Original Research

Hydrological Properties of Soils in Reclaimed and Unreclaimed Sites after Brown-Coal Mining

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Abstract

Bulk density, porosity, water holding capacity, water field capacity, wilting point, clay content, hydraulic conductivity, and soil moisture were studied in unreclaimed sites (5, 15, and 25 years old) and reclaimed sites (20-30 years old) on a post-mining spoil heap near Sokolov, Czech Republic. The unreclaimed sites had been spontaneously colonized by shrubs, and the reclaimed sites had been planted with pine, spruce, oak, alder, or meadow (the meadows were created by the spreading of topsoil and grass seed). Soil bulk density decreased with site age and was similar in unreclaimed and reclaimed sites except in the meadow sites, where bulk density was highest. Field capacity (in terms of volumetric soil water content) increased with site age and was similar in unreclaimed and reclaimed sites except for the meadow sites, which had the lowest field capacity. The wilting point (in terms of volumetric soil water content) decreased with age in unreclaimed sites, was higher in reclaimed sites than in unreclaimed sites, and was higher for the meadows than for other sites. Hydraulic conductivity was generally low but was highest in young sites. Soil moisture content had no clear seasonal pattern in young, unreclaimed sites (which had little vegetation), but decreased in summer in all vegetated sites. Soil moisture was highest in the reclaimed alder sites and was lowest in the reclaimed pine and meadow sites. Relative to unreclaimed sites, reclaimed sites had a higher ability to hold water but a higher wilting point, such that water availability for plants was similar in both kinds of sites. The water deficit was highest in the reclaimed oak sites followed by the meadow sites. The latter finding indicates that the spreading of topsoil during reclamation does not result in improved soil moisture conditions 20 years later.

Keywords: physical properties, moisture regime, spoil heaps, reclaimed, unreclaimed sites

Introduction

Open-cast coal mining causes massive disturbance to ecosystems. In this kind of mining, "spoil" material overlying the coal layer is removed and deposited in heaps on the soil surface. Because the spoil material is excavated from great depths, it differs substantially from recent soils [1]. It may have an unusual texture and a high content of heavy metals, and it may also be hydrophobic. Given these characteristics, soil restoration is a prerequisite for ecosystem recovery at post-mining sites [2], and this restoration must concern the hydrological characteristics of the soil and the water regime [2-4].

The development of post-mining soils is determined by overburden, climate, vegetation, and soil organisms, all of which affect soil-forming processes [5, 6]. Previous research has indicated that the effect of the soil biota is closely linked to the prevailing vegetation [7]. Although reclamation technologies such as the planting of specific tree species and the spreading of topsoil greatly affect soil

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Table 1. Characteristics of the 12 types of post-mining sites and microhabitats in unreclaimed and reclaimed sites used in this study. Note that the surfaces of unreclaimed sites had a wave-like character created by heaping. Each type of site was represented by two replicate sites.

Type of site and microhabitat		Age (years)	Reclamation measure	Microhabitat description	Plant community
S5/10	T	5 or 10	unreclaimed wave-like surface created by heaping	wave top	sparse vegetation dominated by *Calamagrostis epigeios*
S5/10	B	5 or 10	unreclaimed wave-like surface created by heaping	wave bottom	sparse vegetation dominated by *Calamagrostis epigeios*
S	T	25-30	unreclaimed wave-like surface created by heaping	wave top	shrub community dominated by *Salix caprea*
S	B	25-30	unreclaimed wave-like surface created by heaping	wave bottom	shrub community dominated by *Salix caprea*
S	S	25-30	unreclaimed wave-like surface created by heaping	wave side	shrub community dominated by *Salix caprea*
PN		25-30	reclaimed, leveled, planted with pine		*Pinus contorta*
PC		25-30	reclaimed, leveled, planted with spruce		*Picea omorika* and *Picea pungens*
M		20	reclaimed, topsoil was spread, and grass mixture was seeded		cultural grasses and legumes, *Daxtilis glomerata, Alopecurus pratensis, Trifolium pratensis*
Q		25-30	reclaimed, leveled, planted with oak		*Quercus robur*
A		25-30	reclaimed, leveled, planted with alder		*Alnus glutinosa, Alnus incana*

formation on post-mining sites [7], their effects on soil hydrological properties and water regimes are insufficiently understood [8]. The main objective of this study was to compare the basic soil hydrological properties and soil moisture status in reclaimed sites and unreclaimed post-mining sites of various ages.

