Environ Earth Sci (2013) 69:1685–1698
DOI 10.1007/s12665-012-2004-5

ORIGINAL ARTICLE

Soil carbon accumulation after open-cast coal and oil shale mining in Northern Hemisphere: a quantitative review

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Received: 22 November 2011 / Accepted: 12 September 2012 / Published online: 30 September 2012

Abstract Meta-analysis and other statistical methods were used to evaluate how changes in soil organic carbon (SOC) content in post-mining soils are related to different factors; the data were obtained from 17 studies covering 93 temperate post-mining sites in the Northern Hemisphere that had been revegetated by forest or grassland either by reclamation or natural succession. Because many studies have failed to report any measures of variance, only part of the data were used for meta-analysis. According to the meta-analysis, the rate of SOC accumulation was unrelated to vegetation type. In a separate analysis that included all available data and in which rates of SOC accumulation at each site were used as individual entries, the rate of SOC accumulation differed depending on the age of the site and vegetation type. Under deciduous forests, the rate reached a maximum after 5–10 years and then decreased. Under coniferous forests, the initial SOC values were lower than under deciduous forests, but slowly increased with age and reached a maximum after 30–40 years. No significant temporal trend was found in grasslands, probably because the data set included only relatively young grassland sites. Based on data from sites younger than 30 years, sites with grasslands and deciduous forests accumulated SOC faster than sites with coniferous forests. The rate of accumulation was negatively correlated with temperature under coniferous forests, but positively correlated with temperature in grasslands. This suggests that carbon sequestration is favored by cold climates in coniferous forests, but by warm climates in grasslands. Deciduous forests were intermediate. Compared to conifers, deciduous trees may support SOC sequestration deeper in the soil profile, which may enhance SOC stability. A large proportion of post-mining sites reach the pre-mining SOC stock within 20 years or less after reclamation.

Keywords Soil carbon · Land use change · Sequestration · Meta-analysis · Mine soils · Reclamation

Introduction

Soil organic matter plays a principal role in many soil functions and processes. It increases the soil potential in storing both nutrients and toxic substances. It enhances soil structure and reduces the risk of erosion and compaction. It increases soil porosity, aeration, and water-holding capacity. Finally, soil organic matter represents a source of nutrients and energy for soil organisms and is therefore central to nutrient cycling (Carter 2002).

Mining substantially affects many ecosystem processes (Bradshaw 1983, 2000; Ricka et al. 2010). When deposited in the form of overburden (spoils), the post-mining soils have generally low or even zero content of recent soil organic carbon (SOC) (Bradshaw 1983, 2000). The overburden material itself lacks recent SOC (Rumpel et al. 2003; Fettweis et al. 2005), but in part of the reclamations topsoil with a recent SOC content is applied on top of this deposited overburden. The SOC content in such topsoil at the time of deposition is likely lower than in undisturbed soils due to losses from mineralization during manipulation and storage of topsoil (Abdul- Kareem and McRae 1984; Stahl et al. 2003; Shrestha and Lal 2011). Since soil organic carbon content is determined by the balance between inputs and outputs, the revegetation of spoils leads to SOC accumulation as a consequence of the increased carbon input from litter and belowground biomass.

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As explained above, SOC accumulation improves soil quality and hence is important for post-mining site restoration. Moreover, previous studies have indicated that accumulation of SOC in post-mining soils is rather high and these soils could play an important role in mitigation efforts (Akala and Lal 2001; Karu et al. 2009). In general, the rate at which SOC accumulates is greatly affected by many factors including vegetation, climate, drainage conditions, and soil texture (Carter 2002), but in post-mining soils it is also affected by reclamation practices (Bradshaw 1983, 2000). Selection of an effective reclamation practice for post-mining sites requires an understanding of how SOC accumulates in these sites.

Changes in SOC content also occur in agricultural soils after changes in land use. These changes have been discussed in a number of reviews, some of which used meta-analytical approach (Post and Kwon 2000; Guo and Gifford 2002; Paul et al. 2002; Laganiere et al. 2010). Similar studies devoted to post-mining soils are lacking.

The current study, using both meta-analysis and other statistical methods, attempted to determine how SOC accumulation in post-mining soils is affected by the following factors: type of vegetation, age of site, application of topsoil, soil texture, sampling depth, and climate. Other factors such as variation in reclamation technologies or using of amendments were also considered, but data in individual studies were too inconsistent to be compared. Because many types of mining activities exist with very different technologies and type of geological material, we focused exclusively on open-cast mining of coal and similar materials used for energetic purposes (coal, lignite, oil shales) due to the fact that geological mining conditions are alike in large geographical areas and also because open-cast mining causes expensive and large-scale disturbance of ecosystems.

Materials and methods

Data collection

The data collection was restricted to sites formed after open-cast mining of coal or similar organic materials. It was also required that all selected sites were located in upland conditions and thus well drained to avoid the effect of waterlogging on SOC accumulation. Data were extracted from 17 recent studies (published within the last 10 years) dealing with SOC accumulation in post-mining soils in the temperate zone of the Northern Hemisphere. Of these 17 studies, 15 were published in peer-reviewed journals and 2 in journals without peer review. These 17 studies contained data from 93 post-mining sites and 15 adjacent undisturbed sites (the latter sites were used as indicators of the pre-mining SOC content). For 54 sites, separate data were obtained for different horizons of the soil profile. In six cases, the authors were contacted and asked to supply unpublished data that were needed for the calculations (see “Acknowledgments”).

To be included in the data set, studies had to report either the rate of SOC accumulation (one study) or data that would enable calculation of this rate, i.e., age of site (number of years since reclamation or the dumping of overburden for unreclaimed sites) and the amount of recently sequestered SOC. Only two studies conducted repeated sampling and reported the SOC stocks of the sites at time zero (right after reclamation) (Nii-Annang et al. 2009; Shrestha et al. 2009).

