Vol.2, No.9, 1015-1021 (2010)
http://dx.doi.org/10.4236/ns.2010.29124

Natural Science

Potential for carbon sequestration in reclaimed mine soil on reforested surface mining areas in Poland

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Received 16 June 2010; revised 17 July 2010; accepted 23 July 2010.

ABSTRACT

Reclaimed mine soils (RMS) which develop on post-mining sites play significant role in Carbon sequestration in new ecosystems, especially in local range on areas disturbed by human activity. This study presents the potential for Carbon sequestration in RMS developing on 3 post surface mining areas in Poland (Central Europe) reforested with Scots pine (*Pinus sylvestris* L). Research was conducted on waste heaps and quarry which accompany open cast lignite, sulfur, and sand mining. Control plots were arranged in managed pine forests on natural sites in the surrounding area. The results shows high Carbon accumulation in RMS, estimated on 16.77 Mg·ha^{-1} in poor (oligotrofic) soils on Quaternary sands on sand quarry and up to 65.03 Mg·ha^{-1} on external waste heap after Sulfur surface mining exploitation on Quaternary sands mixed with Tertiary clays. These results were very similar to natural forest soils on control plots. Potential rate of Carbon sequestration in RMS was estimated on 0.73 (on the poorest sandy soils on quarry) to 2.17 Mg·ha^{-1}·yr^{-1} (on potentially abundant sandy-clayish soils on Sulfur waste heap), and 5.26 Mg·ha^{-1}·yr^{-1} (on Tertiary sands substrate soils on lignite mining waste heap). In conslusion the average Carbon accumulation in RMS was estimated on 41 Mg·ha^{-1} and Carbon sequestration rate was 1.45 Mg·ha^{-1}·yr^{-1}. According to the result of this study and range of post-mining areas reclaimed to forestry in Poland (ca 15000 ha) total Carbon accumulation in RMS was estimated on 615 × 10^{3} Mg and potential Carbon sequestration rate in new ecosystems on 21.75 × 10^{3} Mg·ha^{-1}·yr^{-1}. However, the main factors affecting Carbon sequestration and protection in RMS under tree stand were substrate, percentage of clay and silt sized fraction, in order to formulate guidelines for sustainable management of post-mining ecosystem, further study must be continue for better understanding.

Keywords: Post-Mining Ecosystem; Reclaimed Mine Soils; Reforestation; Carbon Sequestration

1. INTRODUCTION

Global warming risks from emission of green house gases (GHGs) by anthropogenic activities, and possible mitigation strategies of terrestrial Carbon (C) sequestration have increased the need for the identification of ecosystems with high C sink capacity [1]. In compliance with the Kyoto protocol, the emission of GHGs is to be reduced on average by 5.2% in relation to the 1990 level until 2012. These requirements are being implemented in the EU by introducing energy saving technology and increasing the share of renewable energy sources. A potential approach to mitigating the rising CO_2 concentration is to enhance sequestration of C in terrestrial ecosystems [2]. This can be achieved by enhancing the biological processes like photosynthesis that assimilated CO_2 increasing biomass productivity, and allocating the assimilated C into long-lived plant and soil organic matter (SOM) pools resistant microbial decomposition. Thus the Kyoto protocol talks about the possibility of alleviating the results of the GHGs by appropriate land use and this is where forestry plays a particular role. It is widely known that forests have a significant share in Carbon accumulation and absorbing carbon dioxide (CO_2) [3-6]. In forest ecosystems it is possible to increase the ability to sequester Carbon by appropriate forestry and by increasing woodiness. It may also be done by reforesting former industrial and post-mining sites.

Mining is a human activity, which causes drastic surface disturbance, including soil - the base element of te-

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*This work was supported by JM Rector of University of Agriculture in Krakow in frame of Alina and Jan Wagowie Scholarship for young scientist research program in 2009 year.

rrestrial ecosystems. These disturbed areas, where reclaimed mine soils (RMS) are developing, may play locally significant role for potential of C sequestration [6], especially through restoration by reforestation. Although a key objective in C management research is to enhance the natural capacity of plants' biomass and soils to sequester C, the functionality of C storage in terrestrial ecosystem as whole, especially in post-mining ecosystem and RMS, is poorly understood.

