Y., GRIGGS D. J., NOGUER M., VAN DER LINDEN P. J., DAI X., MASKELL K., JOHNSON C. A., Climate change 2001: the scientific basis. Contribution of working group I to the third assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, **2001**.
16. WARNING R. H. SCHELESINGER W. H., Forest Ecosystems concepts and Management. Academic Press., **1996**.
17. INSTRUKCJA URZĄDZANIA LASU, Cz. II Instrukcja wyróżniania i kartowania siedlisk leśnych. PGLLP, Warszawa, **2003**.
18. OSTROWSKA A., PORĘBSKA G., BORZYSZKOWSKI J., KRÓL H., GAWLIŃSKI S., Właściwości gleb leśnych i metody ich oznaczania. Instytut Ochrony Środowiska, Warszawa, **2001**.
19. DEGÓRSKI M., Zapasy węgla organicznego w glebach borów sosnowych w środkowej i północnej Europie (w:) B. Gworek, A. Mocek (red.), Obieg pierwiastków w przyrodzie. Monografia. T. 1, Instytut Ochrony Środowiska, Warszawa, pp. 103-112, **2001**.
20. WUTZLER T., KÖSTNER B., BERNHOFER CH., Spatially explicit assessment of carbon stocks of a managed forest area in eastern Germany. Eur. J. Forest Res. **126**, 371-383, **2007**.
21. WÓJCIK J., Zasoby węgla organicznego w glebach leśnych na podstawie monitoringu lasu. W: Monitoring lasów ocena stanu zdrowotnego lasów w latach 1991-2005, PIOŚ. Warszawa, pp. 263-280, **2007**.
22. DOVYDENKO N., Zawartość węgla w glebach wybranych drzewostanów sosnowych i świerkowych na gruntach porolnych. Leśne Prace Badawcze, **2**, 49-66, **2004**.
23. KOCH J. A., MAKESCHIN F., Carbon and nitrogen dynamics in topsoils along forest conversion sequences in the Ore Mountains and the Saxonian lowland. Germany. Eur. J. Forest Res. **123**, 189-201, **2004**.
24. DEGÓRSKI M., Wpływ sposobu użytkowania lasu na zapasy węgla organicznego w glebie. Monitoring Środ. Przyr., **6**, 75-83, **2005**.