Estimating the amount of recently sequestered SOC requires that the measured carbon content is reduced by the fossil SOC content in the dumped overburden. The proportion of recently sequestered and fossil SOC is measured either by radiocarbon dating using ^{14}C AMS (Morgenroth et al. 2004; Rumpel et al. 2003), which was done in three studies (Karu et al. 2009; Fettweis et al. 2005; Rumpel et al. 2003), or estimated once using a site-specific coal-correction equation developed by Amichev (2007) and used in Amichev et al. (2008). In three studies, the authors estimated the content of recently sequestered SOC by subtracting the C content of a deeper soil horizon from the total C content (Reintam 2004; Reintam et al. 2002; Frouz et al. 2009). For those studies that did not deal with correction for fossil SOC, recently sequestered SOC was estimated based on available data. One study (Sourkova et al. 2005) subtracted the C content of the dumped overburden from the total C content. The authors had estimated the C content of the dumped overburden based on a linear regression between the age of the plot and C content.

In four chronosequence studies (Akala and Lal 2001; Lorenz and Lal 2007; Chatterjee et al. 2009; Ganjegunte et al. 2009), the SOC stocks of reported sites were corrected by subtracting the SOC stock of the youngest available site (0–2 years old). This approach has been successfully used elsewhere (Shrestha and Lal 2010). In three studies (Sever and Makineci 2009; Keskin and Makineci 2009; Frouz and Kalčík 2006), a similar approach was used for the correction as in the studies described above, i.e., the C content of a layer in which SOC did not accumulate over time was subtracted from the total C content. This method is applicable only in sites without topsoil application and assumes that the soil profile of young post-mining soils is homogeneous, because the overburden material is mixed during heaping. This mixing is indicated by a general lack of SOC stratification in young sites (Chatterjee et al. 2009). Studies from which it was not possible to calculate the recently sequestered SOC in any of the ways described above were not included in the data set.

For studies that did not provide C data in terms of weight per area, the SOC stock (S_{SOC}, t ha^{-1}) was calculated as follows:

$$S_{\mathrm{SOC}} = \mathrm{SOC} \times \mathrm{BD} \times d \tag{1}$$

where SOC is the SOC concentration (g kg^{-1}), BD is bulk density (t m^{-3}), and d is the depth (m). If reported, organic matter content was converted to SOC based on the assumption that organic matter contains 58 % organic C (Nelson and Sommers 1996). Those studies that did not provide bulk density data were not included. Even though some authors of quantitative reviews have estimated bulk density based on its relation with SOC content (Post and Kwon 2000; Guo and Gifford 2002; Poeplau et al. 2011), others have avoided these estimations and emphasized that bulk density can be substantially influenced by land use change (Laganiere et al. 2010). Because the bulk density of post-mining soils is quite variable (Lal and Kimble 2001), estimation of bulk density based on SOC content could introduce substantial error.

Some studies reported data on SOC accumulation in surface organic layers (LFH or Oe horizon) and were compiled separately for further analysis. In the case of one study (Reintam et al. 2002), the SOC stock in the organic layer was calculated by using the bulk density of litter (pine needles) from another study (Frouz et al. 2009), as previously done by Fettweis et al. (2005).

For sites to be included in the analysis, the publication also had to provide data on: type of mined material (coal, 10 studies including 74 sites; lignite, 3 studies including 9 sites; oil shale, 3 studies including 10 sites), type of reclamation (with or without topsoil application), vegetation type (grassland, shrubland, or forest; in the case of forest—coniferous, deciduous, or mixed), soil sampling depth, and soil texture. Soil texture was given either as particle size distribution (in 4 studies) or as a texture class. If a texture class was not presented according to the USDA system, it was transformed to it. Sites were divided into three categories based on their clay content: low (<10 %), intermediate (10–35 %), and high (>35 %).

Optional characteristics of sites were: number of replicates (n), standard deviation of SOC accumulation rate, SOC stock of an adjacent undisturbed site, species composition of vegetation, information on amendments and management, mean annual temperature, mean annual precipitation, and geographic coordinates. Wherever possible, missing climate data (mean annual temperature, mean annual precipitation) were obtained from http://www.weatherbase.com using geographic coordinates or described location, as previously done by Poeplau et al. (2011).

Statistical analysis

Meta-analysis is a statistical approach initially introduced in medicine that enables evaluation of data from different studies accounting for different variability and number of replicates of each study (giving due weight to every mean value). In this study, the meta-analysis was used to explore the effect of vegetation type on the rate of SOC accumulation. The calculations were performed using MetaWin 2.0 (Hedges and Olkin 1985) as described previously, e.g., by Curtis and Wang (1998) or Liao et al. (2008). Generally, meta-analysis is based on the calculation of treatment effect size. There are several possibilites for calculating the effect size. The approach chosen in this study was the Hedges' d (also called the d-index) which is a standardized difference between an experimental and control mean. For this study, it was equivalent to SOC accumulation rate and was calculated as follows:

$$d = \frac{S_{\mathrm{SOC},x} - S_{\mathrm{SOC},0}}{x} \tag{2}$$

where $S_{\mathrm{SOC},0}$ (representing the control mean) is the SOC stock of the site at year 0 (just after dumping), $S_{\mathrm{SOC},x}$ (representing the experimental mean) is the SOC stock of a reclaimed site (one or more years after dumping), and x is the age of the site.

In the next step of meta-analysis, effect sizes from all studies are averaged into a weighted mean based on their sample size and measure of variance. Larger studies and studies with less random variation are given greater weight than smaller and less precise studies.

In our meta-analysis, weighted mean effect sizes as well as their confidence intervals (CI) were computed for each vegetation type for the comparison of their effect. If the 95 % CI would not overlap between the vegetation types, then the effect of revegetation on SOC accumulation would be significantly different between the vegetation types.