In Poland lands taken up by mining and power industry are estimated at around 70 thousand hectares, ca. 25 000 thousand of which has been reclaimed. A large part of these areas in Poland (approximately 60%) are reclaimed to forestry [7]. The Scots pine (*Pinus sylvestris* L.) is one of the main species introduced when reforesting post-mining sites in central Europe [7,8] due to its low habitat requirements and pioneering character [9]. Forest ecosystems, especially soils, which develop in these areas, may play significant role in Carbon sequestration which will increase as communities' biomass and soils developing. According to this the aim of study was to estimate the potential for Carbon sequestration of reclaimed post-mining soils (RMS) and in soil organic matter (SOM) at different reclamation treatments and substrates (parent rock material).

2. MATERIALS AND METHODS

2.1. Study Site and Sampling

The research was conducted on three post-mining sites reclaimed to forest and covered by 12 to 30 years-old pine (*Pinus sylvestris* L.) stands in central and southern Poland. The study sites were located at a waste heap in Lignite Mine Bełchatów (BEL; 19°25' E; 51°13'N), a pit bottom of sand quarry Szczakowa (SZCZ; 19°25' E; 50°14' N) and a waste heap of open-cast Sulfur mine Piaseczno (PIAS; 21°34' E; 50°33' N). Some characteristics of the sampled sites are given in **Table 1**.

Table 1. Study site characteristics.

	Post-minig facilities and substrate variant					
Characteristic	Waste heap in Lignite Mine Bełchatów		Bottom of sand quarry Szczakowa		Waste heap of open-cast sulfur mine Piaseczno	
	BEL 1	BEL 2	SZCZ 1	SZCZ 2	PIAS 1	PIAS 2
Latitude	51°13' N		50°14' N		50°33' N	
Longitude	19°25' E		19°25' E		21°34' E	
Mean annual precipitation (mm)	580		700		650	
Mean annual temperature (°C)	7.6		8		7.0	
Parent material	Quaternary loamy sands, loam, bouldery clay;	Tertiary sands with loam and clay, carbonated and sulfurised	Fluvioglacial Quaternary sands and loamy sands	Fluvioglacial Quaternary sands	A mixture of tertiary clays and mudstones and Quaternary sands	Quaternary sands
Basic reclamation treatments	NPK fertilisation (60 kg N ha^{-1}, 70 kg P ha^{-1}, 60 kg K ha^{-1}); one year cultivation of grasses and leguminous plants (sowing 60 kg·ha^{-1}); planting of trees.	Neutralisation with bog lime; NPK fertilisation (60 kg N ha^{-1}, 70 kg P ha^{-1}, 60 kg K ha^{-1}); one year cultivation of grasses and leguminous plants (sowing 60 kg·ha^{-1}); planting of trees.	Organic amendment addition (300 m^3 ha^{-1} approx. 1.0% C_{org}); liming (1.5 Mg dolomite ha^{-1}); NPK fertilization (140 kg N ha^{-1}, 130 kg P ha^{-1}, 150 kg K ha^{-1}); 2-years lupine (*Lupinus luteus* L.) cultivation (sowing 240 kg ha^{-1}); planting of trees.		NPK fertilisation (80 kg N ha^{-1}, 50 kg P ha^{-1}, 60 kg K ha^{-1}); 2-years cultivation of *Papilionaceae* and grasses; planting of trees (*Pinus sylvestris* L.).	
Tree stand aboveground biomass (mean and SD in Mg·ha^{-1})	44.26 (8.34)	8.12 (2.60)	76.75 (6.15)	80.93 (7.36)	102.12 (2.80)	129.98 (15.63)
Forest flour (herbaceous and shrubs) aboveground biomass (mean and SD in Mg·ha^{-1})	0.135 (0.091)	0.033 (0.021)	0.015 (0.010)	0.013 (0.011)	0.170 (0.245)	0.073 (0.062)

