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STORAGE CAPACITY OF ORGANIC CARBON IN THE RECLAIMED POST-MINING TECHNOSOLS

Soil is a huge reservoir of carbon, which is both organically and chemically bounded. Sequestration ability of soil amounting to 0.9±0.3 Pg C·y^{-1} represents significant item in carbon balance. Reclamation activities aimed at soil creating contributes to the carbon binding in the form of complex compounds. This work characterizes fluctuations of organic carbon in post-lignite-mining sites located in Łęknica (Poland, Lubuskie Province) after afforestation with *Pinus sylvestris*. The results present the situation 25 years after the reclamation field experiment commencement. Satisfactory effect in growth and development of pine forest was accomplished by liming and NPK application. After 25 years of the experiment start point, the litter deposition gained 2.5–4.0 cm and the initial humic horizon, lying directly beneath reached 4.0–6.5 cm. An average carbon accumulation in surface litter amounted to 2.86 kg·m^{-2} and in initial humic horizons to 0.68 kg·m^{-2}. This indicates an average sequestration of 130 Mg CO_2 per 1 ha of reclaimed area.

1. INTRODUCTION

Soil carbon cycle that comprises several natural processes is significantly modified by human activity. Carbon dioxide (CO_2) as a product of carbon cycle is considered the main factor contributing to global warming potential. Soil is a huge reservoir of carbon, which is both organically and chemically bounded [1], and study on soil organic carbon provides significant contribution to carbon cycle research [2]. However, Van Breemen and Buurman [3] demonstrated that soil organic matter in aerobic conditions is thermodynamically unstable, what causes CO_2 release to the atmosphere:

$$CH_2O \text{ (organic matter)} + O_2 \rightarrow CO_2\uparrow + H_2O$$

Smith et al. [1] indicate strong impact of anthropological factor in depletion of soil organic matter reservoir leading to enhancing in CO_2 emission. In the worldwide scale,

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sequestration ability of soil amounts to 0.9±0.3 $Pg\cdot y^{-1}$ what represents significant item in carbon balance [4]. However, the carbon pool is very unstable and at the end of this century soil will be able to sequester only 2–5% of carbon emitted as a CO_2 [1, 4]. Nevertheless, during the nearest 20–30 years any activity which directs reduction of CO_2 emission to the atmosphere should be considered important, and soil carbon sequestration remarkable [5].

Areas of former lignite mines located in Western Poland, west of Germany and northern part of Czech Republic are characterized by vast participation of tertiary and quaternary sediments in over coal horizons. Such material is abundant in debris of lignite coal but contains very little pedogenic carbon [6]. This is disadvantage of post mining areas reclamation and formation of stabilized ecosystems [7]. Transformation of pedogenic carbon and establishment of soil organic matter by decomposition of plant residues is essential to gain success in reclamation activity [8]. Several authors report that this quantity is overestimated especially for intensive agricultural soils and post-mining areas. In many post-mining areas including the present study, surface material is characterized by sandy texture and strongly acid reaction because of pyrite oxidation. In consequence, reclamation activities should include liming, which significantly affects soil organic matter formation. Decomposition of soil organic matter (SOM) is the most intensive when pH is close to neutral and decreases considerably on acid soils [3]. Also other factors affect direction and rate of biochemical processes of SOM accumulation, especially in early stages of soil formation process. Berg and Meentemeyer [9] pointed to N fertilization as a factor promoting carbon increase in soils by intensive plant growth and enhancement of humification processes. The areas examined in the study were covered by pine forest before lignite coal exploitation. Presently, in the same way post mining areas are subjected to reclamation that is a basic activity on such type of lands in Western Poland. Afforestation is recommended as a very good reclamation method in terms of high biomass production, deep and intensive infiltration and biological activity of soil [10]. In typical sites, pine forests cover poor sandy soils, mainly podzols. Podsolization process is initiated and sustained by coniferous trees. Podzolic soils cumulated 9.1 $kg\cdot m^{-2}$ of carbon with annual restoration of 12.9 $g\cdot m^{-2}$ [11]. In properly reclaimed pine areas, the intensity of accumulation and transformation of soil organic matter can be similar to that in natural coniferous systems.