To include a study into the meta-analysis, it had to report the number of replicates (n) and measures of variance (SD or SEM) of one or both means. Only the variability of the experimental mean (reclaimed site) was considered, because the variability of the control mean (site just after dumping) was not reported in any of the studies. Many studies also lacked SD or SEM values for the reclaimed sites. The authors were contacted to obtain these data. In cases when the measures of variance were unavailable and the study contained a number of similar sites, the data from the sites were averaged (or were first divided into groups according to site age and then averaged) and the standard deviation of this newly formed mean was used as a measure of the variance. Data from one study (Sourkova et al. 2005) were treated this way (i.e., the mean and variance of sites grouped according to site age were used rather than data from each individual site), because including data from the individual sites of that study would have strongly influenced the analysis. For those studies that reported least significant differences rather than measures of variance, it was assumed that the SD was directly proportional to the mean and the SDs were calculated from the maximum possible confidence intervals that would still result in a significant difference.

Despite the described effort, it was possible to include only 87 sites in the meta-analysis. To use as much of the collected data as possible, an analysis of the entire data set using the rate of C accumulation at individual sites as individual entries was performed. In this analysis, the SOC accumulation rates among the different vegetation and soil texture categories were compared by one-way ANOVA followed by Fisher's least significant difference (LSD) post hoc test, and studied by linear regression between rate of accumulation and the age of the site, climate data, or depth of sampling. These calculations were performed using Statistica 10.0. In the major part of the analyses, sites with deciduous and mixed forest were considered as a single category, because the mixed forest sites represented only 10 % of all forest sites. Shrublands were assigned to (deciduous) forest sites for a similar reason.

To analyze how forest type influences the proportion of carbon sequestered in the organic layers compared to the mineral soil, SOC stocks were calculated separately for organic layers (LFH or O_e) and for mineral soil as in Eq. 1.

For the evaluation of SOC accumulation, SOC stock of the post-mining site was compared with that of an adjacent undisturbed site (forest, pasture). With this approach, we could estimate the rate at which SOC content recovered to the pre-mining level. For the calculation of this ratio, the total SOC stock was used for sites reclaimed with topsoil application. Thus, for this variable, SOC stock included also the SOC that was present in the topsoil applied during reclamation. In the sites reclaimed without topsoil application, the initial stock was subtracted from the total stock to correct for fossil carbon content.

Results and discussion

Rate of SOC accumulation in relation to site age and vegetation type

Revegetation of post-mining sites led to SOC sequestration in all but two sites (Table 1). Most of the rates of SOC accumulation were higher than typical rates for revegetated agricultural soils reported by Post and Kwon (2000).

The decrease in SOC on the two sites may have been an artifact caused by an overestimation of the initial carbon stock (e.g., due to heterogeneous coal residuals). The decrease could also have been real; because both sites were reclaimed by topsoil application and revegetation by trees or shrubs, the reclamation might decrease SOC stock in the applied topsoil layer similarly as reported in the first few years after afforestation on pastures (Paul et al. 2002). The applied topsoil layers have a relatively high default organic matter content compared to the overburden, which contains no recent organic matter. If the SOC is measured directly after the topsoil is spread on the spoil, part of the SOC in the topsoil may be lost because of intensive mineralization (Ingram et al. 2005), which is not compensated for by litter input in the first few years, just as litter input does not initially compensate for mineralization in afforested pastures. This explanation is consistent with the young age of the two sites (4–16 years old).

The rate of accumulation decreased linearly with increasing site age (Fig. 1). The variability in the rate also decreased with site age. The maximum rates occurred in young sites (<20 years old). In their chronosequence study of post-mining soils, Shrestha and Lal (2010) similarly reported that the maximum rates of accumulation occurred after 14 years under forest and after 6 years under pasture. Our data did not conform to the polynomial trend in their study, probably because our data set did not include sites younger than 4 years, which we have often used as reference for calculation of sequestered SOC in older sites. The average rate of accumulation was 2.46 t ha^{-1} y^{-1} after 10 years and 0.87 t ha^{-1} y^{-1} after 40 years. A somewhat higher but comparable rate (1.171 t h^{-1} y^{-1}) was found by Anderson et al. (2008) for a chronosequence of 13 post-mining sites that ranged in age from 11 to 26 years; this rate would have been reached after approximately 30 years based on our linear regression.

According to the meta-analysis, the rate of SOC accumulation based on effect sizes did not differ significantly according to the type of vegetation (data not shown). When we reduced the data set to include only sites younger than 30 years so as to include only clearly defined grasslands, coniferous, or deciduous forests (grasslands with shrubs and mixed forest were excluded), then the meta-analysis for the remaining 42 sites also failed to reveal a significant association between the rate of SOC accumulation and type of vegetation ($p = 0.079$). However, when we conducted a one-way ANOVA using the mean SOC accumulation rates (i.e., the accumulation rate averaged for all years, for which we can use also studies that do not provide any SD estimate and cannot be used to calculate effect sizes) from sites less than 30 years old, which once again meant that only clearly defined grasslands, coniferous forests, or deciduous forest were included ($n = 50$), the ANOVA model was significant ($p = 0.002$) and the accumulation rate was significantly lower in coniferous forests (0.81 ± 0.38 t h^{-1} y^{-1}, $n = 14$) than in grasslands (1.81 ± 1.55, $n = 21$) or in

Table 1 Rates of carbon accumulation in post-mining soils (mean ± SD) and other supporting data used for determining the accumulation rate reported in previous studies