Areas of Tertiary sandy strata with loam and clay on Bełchatów heap are frequently carbonated and sulfurised, which are very acidic, displaying toxic properties [10]. These tertiary pyritic strata was earlier neutralised with bog lime incorporated into the surface horizon to a depth of 40 cm. Reclamation treatments on the Szczakowa open cast sand quarry included forming and grading the surface and adding organic amendment (approx. 300 $m^3 \cdot ha^{-1}$). The organic amendment used was a mixture of local forest litter and mineral Ai horizons with an average organic Carbon content of 0.3 to 1.0%, selectively collected from forest soils in areas to be mined [11].

A total of 24 research plots (100 m^2 each) were arranged in pine stands with 4 replications for 2 parent material (substrates) and trophy variants at each post-mining object:

1) variant 1 on potentially abundant soils with the best particle size distribution at the post-mining object, *i.e.* loamy sands, sands mixed with clays (BEL 1, SZCZ 1, PIAS 1);

2) variant 2 on potentially less fertile substrates with particle sizes of loose sands or sands with little clay (SZCZ 2 and PIAS 2). However, at the Bełchatów waste heap (BEL 2), variant 2 were located on Tertiary pyritic strata (mainly sands) following neutralization.

Four control plots (100 m^2 each) were also set up in NPE (natural pine ecosystems) adjacent to post-mining sites, in tree stand age classes 1 and 2 in habitats of coniferous forests and mixed fresh forests. In Poland and in Central Europe these are appropriate habitats for Scots pine [12].

On each study plots soil pits were dug up to 110 cm depth (on reclaimed sites) and 150 cm (on natural forest sites) and detailed morphology of soils was described. Additionally, 5 bore holes were made on each plot with soil augers (Eijkelkamp set) on grid (an envelope scheme) and mixed soil samples were taken (1.0 kg mass of fresh sample) to determine basic soil chemical and physical properties and Carbon content at depths: 0-8 cm (initial organic-mineral horizons AiC with features of parent rock); 8-110 cm (C horizon as parent rock spoils). Sampling for bulk density was done by core method using standard sharpened steel cylinders of 250 cm^3 [13] (3 replication for each horizon in soil pits).

Samples of organic horizons (OLf horizon at 0 + 2 cm for reclaimed mine soils, and OL, Of, Oh, Ofh horizons for natural forest soils at depth depends on horizons development) were collected in autumn after litterfall from 1 m^2 sub-plots with 3 replications for each plots of 100 m^2. Next, the mass of fresh organic horizons was determined and mixed samples (0.5 kg mass fresh sample) were collected for laboratory analyses.

2.2. Laboratory Analyses

In the lab, soil samples from mineral horizons were dried and sieved through a 2 mm diameter sieve and samples from organic horizons were ground. The following parameters were determined in the soil samples using soil science procedures (described by Jackson [14] and Ostrowska *et al.* [15]. Particle size distribution was determined by hydrometer analysis method and additionally sand fractions by sieving. Soil pH was determined in H_2O and 1 M KCl while maintaining at 1:2.5 soil: solution ratio for mineral horizons and 1:5 ratio for organic horizons; CEC by as the sum of alkaline cations (Ca^{2+}, Mg^{2+}, K^+, Na^+ extracted with 1 mol L^{-1} NH_4OAc) and exchangeable acidity (H_h). Samples were mixed with a small portion of extracting and equilibrated. After 24 h, the suspensions were filtered, the soils were washed with additional extracting, and the total volume was made up to 100 mL [14]. The concentration of cations was determined by atomic absorption spectroscopy (AAS). Total acidity was measured using 1 mol L^{-1} $(CH_3COO)_2Ca$ extraction, followed by potentiometric titration to pH 8.2 with 0.1 mol L^{-1} NaOH [15]. Soil organic Carbon (C_{org}) content using the FT-IR method; total Nitrogen (N_t) content using the method of measuring thermal conductivity with a 'Leco CNS 2000' analyzer were made. Before procedure samples containing $CaCO_3$ were washed in 10% HCl to remove carbonates.