This work presents the results of reclamation from the experiment which started in 1986 on the post lignite mining area in Western Poland. The main purpose was to show fluctuation of various forms of carbon in reclaimed land after 25 years of the trial under various fertilizer combinations.

2. MATERIALS AND METHODS

Localization and description of the experiment. The field experiment was established on the outside spoil of the former lignite mine Przyjaźń Narodów located in Łęknica, Lubuskie province (51°33′45″N, 14°46′25″E) (Fig. 1).

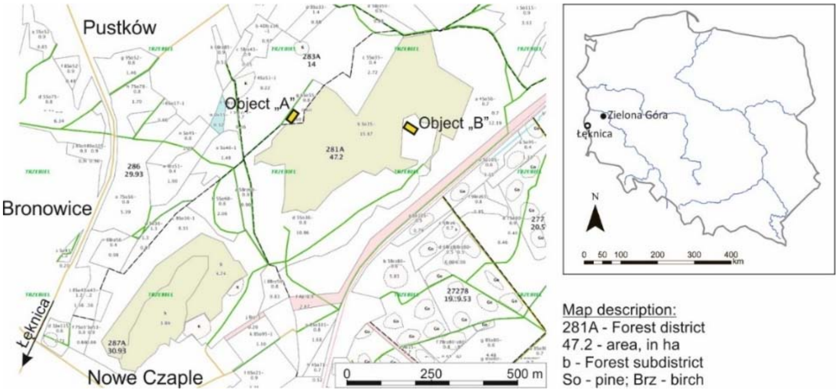

Fig. 1. Localization of the experimental field

The field was founded on previously unsuccessfully reclaimed area during the late 70's and early 80's of XX century. Reclamation was conducted through: (i) the application of technical procedures, (ii) pH neutralization with waste lime in an amount of 50 Mg·ha^{-1} in two doses (30 + 20 Mg·ha^{-1}), (iii) fertilization with 5 Mg·ha^{-1} of phosphorite meal, 200 kg·ha^{-1} of 25% N-ammonia nitrate with calcium carbonate, 200 kg·ha^{-1} of 18% ammonium phosphate, 400 kg·ha^{-1} of 60% potassium salt, and (iv) the planting of Scots pine. In the first year, i.e., in 1980, and in the second and third year of plant development, Scots pine was fertilized with urea at 200 kg·ha^{-1}. There were no satisfactory results of such reclamation. Many trees were lost and the development of trees that survived was poor with symptoms of nutrient deficiencies.

The experiment established in 1986 was arranged according to the Polish Academy of Sciences (PAS) reclamation model adjusted from an agricultural project to afforestation purposes [12]. The experiment was established according to randomized block design with three replicates. There were plots of 35×8 m, with various combinations of mineral fertilization (Table 1): (i) to provide proper development of forest growth (combinations 3–5 and 7– 9), (ii) to reclaim according to the PAS model (combinations 6 and 10), and (iii) to control (combinations 1 and 2). Combinations 3–5 and 7–9 varied to find optimal fertilization before introduction forest culture to soilless ground.

Lime was applied once in November 1986. Nitrogen, phosphorus and potassium were used in the following forms: N – ammonium nitrate (34% N), P – dusty single superphosphate (18% P_2O_5), K – potassium salt (50% K_2O), applied in the first quarter of 1986.