Reference	Age (y)	C stock (t ha^{-1})	Control C stock (t ha^{-1})	Accumulation rate (t ha^{-1} y^{-1})	n	Fossil c correction method	Vegetation type	MAP (mm)	MAT (°C)	Soil texture	Mined material	Amendments	Location
Akala and Lal (2001)	5	27.20	17.00	2.4	1	Young site	Grassland	1020	11	Silty clay loam	Coal	No	SE Ohio, USA
	10	40.90	17.00	2.39	1	Young site	Grassland	1020	11	Silty clay loam	Coal	No	SE Ohio, USA
	15	54.90	17.00	2.53	1	Young site	Grassland	1020	11	Silty clay loam	Coal	No	SE Ohio, USA
	20	67.40	17.00	2.52	1	Young site	Grassland	1020	11	Silty clay loam	Coal	No	SE Ohio, USA
	25	93.20	17.00	3.5	1	Young site	Grassland	1020	11	Silty clay loam	Coal	No	SE Ohio, USA
	4	19.50	22.30	−0.70	1	Young site	Deciduous forest	1020	11	Silty clay loam	Coal	No	SE Ohio, USA
	10	31.30	22.30	0.90	1	Young site	Deciduous forest	1020	11	Silty clay loam	Coal	No	SE Ohio, USA
	15	46.00	22.30	1.58	1	Young site	Deciduous forest	1020	11	Silty clay loam	Coal	No	SE Ohio, USA
	21	62.90	22.30	1.93	1	Young site	Deciduous forest	1020	11	Silty clay loam	Coal	No	SE Ohio, USA
Amichev et al. (2008)	47	48.60	N/a	1.3	1	Equation	Coniferous forest	1010	11	Silt loam	Coal	No	Indiana, USA
	34	34.10	N/a	1.00	1	Equation	Coniferous forest	1110	13	Sandy clay loam	Coal	No	Kentucky, USA
	39	25.00	N/a	0.64	1	Equation	Coniferous forest	1010	8	Sandy loam	Coal	No	Pennsylvania, USA
	28	33.90	N/a	1.21	1	Equation	Coniferous forest	970	11	Sandy loam	Coal	No	West Virginia, USA
	45	25.70	N/a	0.57	1	Equation	Mixed forest	1010	11	Silt loam	Coal	No	Indiana, USA
	38	28.40	N/a	0.75	1	Equation	Mixed forest	1110	13	Sandy clay loam	Coal	No	Kentucky, USA
	35	23.30	N/a	0.67	1	Equation	Mixed forest	1010	11	Sandy loam	Coal	No	West Virginia, USA
	27	40.70	N/a	1.51	1	Equation	Mixed forest	970	11	Sandy loam	Coal	No	West Virginia, USA
	47	22.70	N/a	0.48	1	Equation	Deciduous forest	1150	13	Silt loam	Coal	No	Illinois, USA
	44	39.70	N/a	0.90	1	Equation	Deciduous forest	1010	11	Silt loam	Coal	No	Indiana, USA

Table 1 continued

Reference	Age (y)	C stock (t ha^{-1})	Control C stock (t ha^{-1})	Accumulation rate (t ha^{-1} y^{-1})	n	Fossil c correction method	Vegetation type	MAP (mm)	MAT (°C)	Soil texture	Mined material	Amendments	Location
	35	22.80	N/a	0.65	1	Equation	Deciduous forest	1110	13	Sandy clay loam	Coal	No	Kentucky, USA
	50	24.10	N/a	0.48	1	Equation	Deciduous forest	930	10	Silt clay loam	Coal	No	Ohio, USA
Fettweis et al. (2005)	19	26.00	N/a	1.37	1	Radiocarbon	Coniferous forest	580	9	Loamy sand	Lignite	Ash	Cottbus, Germany
	19	22.00	N/a	1.16	1	Radiocarbon	Coniferous forest	580	9	Loamy sand	Lignite	Ash	Cottbus, Germany
	37	47.00	N/a	1.27	1	Radiocarbon	Coniferous forest	580	9	Loamy sand	Lignite	Ash	Cottbus, Germany
Frouz et al. (2009)	28	36.91	N/a	1.32 ± 0.72	4	Deep layer	Deciduous forest	650	6.8	Clay	Coal	No	Sokolov, Czech Rep.
	31	38.03	N/a	1.23 ± 0.23	4	Deep layer	Deciduous forest	650	6.8	Clay	Coal	No	Sokolov, Czech Rep.
	28	16.54	N/a	0.59 ± 0.27	4	Deep layer	Deciduous forest	650	6.8	Clay	Coal	No	Sokolov, Czech Rep.
	27.8	4.39	N/a	0.16 ± 0.13	4	Deep layer	Deciduous forest	650	6.8	Clay	Coal	No	Sokolov, Czech Rep.
	29.5	23.11	N/a	0.78 ± 0.17	4	Deep layer	Deciduous forest	650	6.8	Clay	Coal	No	Sokolov, Czech Rep.
	27	9.32	N/a	0.35 ± 0.20	4	Deep layer	Coniferous forest	650	6.8	Clay	Coal	No	Sokolov, Czech Rep.
	22	9.70	N/a	0.44 ± 0.16	4	Deep layer	Coniferous forest	650	6.8	Clay	Coal	No	Sokolov, Czech Rep.
Ganjegunte et al. (2009)	14	32.15	23.34	0.63 ± 0.32	4	Young site	Grassland	376	6.7	Loam	Coal	No	Wyoming, USA
	26	39.37	23.34	0.62 ± 0.19	4	Young site	Grassland	376	6.7	Loam	Coal	No	Wyoming, USA
	5	31.47	23.34	1.63 ± 0.97	4	Young site	Shrubland	266	7.4	Loam	Coal	No	Wyoming, USA
	10	27.78	23.34	0.44 ± 0.33	4	Young site	Shrubland	266	7.4	Loam	Coal	No	Wyoming, USA
	16	18.16	23.34	-0.32 ± 0.16	4	Young site	Shrubland	266	7.4	Loam	Coal	No	Wyoming, USA