Materials and Methods

Our study was conducted on one large post-mining spoil heap in the Sokolov coal mining area in North Bohemia; the spoil material was deposited from the 1970s to 2005 [9, 10], and the coordinates of the centre of the spoil heap are 50º14'21" N, 12º39'24" E. The spoil heap occupies 1957 ha and has an average altitude of 600 m a.s.l., a mean annual precipitation of 650 mm, and a mean annual air temperature of 6.8ºC. Most of the spoil material in this heap consists of alkaline (pH 8) tertiary clay [11]. For this study, seven types of sites were selected. Each of the 7 types of sites (Table 1) was represented by two sites that were at least 250 m apart, each ranging in area from 1 to 10 ha were selected. Two of this site type (both unreclaimed sites) have characteristic wavelike structure and hence several microhabitats were distinguished on each site. At each site, research was conducted in a 50×50 m area that was at least 25 m from the margin of the site (from the zone where vegetation type changed). Sites were reclaimed or unreclaimed (Table 1). Sites were reclaimed by the planting of specific kinds of trees in plantations (alder, oak, spruce, and pine, abbreviated hereafter as A, Q, PC, and PN; one kind of tree plantation per site) 25-30 years before this study or by the spreading of topsoil and seeding of grasses 20 years before the study (abbreviated as M). The unreclaimed sites about 25 year old (abbreviated as S) were dominated by the *Salix caprea* shrubs. Young unreclaimed sites (S5/10) were covered by sparce vegetation dominated by *Calamagrostis epigeios* grass and the herb *Tusilago farfara*. The surfaces of the unreclaimed sites have a wave-like character created by heaping, and three microhabitats were designated within each study area according to their location on the wave: T, B, and S refer to the top, bottom, and side of the wave.

The term "site age" refers to the age since the last major disturbance. For reclaimed sites, site age indicates the number of years before the study when trees and grasses were planted. For unreclaimed sites, site age refers to the number of years before the study when the last spoil material had been deposited. The age of the unreclaimed sites with *Salix caprea* was similar to that of the reclaimed sites. The younger unreclaimed sites with *Calamagrostis epigeios* were 5-10 years old, because it typically takes several years after heaping before a plot is leveled and prepared for reclamation. These young sites can be assumed as a starting point for all other sites (Table 1). Hence we can compare the effect of reclamation in two ways. Firstly as a difference between young unreclaimed sites (5-10 year old) and a particular reclaimed site, this gives us the impression about absolute changes achieved during 20+ years of development. Another view is to compare reclaimed and unreclaimed sites about the same age, which gives added value of reclamation compared to a situation when no action was taken.

Volumetric soil moisture content (g of water per 100 cm^3 of soil × 100) was measured monthly at each site (two measurements per sampling date per site) from August

Table 2. Soil physical properties of soils at 12 types of sites on spoil heap in the Czech Republic.