The results, such as the C accumulation and estimated C sequestration rate in soil (in mineral and organic horizons), were statistically analyzed using the *Statistica 8.1* programme [16]. Differences between mean values of features from differing groups (e.g., variants 1 and 2 for each post-mining sites) were tested by a student's t-test for independent variables (at p = 0.05). Linear regresion between C accumulation and soil features were also tested (at p = 0.05).

3. RESULTS AND DISCUSSION

3.1. Soil Characteristic

Soils in post-mining areas were classified as Urbic Anthrosols (according to FAO [17]) and had poorly developed AiC organic mineral initial horizons and OLf initial horizons of forest litter and partially decomposed hums layers. In the site variant 1, reclaimed mine soils (RMS) differed significantly (at p = 0.05) in % silt sized fraction at the Bełchatów waste heap (BEL 1 vs. BEL 2) and in % clay sized fractions on the Szczakowa (SZCZ1 vs. SZCZ 2) and Piaseczno (PIAS 1 vs. PIAS 2) sites (**Table 2**). The H_2O:soil pH differed only in by site trophy variants (1 vs. 2) in the forest litter horizons OLf at the Bełchatów (BEL) and Piaseczno (PIAS) sites and in parent rock horizons only at Bełchatów (BEL). An extra factor for sandy soils developing on the Szczakowa sand quarry (SZCZ) was the lowest Cation Exchange Capacity CEC (**Table 2**).

Native podzolic forests soils (NPE) on adjacent to post-mining sites were in habitats of coniferous forests and mixed fresh forests developing on Albic Arenosols and Haplic Podzols (according to FAO [17]).

3.2. Carbon Accumulation and Potential for Carbon Sequestration

Total Carbon accumulation in soil (the sum for mineral and organic horizons) ranged from 16.77 Mg·ha^{-1} at sand quarry in SZCZ 2 variant (in the poorest sandy soils) to over 65.03 Mg·ha^{-1} in PIAS 1 waste heap on abundant sandy-clayish deposits (**Table 3**). This value was even higher than the estimated average total Carbon accumulation in soil for NPE, which in mineral and organic horizons together was on average 59.14 Mg·ha^{-1} (**Table 3**). In research conducted on natural sites of inland dunes in Holland under initial communities which had developed by way of natural succession and aged 5, the Carbon accumulation in soil organic matter (SOM) was around 6.0 Mg·ha^{-1}, whereas under 120-year-old mixed forest it was around 104 Mg·ha^{-1} [18]. In forest habitats of Central Europe, in organic and organic-mineral Haplic Podzols developing on bank and water glacial sand, the amount of C_{org} accumulation may be estimated at around 76.0 to 122.0 Mg·ha^{-1}, and in case of the poorest Haplic Podzols (according to FAO soil subtype [17]) developing on eolian sands, it is around 126.0 Mg·ha^{-1} (calculated on the basis of data from the Atlas of Forest Soils in Poland [19]. As in the case of carbonated Tertiary (Miocene strata) sands on coal mine spoil heaps BEL 2 variant the 'geological coal' has a large share in the total content. It had to be assessed in the context of the origin and properties of these deposits. The determination of Carbon content in SOM and later the determination of accumulated Carbon in soils developing on reclaimed mine soils (RMS) is particularly difficult from the methodology point of view in case of carbonated deposits which constitute banks [20,21].

Table 2. Some characteristics of reclaimed mine soil (RMS) on three post-mining sites in Poland (Central Europe).