Table 1 continued

Reference	Age (y)	C stock (t ha^{-1})	Control C stock (t ha^{-1})	Accumulation rate (t ha^{-1} y^{-1})	n	Fossil c correction method	Vegetation type	MAP (mm)	MAT (°C)	Soil texture	Mined material	Amendments	Location
Karu et al. (2009)	15	6.30	N/a	0.42 ± 1.13	3	Radiocarbon	Mixed forest	639	4.8	Sand	Oil shale	No	Narva, NE Estonia
	22	10.50	N/a	0.48 ± 0.32	3	Radiocarbon	Coniferous forest	639	4.8	Sand	Oil shale	No	Narva, NE Estonia
	37	44.60	N/a	1.21 ± 1.05	3	Radiocarbon	Coniferous forest	639	4.8	Sand	Oil shale	No	Narva, NE Estonia
Keskin and Makineci (2009)	17	33.90	21.48	0.73 ± 0.82	7	Deep layer	Deciduous forest	1049	14	Sandy clay loam	Coal	No	Istanbul, Turkey
	17	19.46	10.50	0.53 ± 0.80	5	Deep layer	Coniferous forest	1049	14	Sandy loam	Coal	No	Istanbul, Turkey
Chatterjee et al. (2009)	30	48.18	26.39	0.73 ± 0.34	3	Young site	Grassland	1039	10.7	Silt loam	Coal	NPK	Morgan, OH, USA
	9	56.70	26.39	3.37 ± 0.99	3	Young site	Grassland	1039	10.7	Silt loam	Coal	NPK	OH, USA
	11	48.90	26.39	2.5 ± 0.39	3	Young site	Mixed forest	1039	10.7	Silt loam	Coal	N/a	Noble, OH, USA
Lorenz and Lal (2007)	31	41.79	4.86	1.19 ± 0.44	9	Young site	Mixed forest	965	13	Loamy-gravel	Coal	No	Morgan, Ohio
Nii-Annang et al. (2009)	9	16.67	N/a	1.85 ± 0.70	3	Time shift	Deciduous forest	569	9.4	Loamy sand	Lignite	CaO, NPK	Lusatia, Germany
	9	18.54	N/a	2.6 ± 0.74	3	Time shift	Deciduousforest	569	9.4	Loamy sand	Lignite		Lusatia, Germany
	9	15.23	N/a	1.69 ± 0.75	3	Time shift	Deciduous forest	569	9.4	Loamy sand	Lignite		Lusatia, Germany
Reintam et al. (2002)	29	31.22	N/a	1.8	1	Deep layer	Coniferous forest	584	4.2	Sand	Oil shale	No	Sirgala, Estonia
	31	32.25	N/a	1.4	1	Deep layer	Coniferous forest	584	4.2	Sand	Oil shale	No	Sirgala, Estonia
	31	82.52	N/a	2.66	1	Deep layer	Coniferous forest	584	4.2	Sand	Oil shale	No	Sirgala, Estonia
	34	56.36	N/a	1.66	1	Deep layer	Coniferous forest	584	4.2	Sand	Oil shale	No	Sirgala, Estonia
Reintam (2004)	25	N/a	N/a	1.41	5	Deep layer	Coniferous forest	584	4.2	Sand	Oil shale	No	NE Estonia
	25	N/a	N/a	1.4	5	Deep layer	Coniferous forest	584	4.2	Sand	Oil shale	No	NE Estonia
	25	N/a	N/a	1.57	5	Deep layer	Deciduous forest	584	4.2	Sand	Oil shale	No	NE Estonia

Table 1 continued

Reference	Age (y)	C stock (t ha^{-1})	Control C stock (t ha^{-1})	Accumulation rate (t ha^{-1} y^{-1})	n	Fossil c correction method	Vegetation type	MAP (mm)	MAT (°C)	Soil texture	Mined material	Amendments	Location
Rumpel et al. (2003)	11	6.00	0.00	0.55 ± 0.25	2	Radiocarbon	Coniferous forest	580	9	Sand	Lignite	Ash	Lusatia, Germany
	17	12.20	0.00	0.72 ± 0.28	2	Radiocarbon	Coniferous forest	580	9	Sand	Lignite	Ash	Lusatia, Germany
	32	35.70	0.00	1.12 ± 0.29	2	Radiocarbon	Coniferous forest	580	9	Sand	Lignite	Ash	Lusatia, Germany
Sever and Makineci (2009)	17	30.38	23.35	0.41 ± 0.98	14	Deep layer	Coniferous forest	1049	14	Sandy loam	Coal	No	Istanbul, Turkey
Shrestha et al. (2009)	5	44.40	31.40	2.60 ± 0.36	3	Time shift	Grassland	934	9.8	Loam	Coal	CaO, NPK, mulch	Harrison, OH, USA
	5	36.70	32.90	0.76 ± 1.08	3	Time shift	Grassland	934	9.8	Clay loam	Coal		Noble, OH, USA
	5	54.10	50.60	0.70 ± 1.52	3	Time shift	Grassland	1070	9.2	Sandy clay loam	Coal		Belmont, OH, USA
	5	47.20	31.40	3.16 ± 0.36	3	Time shift	Grassland	934	9.8	Loam	Coal	CaO, NPK, mulch, chiseling	Harrison, OH, USA
	5	47.00	32.90	2.82 ± 1.08	3	Time shift	Grassland	934	9.8	Clay loam	Coal		Noble, OH, USA
	5	62.90	50.60	2.46 ± 1.52	3	Time shift	Grassland	1070	9.2	Sandy clay loam	Coal		Belmont, OH, USA
	5	45.00	31.40	2.72 ± 0.36	3	Time shift	Grassland	934	9.8	Loam	Coal	CaO, NPK, mulch	Harrison, OH, USA
	5	35.20	32.90	0.46 ± 1.08	3	Time shift	Grassland	934	9.8	Clay loam	Coal		Noble, OH, USA
	5	52.60	50.60	0.40 ± 1.52	3	Time shift	Grassland	1070	9.2	Sandy clay loam	Coal		Belmont, OH, USA
	5	47.70	31.40	3.26 ± 0.36	3	Time shift	Grassland	934	9.8	Loam	Coal	CaO, NPK, mulch, manure	Harrison, OH, USA
	5	45.40	32.90	2.50 ± 1.08	3	Time shift	Grassland	934	9.8	Clay loam	Coal		Noble, OH, USA
	5	61.10	50.60	2.10 ± 1.52	3	Time shift	Grassland	1070	9.2	Sandy clay loam	Coal		Belmont, OH, USA