Site type	Bulk density	Porosity	Water-holding capacity	Field-water capacity	Wilting point	Clay content	Hydraulic conductivity $*10^{-7}$
	$g \cdot cm^{-3}$	% volumetric	% volumetric	% volumetric	% volumetric	% volumetric	$[m \cdot s^{-1}]$
S5T	1.15±0.07a	61±1cba	50±3g	36±3e	32±1edc	22±4dc	7.6±0.5a
S5B	1.10±0.08ba	65±2ba	48±2g	38±3edc	30±3edc	22±3dc	4.8±0.3edcb
S10T	1.00±0.07cba	61±3cba	57±4dcb	38±2edc	35±3cba	30±1ba	7.6±0.5a
S10B	0.98±0.08dcb	67±2a	53±2ed	37±6ed	28±5edc	27±5cba	5.3±0.5dcb
ST	0.83±0.07fe	51±4d	63±5b	53±4ed	29±2edc	17±2ed	5.9±0.3b
SB	0.93±0.08edc	61±5cb	63±5b	55±5a	28±3ed	13±1e	4.8±0.3dc
SS	0.89±0.06ed	56±4c	49±4fe	35±2ed	26±3e	13±3e	5.5±0.9cb
PN	0.91±0.05ed	62±2ba	55±2cd	47±3cb	26±3e	26±5cb	4.9±0.9dc
PC	0.86±0.07ed	65±3ba	62±6b	47±6cb	32±6dc	31±4a	5.2±0.4dcb
M	1.17±0.13a	55±4dc	45±5f	40±6dc	34±7cb	25±4cb	4.4±0.7ed
Q	0.83±0.05fe	63±5ba	60±5cd	54±4ba	39±3a	16±2e	3.7±0.6e
A	0.73±0.08f	67±4a	72±4a	57±3a	39±3ba	27±6cba	4.9±0.3dc

Values are means ±SD. Means in a column followed by the same letter are not significantly different (one-way ANOVA, LSD *post hoc* test, $p<0.05$).

2007 to July 2011, except that the two M sites were first measured in September 2009. This measurement was made at 5, 10, 35, and 40 cm depth with a dielectric moisture meter and access tubes [12-14].

Hydraulic conductivity was measured in autumn 2009 with a Guelph permeameter [3, 15, 16] to 10 cm depth with three replicate measurements per site. At the same time, three undisturbed soil cores were taken from each site or microhabitat for determination of bulk density, water holding capacity, water field capacity, and wilting point [3, 17]; the unit of measurement for the latter three determinations was volumetric water content, as described earlier. Material from the soil cores was then used to determine the clay content using the Casagrande method [17-19] and to determine specific density [17, 19]. Porosity was calculated from bulk density and specific density values as 100 × (specific density – bulk density)/bulk density, and porosity was expressed as a percentage.

Data for the two replicates per type of site were averaged before analyses. A three-way analysis of variance (ANOVA) was used to determine the effects of site, date and year of measurement, and soil depth on soil moisture. A one-way ANOVA, followed by an LSD *post hoc* test, was used to explore differences in soil moisture and other parameters among sites.

Results

Soil Physical Properties

Bulk density ranged from 0.73 to 1.17 $g \cdot cm^{-3}$ (Table 2). It decreased with site age and was similar in reclaimed and unreclaimed sites, except that bulk density was higher in the M than in the other sites. Among the sites reclaimed by the establishment of plantations, bulk density was highest in the PN sites and lowest in the A sites.

Porosity ranged from 51 to 67% but had no clear pattern with respect to reclamation and site age (Table 2).

Water holding capacity ranged from 45 to 63% (Table 2). It was generally higher at the older sites than at the younger sites (Table 2). Water holding capacity was highest in A sites and lowest in the depressions and tops of the waves in the 5-year-old unreclaimed sites (S5B and S5T). Among the reclaimed sites, water holding capacity was lowest in the M sites.

Field capacity ranged from 35 to 57% (Table 2). With the exception of the SB sites, field capacity was generally higher in the reclaimed soils than in the unreclaimed soils.

The wilting point ranged from 26 to 39% (Table 2). It decreased with site age in unreclaimed sites, was generally higher in reclaimed sites than in unreclaimed sites, and was highest in Q and A sites (Table 1).