Feature	Horizon	Waste heap in Lignite Mine Bełchatów		Bottom of sand quarry Szczakowa		Waste heap of open-cast sulfur mine Piaseczno	
		BEL 1	BEL 2	SZCZ 1	SZCZ 2	PIAS 1	PIAS 2
Silt (0.05-0.002 mm) [%]	AiC and C	**31.75**^{a} (11.44)	**7.50**^{b} (1.73)	8.25 (2.63)	4.50 (1.29)	10.50 (5.74)	3.75 (1.71)
Clay (< 0.002 mm) [%]		3.00 (2.94)	2.75 (1.89)	**3.50**^{a} (0.58)	**1.25**^{b} (0.96)	**8.50**^{a} (2.08)	**3.50**^{b} (1.29)
pH H_2O	OLf	**4.45**^{a} (0.13)	**4.18**^{b} (0.05)	4.30 (0.14)	4.45 (0.31)	**5.15**^{a} (0.17)	**4.68**^{b} (0.29)
	AiC	7.65 (0.17)	5.70 (1.51)	5.30 (0.00)	6.53 (1.59)	6.18 (1.05)	6.00 (1.12)
	C	**8.06**^{a} (0.10)	**5.33**^{b} (1.44)	6.11 (0.14)	6.98 (1.25)	6.87 (0.62)	6.75 (0.64)
pH KCl	OLf	**4.10**^{a} (0.08)	**3.83**^{b} (0.15)	3.65 (0.25)	3.75 (0.26)	**4.60**^{a} (0.24)	**4.15**^{b} (0.25)
	AiC	7.35 (0.17)	4.95 (1.73)	4.15 (0.06)	5.93 (2.06)	5.58 (1.36)	5.40 (1.60)
	C	**7.50**^{a} (0.12)	**4.69**^{b} (1.50)	4.60 (0.18)	6.18 (1.610	6.40 (0.78)	6.28 (0.90)
C_{org} [%]	OLf	47.85 (0.55)	40.75 (5.34)	31.66 (9.62)	33.33 (7.230	29.78 (4.08)	32.90 (10.34)
	AiC	0.61 (0.28)	0.27 (0.04)	**0.46**^{a} (0.13)	**0.23**^{b} (0.120	**1.32**^{a} (0.19)	**0.48**^{b} (0.04)
	C	0.32 (0.11)	0.29 (0.12)	0.19 (0.04)	0.10 (0.04)	0.65 (0.11)	0.23 (0.03)
N_t [%]	OLf	**0.58**^{a} (0.03)	**0.49**^{b} (0.05)	0.77 (0.22)	0.78 (0.18)	1.01 (0.11)	0.94 (0.30)
	AiC	**0.05**^{a} (0.00)	**0.0**^{b} (0.00)	0.04 (0.01)	0.03 (0.01)	**0.09**^{a} (0.01)	**0.03**^{b} (0.01)
C/N ratio	OLf	82.78 (3.86)	83.58 (5.74)	41.00 (5.15)	42.85 (5.10)	**29.33**^{a} (1.25)	**34.98**^{b} (2.83)
	AiC	11.55 (5.62)	18.83 (0.89)	**11.1**^{a} (1.53)	**7.30**^{b} (1.59)	15.53 (2.32)	13.83 (1.59)
CEC [cmol (+)/kg]	AiC	**27.98**^{a} (5.68)	**5.68**^{b} (1.40)	2.20 (0.72)	3.70 (2.42)	14.10 (8.37)	5.45 (3.450
	C	**27.68**^{a} (4.23)	**5.49**^{b} (0.85)	3.13 (0.49)	2.18 (1.11)	11.75 (7.47)	3.73 (1.36)

Explanations: 37.75(11.44) – mean and standard deviation; BEL 1 – reclaimed mine soil on "Bełchatów" spoil heap and site trophy variant; abbreviations for soil features – see description in text

Table 3. Carbon accumulation in soils in pine ecosystem on afforested post-mining sites and 'natural' forest sites.