Table 1 continued

Reference	Age (y)	C stock (t ha^{-1})	Control C stock (t ha^{-1})	Accumulation rate (t ha^{-1} y^{-1})	n	Fossil c correction method	Vegetation type	MAP (mm)	MAT (°C)	Soil texture	Mined material	Amendments	Location
Sourkova et al. (2005)	4	48.10	23.00	6.27 ± 6.01	3	Regression	Deciduous forest	650	6.8	Clay	Coal	No	Sokolov, Czech Rep.
	5	50.57	23.00	5.51 ± 3.81	3	Regression	Deciduous forest	650	6.8	Clay	Coal	No	Sokolov, Czech Rep.
	6	31.11	23.00	1.35 ± 2.30	3	Regression	Deciduous forest	650	6.8	Clay	Coal	No	Sokolov, Czech Rep.
	6	41.42	23.00	3.7 ± 2.96	3	Regression	Deciduous forest	650	6.8	Clay	Coal	No	Sokolov, Czech Rep.
	10	59.85	23.00	3.69 ± 2.69	3	Regression	Deciduous forest	650	6.8	Clay	Coal	No	Sokolov, Czech Rep.
	13	59.15	23.00	2.78 ± 1.57	3	Regression	Deciduous forest	650	6.8	Clay	Coal	No	Sokolov, Czech Rep.
	13	60.88	23.00	2.91 ± 1.86	3	Regression	Deciduous forest	650	6.8	Clay	Coal	No	Sokolov, Czech Rep.
	14	70.19	23.00	3.37 ± 1.92	3	Regression	Deciduous forest	650	6.8	Clay	Coal	No	Sokolov, Czech Rep.
	15	77.27	23.00	3.62 ± 1.77	3	Regression	Deciduous forest	650	6.8	Clay	Coal	No	Sokolov, Czech Rep.
	25	59.39	23.00	1.46 ± 0.89	3	Regression	Deciduous forest	650	6.8	Clay	Coal	No	Sokolov, Czech Rep.
	25	72.69	23.00	1.99 ± 1.17	3	Regression	Deciduous forest	650	6.8	Clay	Coal	No	Sokolov, Czech Rep.
	26	70.34	23.00	1.82 ± 0.69	3	Regression	Deciduous forest	650	6.8	Clay	Coal	No	Sokolov, Czech Rep.
	34	69.33	23.00	1.36 ± 0.86	3	Regression	Deciduous forest	650	6.8	Clay	Coal	No	Sokolov, Czech Rep.
	34	80.75	23.00	1.70 ± 1.03	3	Regression	Deciduous forest	650	6.8	Clay	Coal	No	Sokolov, Czech Rep.
	36	57.75	23.00	0.97 ± 0.61	3	Regression	Deciduous forest	650	6.8	Clay	Coal	No	Sokolov, Czech Rep.
	36	48.66	23.00	0.71 ± 0.56	3	Regression	Deciduous forest	650	6.8	Clay	Coal	No	Sokolov, Czech Rep.
	38	78.33	23.00	1.46 ± 0.85	3	Regression	Deciduous forest	650	6.8	Clay	Coal	No	Sokolov, Czech Rep.
	64	62.87	23.00	0.62 ± 0.37	3	Regression	Deciduous forest	650	6.8	Gravel-sand	Coal	No	Sokolov, Czech Rep.
	65	82.81	23.00	0.92 ± 0.27	3	Regression	Deciduous forest	650	6.8	Gravel-sand	Coal	No	Sokolov, Czech Rep.

Table 1 continued

Reference	Age (y)	C stock (t ha^{-1})	Control C stock (t ha^{-1})	Accumulation rate (t ha^{-1} y^{-1})	n	Fossil c correction method	Vegetation type	MAP (mm)	MAT (°C)	Soil texture	Mined material	Amendments	Location
Frouz and Kalčík (2006)	11.3	N/a	N/a	0.24 ± 0.10	3	Deep layer	Shrubland	650	6.8	Clay	Coal	No	Sokolov, Czech Rep.
	16.4	N/a	N/a	1.14 ± 0.24	5	Deep layer	Shrubland	650	6.8	Clay	Coal	No	Sokolov, Czech Rep.
	29	N/a	N/a	0.62 ± 0.16	4	Deep layer	Deciduous forest	650	6.8	Clay	Coal	No	Sokolov, Czech Rep.

Fossil C correction methods, by which fossil C is subtracted from total C to determine recently sequestered C, included: radiocarbon dating (radiocarbon); subtraction of data obtained in a young site (young site), or a deep layer (deep layer); comparison between historical and recent contents at the same site (time shift); linear regression of content on age (regression), and a coal-correction equation developed by Amichev (2007) (equation). *MAP* mean annual precipitation, *MAT* mean annual temperature

deciduous forests (2.31 ± 1.02, $n = 15$), but was not significantly different in grasslands versus deciduous forests ($p < 0.05$, LSD post hoc test).

When SOC accumulation was regressed on the age of the site, the nature of the regression differed among vegetation types (Table 2). Because we obtained grassland data only for younger sites (0–30 years old), we compared grassland data with the data from the two forest types within this same age range. For this 30-year period, the rate of SOC accumulation did not change significantly in grassland sites, but significantly increased with age in coniferous forest sites and significantly decreased with age in deciduous forest sites (Table 2). When we compared forest sites using all available data, the relationship between SOC accumulation rate and age of site for coniferous forests was described by a polynomial equation in which accumulation rate reached a maximum of 35 years after reclamation (Table 2). In a similar analysis that used all available data, the relationship between SOC accumulation rate and the age of the site for deciduous and mixed forests reached a maximum after 10–20 years and then tended to decrease logarithmically (Table 2).