Clay content ranged from 13 to 31% by volume (Table 2) and did not clearly differ between reclaimed and unreclaimed sites or with site age. The highest value was found in reclaimed PC sites. The lowest values of clay content among unreclaimed sites were in the wave sides (SS) and in the wave depressions (SB). The lowest value for clay content among the reclaimed sites was at the Q sites (Table 2).

Hydraulic conductivity was low at all sites; it ranged from 3.7 to $7.6 \cdot 10^{-7}$ $m \cdot s^{-1}$ (Table 2). The values tended to be highest on the wave tops in the young, unreclaimed sites (S5T and S10T) and tended to be lowest in the Q sites (Table 2).

Table 3. ANOVA results for the effect of site age, soil depth, site type (site), and their interactions on soil moisture content. Variability (%) indicates the percentage of the variability explained by the source of variance.

Source of variance	df	Variability (%)	p
Season (sampling date)	25	20.5	>0.0001
Depth	3	6.2	>0.0001
Site	11	64.2	>0.0001
Season × depth	75	1.1	0.0066
Season × site	250	5.0	>0.0001
Depth × site	30	2.7	>0.0001
Season × depth × site	750	0.3	ns

Soil Moisture Content

Soil moisture content was significantly influenced by site, seasonal effect represented by date of sampling, and soil depth (Table 3). The percentage of the variability explained by these three factors was highest for site and lowest for soil depth (Table 3). The two-way interactions also were significant, but the three-way interaction was not. Soil moisture content averaged across all depths ranged from 34.3 to 58.2% among the 12 kinds of sites (Table 4). In unreclaimed sites, soil moisture ranged from 38.3 to 48.9%. Soil moisture in unreclaimed sites was highest at SB (wave bottom) and lowest at SS (wave side). In reclaimed sites, soil moisture content ranged from 34.3 to 58.2%, was highest in A sites, and was lowest in PN and M sites (Table 4).

Averaged across all sites, soil moisture content tended to be greater at 10 cm than at other depths (Table 4). At PN sites, soil moisture content was highest at 5 cm depth. In M sites and at many unreclaimed sites, soil moisture content did not change significantly with depth (Table 4).

Moisture fluctuations in the young unreclaimed sites, which were not covered by woody vegetation, were more variable and lacked a clear seasonal pattern with summer depression (Fig. 1). Soil moisture contents in older unreclaimed sites were highest in November, December, and January and lowest in July and August (Fig. 1). Seasonal fluctuations in soil moisture content were similar among reclaimed sites (Fig. 2). Values were highest in October, November, December, and March, and lowest in June, July, and August. Among reclaimed sites, soil moisture content was highest and most stable at A sites. The summer drop in soil moisture was greatest in the PN and Q sites.

The average percentage of days when soil moisture was below the wilting point at one or more sampling depths ranged from 14-88% among the sites (Table 5); this percentage was highest for sites Q and L and tended to be lowest for sites S5B/10B and ST. Analysis by depth did not reveal a significant difference in this variable among sites.

Discussion

Although the water holding capacity was greater in the reclaimed than in the unreclaimed post-mining sites, water

Table 4. Volumetric soil moisture content (g of water per 100 cm^3 of soil × 100) averaged across soil depths and by soil depth. Values are means ±SD for data collected monthly from August 2007 to July 2011 (but from September 2009 to July 2011 for M sites). Means in a column followed by the same letter are not significantly different (one-way ANOVA, LSD *post hoc* test, p<0.05). Means in a row preceded by the same letter (and means in a row without preceding letters) are not significantly different (one-way ANOVA, LSD *post hoc* test, p<0.05).