Variant and tree stand age (years)	Soil Carbon accumulation (CA Mg·ha $^{-1}$) and Carbon sequestration rate (CS Mg·ha $^{-1}$·yr^{-1})					
	Mineral AiC and C horizons up to 110 cm depth (in post-minig soil) and A, B and C horizons (in natural soil)		Organic horizons OLf (row litter and humus) in post-minig soil and il OL, Of, Oh horizons)		Total organic and mineral horizons in soil up to 110 cm depth	
	CA	CS	CA	CS	CA	CS
BEL 1(17)	35.18 (7.65)	2.07 (0.45)	10.69 (4.36)	0.63 (0.26)	45.87 (8.36)	2.07 (0.49)
BEL 2 (12)	53.50 (27.69)	3.15 (1.63)	9.57 (2.30)	0.80 (0.19)	63.07 (28.09)	5.26 (2.34)
SZCZ 1(21)	12.83 (1.95)	0.75 (0.11)	9.78 (1.94)	0.36 (0.23)	**22.61**^{a} (2.21)	**1.08**^{a} (0.11)
SZCZ 2 (23)	8.64 (3.00)	0.51 (0.18)	8.13 (2.06)	0.35 (0.09)	**16.77**^{b} (1.42)	**0.73**^{b} (0.06)
PIAS 1 (30)	**53.97**^{a} (12.38)	**3.17**^{a} (0.73)	11.06 (4.19)	0.37 (0.14)	**65.03**^{a} (16.13)	**2.17**^{a} (0.54)
PIAS 2 (30)	**21.62**^{b} (4.74)	**1.27**^{b} (0.28)	12.76 (3.65)	0.43 (0.12)	**34.38**^{b} (5.25)	**1.15**^{b} (0.17)
NPE (30)	40.42 (9.4)	2.38 (0.55)	18.74 (7.21)	0.62 (0.24)	59.14 (14.36)	1.97 (0.48)

Explanations: 35.18 (7.65) – mean (SD); BEL 1 – Bełchatów waste heap in site trophy variant 1; NPE – natural pine ecosystem (abbreviations see in text); CA – total Carbon accumulation in soil horizons; CS – Carbon sequestration rate as quotient of CA and reclaimed mine soil age; 22.61^{a} – market differences between variants 1 and 2 are significant at p = 0.05 by t-student test with independence variables, Number of replication plot for variant n = 4

Therefore, the rate of Carbon sequestration in these soils may be determined from accumulation in initial organic horizons developing under communities. When comparing BEL variant 2 to other studied sites, accumulated Carbon in organic horizons was the lowest and estimated on 9.57 Mg·ha^{-1}. In OLf organic horizons in other sites, the amount of accumulated Carbon ranged from 8.64 Mg·ha^{-1} (SZCZ 2 variant) to 12.76 Mg·ha^{-1} (PIAS 2 variant). However, the amount of accumulated Carbon in OLf was not a variable which statistically differentiated significant (at p = 0.05) trophy variants 1 vs. 2 within the sites (**Table 3**).