Effect of vegetation on the distribution of SOC in the soil profile

The vertical distribution of SOC in the soil profile differed among forest types. The contribution of SOC sequestered in the mineral soil (rather than in the surface organic layer) to the total SOC stock was significantly ($p < 0.05$, t test) higher in deciduous and mixed forests than in coniferous forests. The surface organic layer contained 23 % of sequestered SOC under deciduous and mixed forests and 62 % under conifers. This difference was more pronounced than that found in a meta-analysis of afforested agricultural soils and grasslands, which indicated that the percentage of SOC in surface organic layer was 57, 52, and 46 % for *Pinus* spp., deciduous species, and coniferous species, respectively, excluding *Pinus* spp. (Laganiere et al. 2010). The value for conifers was comparable in the two studies because *Pinus* was the most frequent coniferous species in the reclaimed sites of our data set. The lower value for SOC in surface layers under deciduous species in the current study versus Laganiere et al. (2010) may be associated with the high percentage of N-fixing species in our data set (at least 40 % of the deciduous trees in our data set were N-fixing species); N-fixing species produce litter that decomposes relatively quickly (Filcheva et al. 2000; Sourkova et al. 2005; Keskin and Makineci 2009). We cannot compare grasslands in this manner because none of the grassland studies mention a litter layer, fermentation layer, or any other kind of surface organic horizon, which indicates that the contribution of these layers to total SOC accumulation in grassland is low.

Although surface organic layers should be included in the calculations of sequestered SOC (Guo and Gifford 2002; Paul et al. 2002; Laganiere et al. 2010), SOC sequestered in the organic layer is less stable than that in the mineral soil because it is more vulnerable to loss by disturbance (fire, erosion, etc.). It follows that the contribution of organic layers should always be reported along with the total SOC stocks (Vogel 1981; Laganiere et al. 2010).

Recovery of SOC stock to pre-mining level

The degree to which the SOC stock of post-mining soils returned to pre-mining levels was highly variable. However, a large proportion of the sites reached pre-mining SOC stock within 20 years or less after reclamation. Topsoil application subset shows better correlation with time than no topsoil application data (Fig. 2). However, this may be mainly because the topsoil subset is more homogeneous, while no topsoil sites show high variability in the data set. The good chance of SOC recovery is consistent with Schwenke et al. (2000), who estimated that it would take 33 years for the SOC level to increase to the level of the undisturbed native forest in post-mining sites in Weipa, Australia, after topsoil application and the planting of native tree species. However, a general linear model with topsoil application as a categorical predictor and age as a continual predictor did not find any significant effect either for time or topsoil application ($p = 0.942$ for age and 0.808 for topsoil application), so we cannot conclude that topsoil application leads to faster recovery to pre-mining SOC stock.

Rate of SOC accumulation in relation to climate, soil texture, and sampling depth

The SOC accumulation rate was not significantly correlated with precipitation based on analysis of the whole data set or on analysis by vegetation type (data not shown). The rate of SOC accumulation, however, was significantly

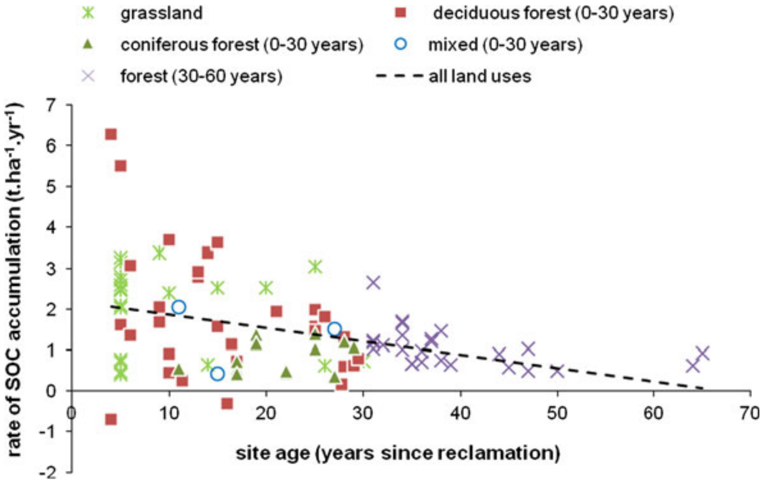

Fig. 1 Rate of SOC accumulation in post-mining soils in relation to vegetation type and the age of the site (all sites are in the temperate zone of the Northern Hemisphere). Regression equations and correlation coefficients for different categories are presented in Table 2

Table 2 Relationship between the rate of SOC accumulation (t ha^{-1} y^{-1}) and the age of the site (years since reclamation) for sites with different types of vegetation

Vegetation type	Regression
Grassland	ns
Coniferous forest, 0–30[a] years	$Y = 0.0436x - 0.0315$ ($n = 12$; $R^2 = 0.3689$; $p < 0.05$)
Coniferous forest, all ages	$Y = -0.0015x^2 + 0.1061x - 0.6575$ ($n = 22$; $R^2 = 0.1959$; $p < 0.05$)
Deciduous forest, 0–30 years	$Y = -0.0956x + 3.44682$ ($n = 27$; $R^2 = 0.281$, $p < 0.05$)
Deciduous and mixed forest, 0–30 years	$Y = -0.0724x + 2.8593$ ($n = 36$; $R^2 = 0.1672$, $p < 0.05$)
Deciduous and mixed forest, all ages	$Y = -0.8614\mathrm{Ln}(x) + 4.0325$ ($n = 50$; $R^2 = 0.2333$; $p < 0.05$)
Forest, 30–60 years	$Y = -0.023x + 1.9573$ ($n = 25$; $R^2 = 0.2403$; $p < 0.05$)
All vegetation types	$Y = -0.0329x + 2.2044$ ($n = 93$; $R^2 = 0.1589$; $p < 0.05$)

[a] Because data for grasslands were only available for younger sites (0–30 years old), we have included 0–30 years categories for forests to facilitate comparisons between sites with grassland and those with forest

related to temperature in sites with coniferous forest and grasslands, i.e., the rate decreased with increasing temperature for conifers and increased with increasing temperature in grasslands (Fig. 3). Deciduous forests show no significant correlation with temperature.