Type of site	Soil moisture content averaged across depths	Soil moisture content by depth			
		5 cm	10 cm	35 cm	40 cm
S5T	38.3±8.3de	a40.5±9.0cde	b45.9±6.7dc	a40.1±7.5dc	a39.4±8.2dc
S5B	43.1±8.7 cde	43.5±9.6bcde	46.3±8.4dc	40.8±8.0c	42.9±7.6c
S10T	41.6±8.8 cde	40.2±9.7de	44.0±7.8dc	42.9±8.6cb	43.2±7.0c
S10B	41.4±7.8de	43.0±8.4bcde	40.0±9.4ed	39.8±6.5dc	41.8±6.1c
ST	43.6±9.6cd	41.0±12.6de	44.6±8.9dc	44.6±7.3cb	44.9±8.0c
SB	48.9±8.7b	a50.2±9.3ab	a52.6±7.4b	b46.9±7.9b	b46.0±8.2c
SS	34.8±9.4b	33.1±11.7abc	34.6±8.1cb	34.6±8.4b	36.8±8.6b
PN	34.3±12.8f	a40.1±11.4e	b34.4±13.4e	b30.8± 2.0e	b31.8±12.1e
PC	44.7±12.1c	47.1±12.5abcd	44.5±12.8dc	44.3±9.6cb	42.9± 12.8c
M	34.8±8.71f	30.9±9.6e	32.7±84e	38.4±5.9e	37.3±8.3e
Q	37.9±13.1e	a41.2± 13.0de	a43.0±10.8d	b33.7±12.7ed	b33.6±13.0de
A	58.2±12.4a	a52.9± 16.2a	b61.0±10.6a	ab59.3± 8.3a	ab59.3± 11.5a

limitation did not differ substantially between these two kinds of sites because the wilting point occurred at a higher percentage of soil water content in the reclaimed sites. Increases in field capacity and wilting point are related because both reflect the weathering of orifinal mudstones, which results in increasing clay content, and the accumulation of organics [4]. Water consumption should be higher in reclaimed than in unreclaimed post-mining sites because plant biomass is much higher in the former [10]. The combination of higher wilting points and greater water consumption in the reclaimed site could result in similar water deficiencies in both kinds of sites. The greatest shortage of soil moisture (as indicated by the percentage of sampling dates on which soil water content was below the wilting point) was detected in sites reclaimed by the planting of oak, which may be explained by the slow development of the soils and the relatively high plant biomass on such sites [10].

Low soil moisture content and high water deficiency also were observed in the meadow, which had been reclaimed 20 years earlier by the spreading of topsoil and seeding of grasses. Although one of the main reasons for topsoil spreading is the improvement of the physical properties of soil, the data from the meadow site in the current study suggest that topsoil spreading does not improve soil moisture conditions, at least when those conditions are measured 20 years later. The failure of topsoil spreading to improve soil moisture can be explained by its effects on water content at the wilting point and on soil porosity;