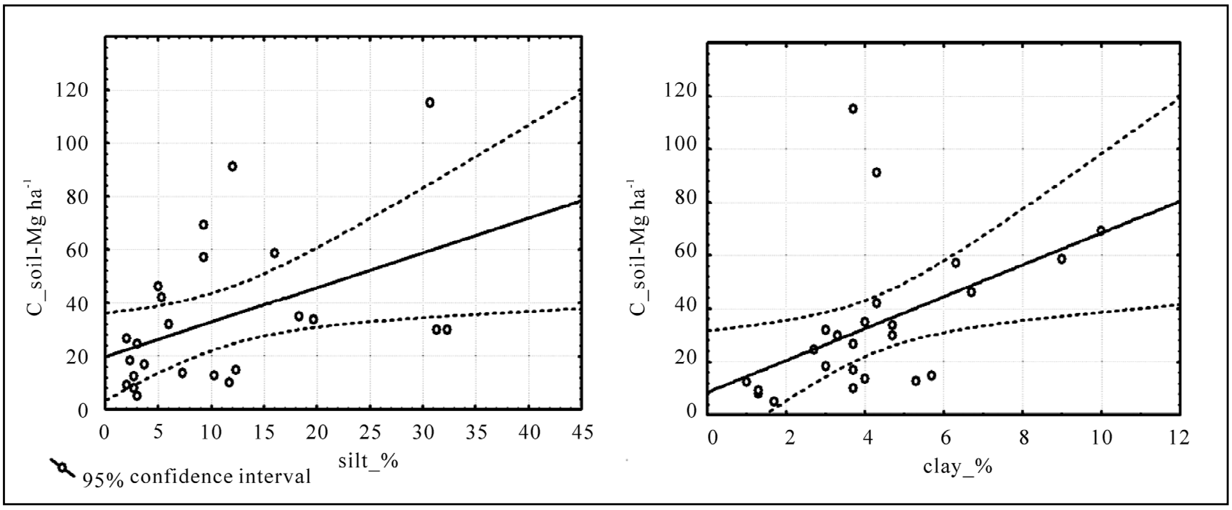
Estimated Carbon sequestration rate in the mineral horizons (up to 110 cm depth) of reclaimed mine soils amounted from 70.73 Mg ha^{-1}·yr^{-1} in the poorest sandy soils in SZCZ 2 variant on sand quarry to 2.17 Mg ha^{-1}·yr^{-1} in fertile sandy-clayish deposits in PIAS 1 variant on Piaseczno waste heap.

However the highest Carbon sequestration rate, estimated on 5.26 Mg ha^{-1}·yr^{-1} was in sandy soils on Tertiary Miocene strata of Bełchatów waste heap in BEL 2 variant, it was connected mainly with 'geologic carbon' content. The potentially Carbon accumulation in RMS on post-mining ecosystems estimated on such bases may amount approximately on 1.45 Mg·ha^{-1}·yr^{-1} (based on data from **Table 3**, excluded BEL 2 variant). It was not so high as Shrestha and Rattan [1] quoted on 3-4 Mg·ha^{-1}·yr^{-1} Carbon for reclaimed mine soil in US prairie climate conditions. However values from studied post mining sites are high compared to published data from another coal mining region, e.g., of North Dakota (USA), where the Carbon accumulation rate in soil under plant communities succession was 0.131 Mg·ha^{-1}·yr^{-1} [22] or 0.282 Mg ha^{-1}·yr^{-1} in reclaimed soils in southern Saskatchewan (Canada) [1] and 0.256 Mg·ha^{-1}·yr^{-1} in the Montana mining region (USA) [25].

In reclaimed mine soils (RMS) the distribution of Carbon accumulation in organic and organic mineral horizons was diversified. In natural Haplic Podzols in control plots, Carbon accumulated in organic horizons constituted around 34% of the total Carbon accumulated in soil. In case of post mining ecosystem soils, the largest amount of Carbon trapped in OLf initial organic horizons, was in sandy soils of sand quarry and significantly exceeded 40% in both variants.

On the investigated lignite mine waste heap it ranged from around 15 in BEL 2 variant to 23% in BEL 1 variant, and for PIAS 1 variant on sulfur waste heap from 17% to 37 % in PIAS 2 variant (estimated on the basis of data from table 3). According to the findings of German research (Lusatian Mine District), most organic Carbon in areas of up to 17 years of age under pine trees accumulated in the overlaying humus horizon (OLf). From the age of 32, Carbon accumulated mostly in the initial organic-mineral horizon (AiC) [23]. A dynamic increase of Carbon accumulation in overlaying humus horizons is connected with the development of tree communities and a growing amount of organic fallout.