Soil sampling and laboratory analysis. This work reports the results of TOC determination in soil samples taken from the profiles after 25 years of running the trial. In 2010, the samples were collected from each plot (3 replications) and each differentiated horizon of spoil technosols (transportic) according to the WRB classification (O – litter horizon, A – initial humus horizon, Cg1 – parent rock horizon, subhorizon 1, pseudogley, and C2 – parent rock horizon, subhorizon 2). Soil samples, after being

Table 1

Experiment design

No. of plot	Combination	NPK dose [kg·ha^{-1}]			Lime dose [Mg·ha^{-1}]
		N	P_2O_5	K_2O	
1	–	–	–	–	–
2	Ca				8
3	NP	100	70	–	–
4	NK		–	160	
5	NPK		70	160	
6	2NPK	200	140	320	
7	NP + Ca	100	70	–	8
8	NK + Ca		–	160	
9	NPK + Ca		70	160	
10	2NPK + Ca	200	140	320	

transported to the laboratory, were dried at 35 °C and then sieved through 2 mm diameter mesh. Samples of forest litter were grounded before sieving using a Laboratory Jaw Crusher LKS-s ZPU Tetchem. All of the samples were thoroughly mixed to obtain homogenized material. Also the same components were determined in soil samples taken from the profiles in 2010. The results collected in 2010 were recalculated to the amount of TOC deposited on a surface of 1 m^2, using the formula given by Shrestha and Lal [13]:

$$\mathrm{Corg}_n\ [\mathrm{kg}\cdot\mathrm{m}^{-2}] = C_n\, SD_n\, BD_n \tag{1}$$

where: n – analyzed horizon, C_n – TOC content for the n horizon, (g·kg^{-1}), BD_n, SD_n – bulk density (Mg·m^{-3}) and thickness of soil material (m) in the n horizon. The TOC was determined by catalytic oxidation, using the NDIR Shimadzu TOC-VCSN with SSM 5000A adapter. Analyses were verified according to certified reference materials: MBH Analytical Ltd. (UK) GBW11101P and Clean sandy soil RTC-CLN SOIL-1-100 (US).

Statistical analysis. Statistical analyses were carried out using Statsoft STATISTICA 9.1 software. Differences between treatments were evaluated using a two-way ANOVA. The means were compared at $LSD_{0.01}$. Basic statistics and correlation coefficients for linear regression were also computed using statistical functions for Microsoft Excel 2007.

3. RESULTS

3.1. TOTAL ORGANIC CARBON

A post-mining dumping site after lignite mining that ceased in 1974, was characterized by high variability in brown coal parts distributed in the profile. Activities conducted during the technical reclamation (heap plateau and excavation floor levelling, formation of surface slopes) resulted only in a slight reduction in diversity of the carbon content in soil. After 25 year duration of the experiment, the differences of soil formation were observed, with clear occurrence of the forest litter horizon of the thickness of 2.5 to 4 cm (Fig. 2).