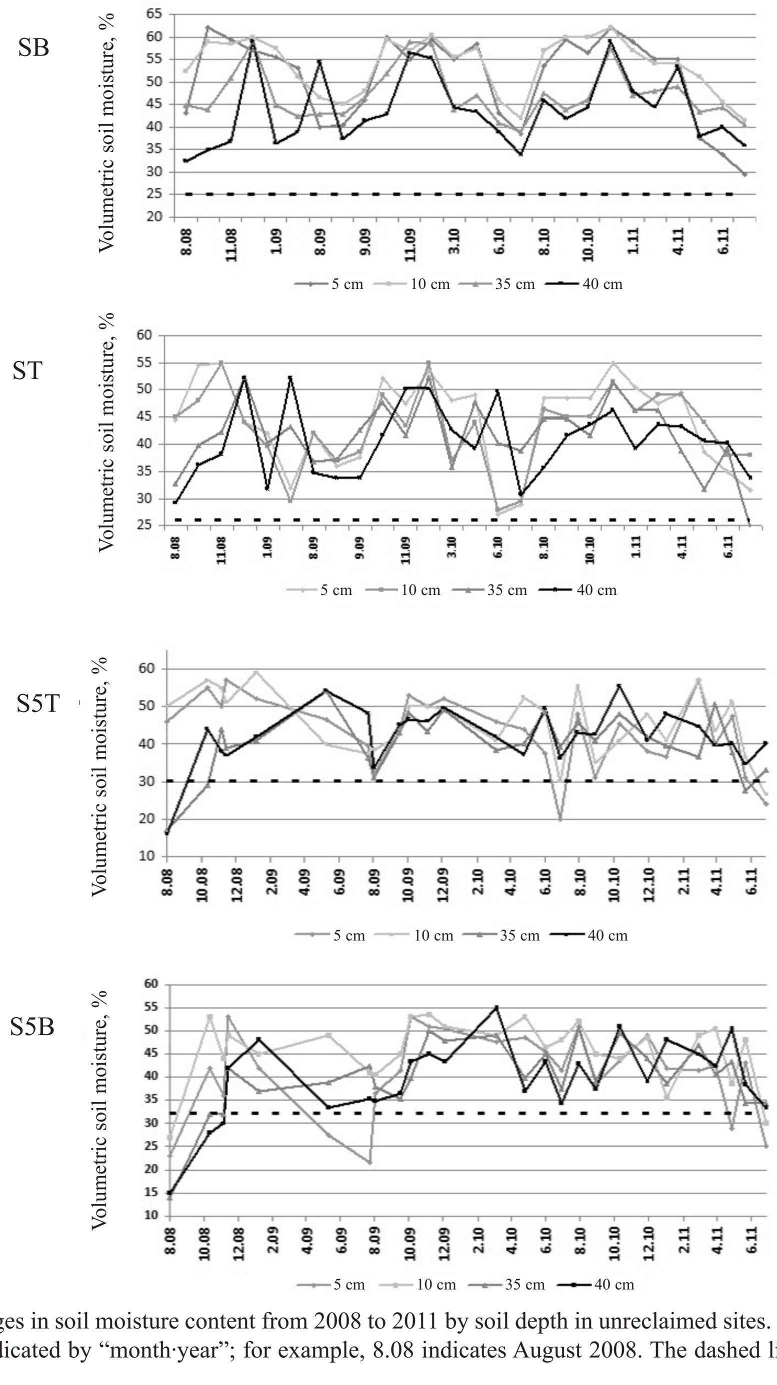

Fig. 1. Examples of changes in soil moisture content from 2008 to 2011 by soil depth in unreclaimed sites. See Table 1 for site details. On the X axis, date is indicated by "month·year"; for example, 8.08 indicates August 2008. The dashed line indicates the permanent wilting point.

topsoil spreading increased the water content at the wilting point and decreased porosity (Table 2). The decrease in porosity is likely caused by the compaction that accompanies the storage and spreading of topsoil. Also, it has been documented that greater soil compaction occurs in spoils amended with topsoil than in spoils allowed to develop without topsoil [20].

The frequent water shortages in the meadow sites (M) also can be explained by evaporative water loss. Forests experience a relatively reduced level of evaporation because the vegetation entraps a layer of relatively still air, but meadows do not create a zone of still air and are therefore more likely to experience greater evaporation.

Wang et al. [21] and Doerr et al. [22] describe how water repellency (hydrophobicity) can limit the moisture content of some soils. Although high water repellency has often been described from post-mining sites similar to those in the current study [23, 24], repellency has not been commonly observed at our study site. On the other hand, dry soil containing a high quantity of organic matter often exhibits some water repellency [23-26], and this may have reduced water absorption in the current study, particularly in the meadow sites after prolonged droughts.