The dependence of Carbon accumulation in soil (in mineral horizons up to 110 cm depth) in reclaimed mine



(a) (b)

Figure 1. Correlation of Carbon accumulation in reclaimed mine soil (in mineral horizons up to 110 cm depth) to % clay sized fraction (< 0.002 mm diameter) (R = 0.48) (**Figure 1(a)**) and % silt sized fraction (0.05-0.002 mm) (R = 0.45 at n = 24) (**Figure 1 (b)**).

soils showed significant linear correlation to percentage silt sized (0.05-0.002 mm diameter) (R, linear regression coefficient with p = 0.05 was 0.45 at N = 24) and percentage clay sized (< 0.002 mm diameter) (R = 0.48) (**Figures 1(a)**, **(b)**). According to this, as mentioned in literature [21,23,24] one of the main factors for Carbon accumulation range in reclaimed mine soils is substrate and particle size distribution, included % silt and clay sized fraction.

4. CONCLUSIONS

The potential for Carbon sequestration in reclaimed mine soil (RMS) in pine ecosystems on post-surface mining sites in Poland turned out to be relatively high compared to native podzolic soils in natural pine ecosystems (NPE) in Central European climatic zone. Currently, young pine tree stands (from 12 to 30-years old) and soils which developed underneath had a comparable Carbon sequestration rate level to average values for NPE control plots. The lowest total Carbon accumulation in soil occurred in the most oligotrophic sites on a sand quarry and exceeded 16 Mg·ha^{-1}, *i.e.*, around 30% as compared to average accumulation in native forest soils (on NPE control plots), over 46 Mg·ha^{-1} on the spoil heap following lignite mining at Bełchatów (BEL 1) sulfur mining (PIAS 1), *i.e.* over 70% of the value in native soils (NPE), and on the waste heap following sulfur mining over 34 Mg·ha^{-1} in PIAS 2 and 65 Mg·ha^{-1} in PIAS 1 variant, *i.e.* even higher than in case of NPE control plots. The range of Carbon accumulation in the youngest (12 years old) RMS on BEL 2 variant (lignite waste heap) was very high and amounted at 63.07 Mg·ha^{-1}. However these results are rather discussed because it was very difficult to estimate Carbon accumulation in RMS on Tertiary Miocene carboniferous strata.

Assuming that Carbon accumulation in RMS of pine ecosystems ranged from 34 to 65 (average of ca. 41) Mg·ha^{-1}, it may be estimated that from 510 to 975 Mg·ha^{-1} total or an average of 615 × 10^{3} Mg·ha^{-1} may be potentially Carbon accumulated in soil in the currently reclaimed to forest post-mining sites in Poland (of ca. 15 000 ha). Estimated rate of Carbon sequestration in soil was 0.73 (on the poorest sandy soils) to 2.17 Mg·ha^{-1}·yr^{-1} (on abundant sandy-clayish soils), and 5.26 Mg·ha^{-1}·yr^{-1} (on Tertiary carboniferous substrate soils). The average Carbon sequestration rate was 1.45 Mg·ha^{-1}·yr^{-1} and potential for Carbon sequestration in RMS was estimated on 21.75 × 10^{3} Mg·ha^{-1}·yr^{-1}. The estimated Carbon sequestration range in Central Europe climatic zone condition was near 2-fold lower than similar data for reclaimed mine soil in e.g., prairie climatic zone (USA) quoted in literature. It means, that similar to dependence of natural biomes (vegetative zones of Earth), very important factor for soil Carbon accumulation and Carbon biogeochemical cycle is climate. Second very important factor for potential of Carbon sequestration was substrate (parent material) and particle size distribution. These factors affected on potentially abundant and fertile of reclaimed mine soil, as well. However, as well-known from references, the factors affecting C accumulation and ability for Carbon sequestration and protection in RMS leading to increase in: substrate properties (especially percentage silt and clay sized), microbial activity, nutrient availability; soil aggregation, C build up and soil profile development under tree stand age must be better understood in order to formulate guidelines for sustainable management of post-mining ecosystem.

5. ACKNOWLEDGEMENTS

This study was financially supported by JM Rector of University of Agriculture in Krakow in 2009 for realization of research program by young scientist in frame of Alina and Jan Wagowie Scholarship. The authors also thank to Jarosław Socha PhD from Department of Forest Mensuration for his assistant in statistical results evaluation.

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