This relationship between temperature, SOC storage, and vegetation type corresponds with natural distribution of grassland, coniferous forest, and deciduous forest (Brown and Gibson 1983). This indicates that for reclamation of post-mining sites, the planted vegetation should be typical for the particular biome in which the post-mining site occurs. In other words, grasses should be planted at warmer sites, conifers at colder sites, and deciduous trees at intermediate sites.

These adverse trends in temperature dependence of SOC storage between coniferous forest and grassland may be related to two different mechanisms involved in the effect of temperature on SOC accumulation. Lower temperatures are associated with lower vegetation productivity resulting in deficient litter input (Karu et al. 2009; Laganiere et al. 2010). On the other hand, higher temperatures have accelerating effect on decomposition (Lal 2005).

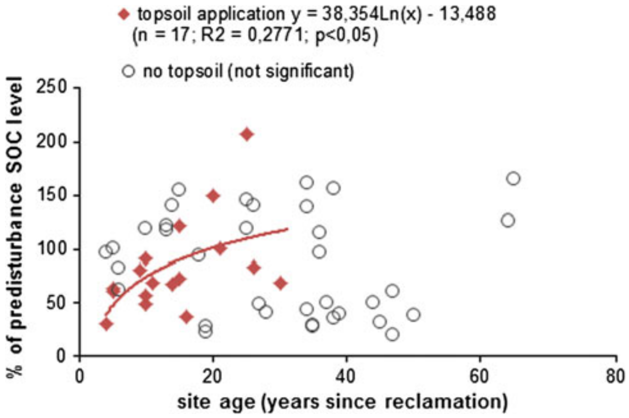

Fig. 2 Return of SOC levels to pre-mining levels in post-mining soils with or without topsoil application as a part of the reclamation practice (all sites are in the temperate zone of the Northern Hemisphere)

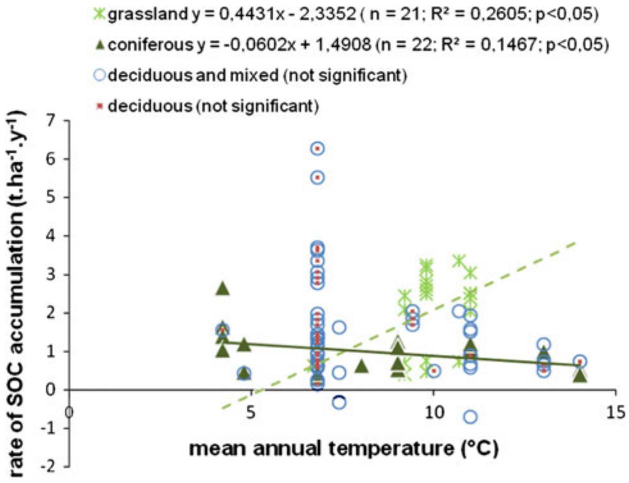

Fig. 3 Rate of SOC accumulation in post-mining soils as related to mean annual temperature and vegetation type (all sites are in the temperate zone of the Northern Hemisphere)

As mentioned earlier, most conifer litter accumulates on the soil surface, while substantial proportions of litter in grasslands accumulate in the mineral soil. In a meta-analysis of agricultural soils, Poeplau et al. (2011) report that accumulation is higher in colder sites if surface organic layers are included in the calculations, whereas the accumulation is higher in warmer sites when only mineral soil is considered. Results on post-mining soils are in agreement with these conclusions, considering that the SOC stocks of coniferous sites are largely formed by litter deposited on the soil surface, whereas the contribution of organic layers in grasslands is very low. This explains why under conifers the decomposability shows greater effect than the production of vegetation, whereas SOC accumulation in grasslands seems to be more input dependent.

Although some studies of agricultural soils have indicated that SOC accumulation may be influenced by clay content or soil depth (Laganiere et al. 2010), it was not related to soil texture or sampling depth in our analysis (data not shown).

Conclusions

This study is the first to summarize SOC accumulation rates in post-mining soils of the northern temperate zone. There are relatively few papers devoted to SOC accumulation and C sequestration in post-mining soils. In addition, comparison of the existing studies is difficult because of: (a) missing bulk density measurements; (b) missing or varying methods for fossil carbon assessment; (c) missing or varying methods for SOC content measurement in topsoil before reclamation; (d) missing or incomplete data on measures of variance (SD, SEM) and number of replicates (*n*). These factors should be taken into account by authors of future research of post-mining sites. In general, measures of variance and number of replicates should be automatically presented along with mean values in all studies to allow for their future interpretation.

Although more studies are needed, we can report some useful preliminary findings based on our analyses of the studies published so far. In our meta-analysis of post-mining soils in the temperate zone of the Northern Hemisphere, the rate of SOC accumulation was not significantly related to vegetation type. However, further statistical analysis revealed that deciduous trees supported the accumulation of organic matter in the mineral soil, which stabilized the sequestered carbon. The maximum rates of SOC accumulation are reached after 30–40 years in sites with conifers and after 10–20 in sites with deciduous trees; the rates then decline as the sites get older. Accumulation is influenced by temperature. Accumulation decreases with increasing temperature in sites with conifers, but increases with increasing temperatures in grasslands. A large proportion of post-mining sites reach the pre-mining SOC stock within 20 years or less after reclamation.

Acknowledgments Our special thanks are due to Helen Karu and Doc. Dr. Ender Makineci for providing unpublished data related to their papers. Many thanks are due to Dr. Raj. K. Shrestha, Dr. Graeme Schwenke, Dr. Christopher Barton, and Dr Lachlan Ingram for sharing their papers and useful ideas. This study was supported by a grant from the Ministry of Education of the Czech Republic 2B80023 and by the Research Plan of BC AS CR, v.v.i.-ISB AV0Z60660521 and MSM0021620855. The authors thank Bruce Jaffee for language correction.

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