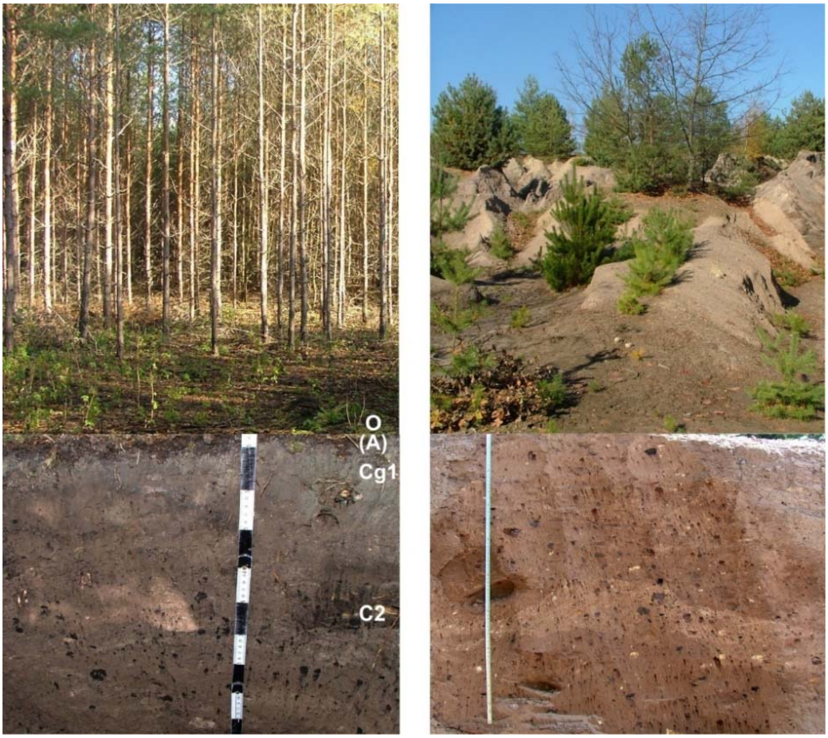

Fig. 2. Initial soil forming process occurring in the spolic technosol profiles;
NPK fertilised plot (left), and control plot (right)

Soil properties were impacted by fertilizer combinations. In the litter horizon on the liming combinations NPK + Ca and 2NPK + Ca the TOC was lower than on NPK and 2NPK (115 vs. 128 and 107 vs. 121 $g \cdot kg^{-1}$, respectively, Table 2).

On the plots fertilized with NPK higher values of TOC were observed compared to most other combinations (e.g., TOC on unlimed plots: the average for NPK and 2NPK 124.6 $mg \cdot kg^{-1}$, vs. the average for other unlimed plots 1 98.5 mg kg^{-1}. There were no significant differences between two mineral top horizons in TOC (Table 2).

The most pedogenic carbon was deposited directly on the soil surface, forming the litter horizon (O). The mineral horizons lying below contained about 20 times less organic carbon than it was noted in the litter horizon. It is very characteristic that the TOC content in the initial humic horizon is not significantly different in comparison with the parent rock material (Table 3).

Table 2

TOC content in samples from post-mining soils in Łęknica (Western Poland), 2010 (means of triplicate)

Combination	Horizon description	TOC [g·kg⁻¹]	Combination	Horizon description	TOC [g·kg⁻¹]
Control (0)	O	351.6	0 + Ca	O	314.1
	(A)	9.3		AC	26.5
	Cg1	4.3		C1	31.1
	C2	5.2		C2	22.0
	Mean value	92.6		Mean value	98.4
NP	O	363.7	NP + Ca	O	335.9
	(A)	16.0		AC	17.5
	Cg1	15.2		C1	22.0
	C2	8.5		C2	13.4
	Mean value	100.9		Mean value	97.2
NK	O	367.2	NK + Ca	O	315.8
	(A)	20.2		AC	20.5
	Cg1	11.7		C1	16.9
	C2	9.4		C2	14.2
	Mean value	102.1		Mean value	91.9
NPK	O	419.0	NPK + Ca	O	421.6
	(A)	28.8		AC	12.2
	Cg1	12.9		C1	15.8
	C2	51.9		C2	10.1
	Mean value	128.2		Mean value	114.9
2NPK	O	436.9	2NPK + Ca	O	384.1
	(A)	17.5		AC	18.9
	Cg1	16.4		C1	14.3
	C2	13.2		C2	11.7
	Mean value	121.0		Mean value	107.3

Statistical parameters for the TOC content [g·kg⁻¹]			
Minimum	4.3	$LSD_{0.01}$ for variants	8.1
Maximum	437	$LSD_{0.01}$ for depth	4.1
Arithmetic mean	80.3	$LSD_{0.01}$ for interactions	16.6
Standard deviation	134		
Standard error	77.2		

Table 3

TOC content in the soil horizons

Horizon	Mean values for horizons separately [g·kg⁻¹]
O	372.2
(A)	18.7
Cg1	16.0
C2	15.7