In agreement with V. Kuraz [3] (who studied soil moisture in the same sites described in this paper), we found that soil moisture content was greater in depressions than at the top of the waves in young, unreclaimed spoil heaps. This difference is greatest in the surface layers, decreases with depth, and is largely explained by the effect of gravity [3]; the difference is more pronounced when soil moisture content is high, e.g., after heavy rains [27]. In addition, the soil at the top of the wave during summer has many cracks and

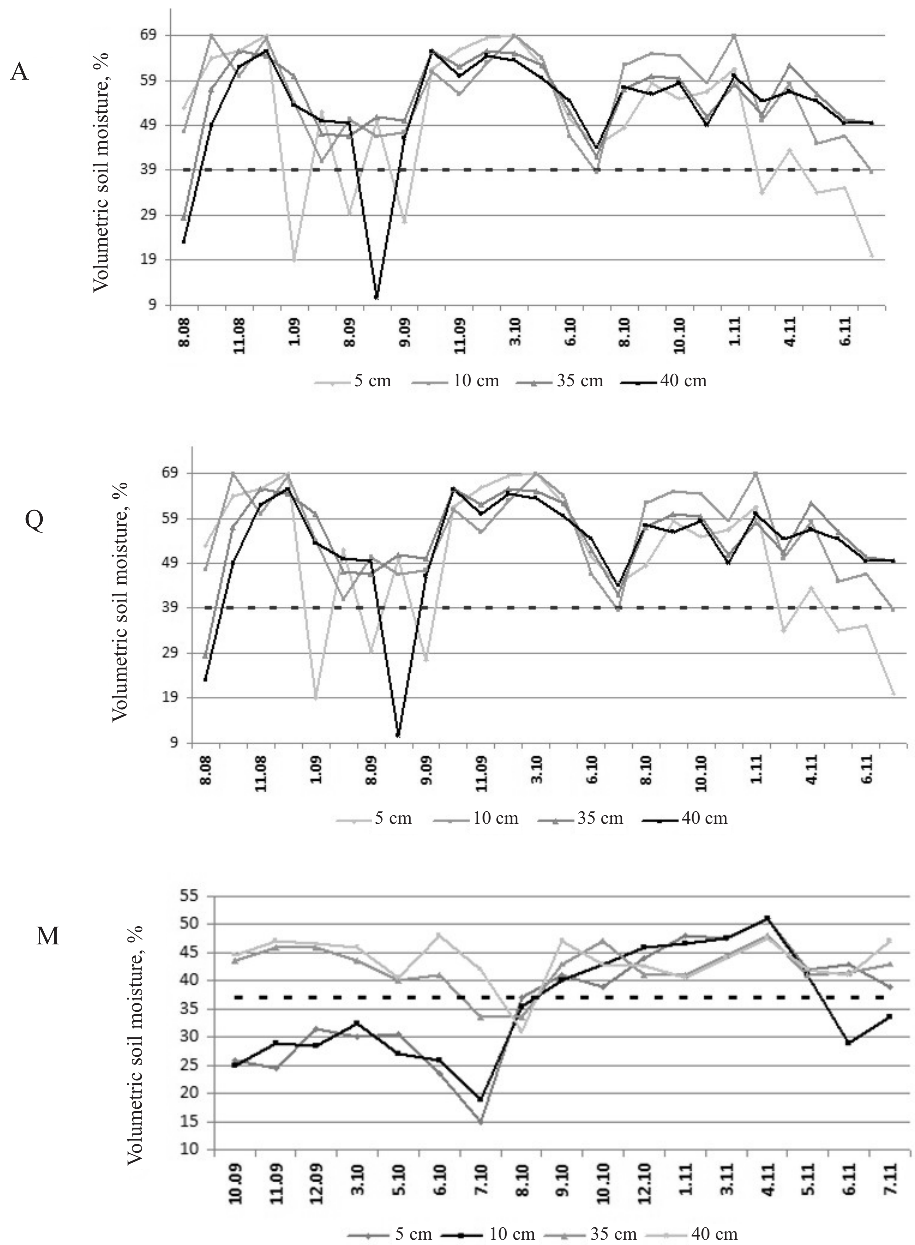

Fig. 2. Examples of changes in soil moisture content from 2008 to 2011 by soil depth in reclaimed sites. See Table 1 for site details. On the X axis, date is indicated by "month·year"; for example, 8.08 indicates August 2008. The dashed line indicates the permanent wilting point.