3.2. THE AMOUNT OF ORGANIC CARBON DEPOSITED ON THE AREA OF 1 M^2

Using the Shrestha and Lal formula (1), the accumulation of organic carbon in the forest litter and in the horizon lying directly under the litter have been calculated, separately for the limed and unlimed plots. Limed plots accumulated 2.29 $kg\cdot m^{-2}$ of C in the litter horizon and 0.68 $kg\cdot m^{-2}$ in the mineral horizon beneath. For the unlimed plots the accumulation of C amounted to 3.43 $kg\cdot m^{-2}$ in the litter horizon and 0.68 $kg\cdot m^{-2}$ in the mineral horizon beneath. It means that the soil covering 1 ha of reclaimed limed area demonstrated ability to sequester of 108.7 Mg of CO_2 per 1 ha (83.9 Mg in the forest litter and 24.8 Mg in directly underlying mineral horizon) and 150.6 Mg per 1 ha on unlimed area (125.7 Mg in the forest litter and 24.9 Mg in directly underlying mineral horizon).

4. DISCUSSION

Deficiency of the pedogenic organic matter is widely described as a disadvantage of post-mining land, designed for reclamation and further plant production. Presented results showed an increase of organic carbon content in soils after reclamation within 25 years. The total organic carbon varied significantly under the influence of different fertilizer combinations (Table 2). After 25 years of our study, the litter deposition gained 2.5–4.0 cm and the initial humic horizon lying directly beneath reached 4.0–6.5 cm. The highest carbon content was in surface litter. In soil surface and in deeper horizons, the content of all forms of carbon was significantly lower (Table 2).

The organic carbon accumulation rate in the litter and the top horizons was adequate to the findings reported for the Lausitz Coal Basin Area in Eastern Germany [7] and Sokolov surrounding areas – the Czech Republic [14–16]. The reclaimed areas of Southern Poland also demonstrated organic carbon accumulation progressing over time: 3.9 after 5 years, 5.4 after 17 years, 6.7 after 20 years and 7.4 $Mg\cdot ha^{-1}$ after 25 years [17].

The intensity of accumulation of organic matter on reclaimed land depended on the age of afforestation. On the reclaimed land surrounding Bärenbrück, the estimated new litter accumulation on 19-year-old pine trees was at 1.7-2.1 $kg\cdot m^{-2}$, and on the surfaces with the 37-year old pine trees at 4.1 $kg\cdot m^{-2}$ [7]. Fettweis et al. [7] reported 7.1 $kg\cdot m^{-2}$ deposition in the natural environment, under the 95-year old pine trees.

The deposition of carbon in reclaimed land is significantly lower compared to natural areas [7, 13]. For areas of Eastern Ohio in the horizons 0–15, 15–30 and 30–45 cm, on the reclaimed land Shrestha and Lal [13] 7.3, 6.7 and 6.3 $g\cdot kg^{-1}$ were found, and in natural areas – 28.9, 13.1 and 8.6 g C kg^{-1}, respectively. Fettweis et al. [7] reported deposition of carbon of 0.5-0.6 $kg\cdot m^{-2}$ in the top horizon (0–10 cm) of reclaimed areas and 2.3 $kg\cdot m^{-2}$in natural areas. In the 60-year-old pine established on reclaimed land, 14% of total ecosystem carbon was collected in litter and about 7% in soil [18]. Taking into consideration the type and age of forest stands, our results obtained after 25 years of reclamation, with average accumulation of 2.86 kg·m^{-2} in litter and 0.68 kg·m^{-2} in top mineral horizon, remain in good agreement with aforementioned reports.

Our findings indicated that C content in the litter and in the horizon lying directly below the litter was higher on unlimed plots compared with the limed ones. Kreutzer [19] reported that liming accelerates decomposition of organic matter. A higher accumulation of coniferous litter in the plots with complete NPK fertilization and doubled NPK fertilization has been observed, comparing to other fertilizer combinations and the control. Johnson [20] reported that application of NPK to forest areas increased accumulation of C in soil by increasing growth and litter production both above and below ground [17, 20, 21].