Table 5. Percentage of days when the soil moisture content was below the wilting point according to type of site and soil depth. Values are means ±SD. Means in the second column followed by the same letter are not significantly different (one-way ANOVA, LSD *post hoc* test, p<0.05). S5/10T combines data for S5T and S10T. S5/10B combines data for S5B and S10B.

	% of days below the wilting point				
Type of site	At least one depth	5 cm	10 cm	35 cm	40 cm
S5/10T	40± 26cde	31± 6	9± 2	10± 3	11± 2
S5/10B	19± 17de	8± 4	12± 6	16± 2	10± 1
ST	14± 16e	7± 3	0± 0	8± 4	0± 0
SB	47± 28de	50± 23	7± 3	0± 0	11± 5
SS	43± 23cd	38± 8	38± 19	23± 10	17± 4
PN	57± 28cb	20± 3	30± 10	32± 26	37± 27
PC	38± 20de	1± 1	17± 8	5± 2	34± 17
M	83± 30ab	61± 27	57± 15	19± 10	37± 30
Q	88± 30a	58± 2	70± 21	76± 6	70± 34
A	38± 23cde	31± 7	6± 3	8± 4	13± 7

macropores that enhance drainage and evaporation [23]. Soil water content may not be much higher at the wave depression than at the top, however, if the depression supports dense herbaceous vegetation, which would remove substantial water from the soil via transpiration. Among the reclaimed sites, soil water content was highest in sites planted with alder (A). The high soil water content was accompanied by a high value for field capacity, which may be associated with intensive soil development [7]. At the alder sites, soil development is enhanced by the input of high-quality litter (litter with a low C/N ratio) and by the consequent increase in the activity of soil fauna [4]. Soil development also is enhanced by a dense layer of herbaceous vegetation [10, 28]. Soil moisture on the surface was also higher and more stable in the alder sites than in the other reclaimed sites. For most sites (reclaimed or unreclaimed), the large fluctuations in soil moisture content occurred mainly between 10 to 35 cm depth. The water content often decreased between 35 and 40 cm but then increased slightly with greater depth. Frouz et al. [10] and Penna et al., [27] state that the soils of spoil heaps are not fully developed, which affects water penetration at the surface and subsurface runoff.

Bulk density in the unreclaimed sites, which were undergoing succession, gradually decreased with age. This may correspond with the accumulation of organic material resulting from litter input and the activity of soil fauna [6, 9, 10, 29, 30, 31]. Bulk density was highest and porosity was lowest in the meadow soil. As discussed earlier, this may have been caused by compaction when the topsoil was spread [20]. Bulk density can have high spatial variability depending mainly on the quantity and composition of soil organic matter [6]. As documented by V. Kuraz [3], large spoil heaps have substantial soil heterogeneity [32, 33]. In the unreclaimed sites, bulk density was lower in the tops and than in the depressions of the waves. Bulk density is generally greater in waves without vegetation because in the absence of vegetation, the clay particles can freely realign [29]. In sites with vegetation, bulk density is generally greater in the depressions than in the tops because the accumulation of litter and the greater biological activity in the depressions cause the clay particles to aggregate with other soil particles [30].

Conclusion

The ability of soils to maintain stable soil moisture conditions all year long is greater on reclaimed sites with the extensive occurrence of soil fauna, litter input, and weathering intensity than on unreclaimed post-mining sites. On unreclaimed sites where we left the original heterogeneity surface, soil moisture conditions were markedly heterogeneous. The soil water content at the wilting point, however, was higher at reclaimed than at unreclaimed sites, such that water availability for plants was similar for both reclaimed and unreclaimed sites. On the group-wide level spoil heaps reflected the influence of a different geological substrate. This study does not support the idea that the spreading of topsoil leads to long-term improvements in soil hydrological soil properties.

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