Currently, much attention is paid to the problem of carbon bonding by the soil and plants, and thus reducing its emission to the atmosphere [1, 18, 22]. Dixon et al. [23] reported that the ratio of soil C to vegetation C in Europe was about 2.81. The global potential of C sequestration by forests is high, about 0.4 Pg·year^{-1} [4]. This shows the importance of soil as carbon storage in the ecosystem. In the Polish Academy of Sciences Reclamation Model, N-fertilizing is considered the most important factor. According to Lal [4], many forest ecosystems are nitrogen limited and an increase in N supply can enhance C accumulation in soils.

One of the main effects of reclamation processes is systematic increase of the pedogenic carbon content in soil in the form of humus [24]. Soil rehabilitation brings changes concerning formation of the soil structure, as well as its physicochemical and biological properties. As a result, there is an occurrence of a soil profile typical of the certain soil-forming factors [3]. Carbon accumulation in topsoil is subsequent to the advantage of humification over mineralization processes which is characterized by periodical fluctuations caused by transforming soilless ground into pedogenic soil carbon storage [1].

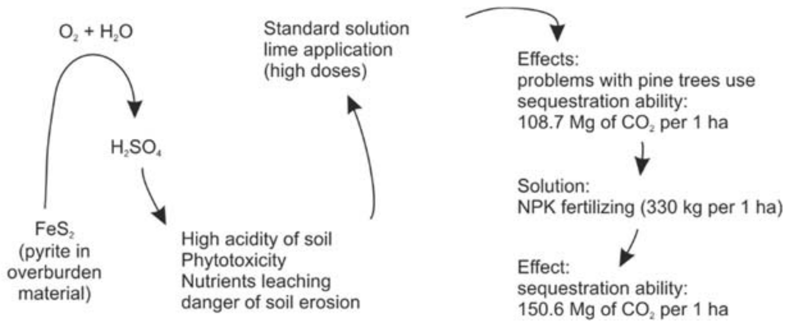

Fig. 3. The graphic description of the analysed process

Achievement in forest reclamation on soilless sandy grounds containing pyrite was dependent on neutralizing acidity and surface horizons enrichment in nutrients by application of NPK fertilization. Satisfactory effect in growth and development of pine forest was accomplished by liming and NPK application before planting and supplementary fertilization of NPK after the first few years of growth. Better growth of trees resulted in an intensive fall of needles and small twigs on the soil surface. The tree roots penetrate the soil to a depth of several tens of centimetres, changing its stricture and other properties. Also the forest undergrowth tends to grow more intensely. As a result, the carbon sequestration increased, mainly as an effect of the formation of the litter horizon (Table 3, Fig. 3).

The 25 year reclamation process developed differentiation of soil profile. The changes were expressed by creation of soil horizons: litter horizon (O), surface horizon enriched in organic matter (A) and parent rock horizons C1g and C2. Even though initial liming of post mining grounds resulted in expected neutralization effect, the subsequent liming was not effective any longer and decelerated organic matter accumulation in formed soil surface layers (O and A) compared to unlimed area.

5. CONCLUSIONS

Soil is a huge reservoir of carbon, with a significant CO_2 sequestration ability, being an important item in the carbon balance.

Deficiency of pedogenic organic matter is a significant disadvantage of post-mining land, complicating the process of reclamation and limiting the ability to achieve positive effects in a short time.

Reclamation activities aimed at soil creating, especially these connected with soil fertilization with high NPK doses, contributes to binding carbon in the form of complex compounds. This increases a deposition of organic carbon in litter and the humic soil horizon.

Building organic and humic horizons of soil is a very complicated and lengthy process. After 25 years of reclamation of the post-mining area, litter deposition increased by 2.5–4.0 cm and the initial humic horizon, lying directly beneath reached 4.0–6.5 cm.

An average carbon accumulation in surface litter amounted 2.86 $kg\cdot m^{-2}$ and in the initial humic horizons 0.68 $kg\cdot m^{-2}$. This indicates an average sequestration of 130 Mg CO_2 per 1 ha of reclaimed area. The results may be described as mean, taking into account different areas being reclaimed. The key to achieving better results lies in better control of the reclamation process.

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