

Evaluation of forest ecosystem restoration on lignite mine spoils using a false-time series ecosystem budget approach

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Abstract

The development of element cycles in afforested sites after lignite mining were studied using a false-time series approach on typical spoil substrates in the Lusatian open-cast mining area (E-Germany). The chronosequences cover a period of about 60 years. Intensive field measurements and modelling were carried out over a several years in order to calculate element budgets.

The two dominating overburden substrates of the sites are derived from tertiary and quaternary sediments, respectively, and are both characterized by sandy texture and low nutrient contents. The main differences between the substrates are the considerably high lignite and pyrite contents in the substrates from tertiary sediments.

The results show that during the first decades enormous element amounts are leached from the soil. The output rates reach up to 50 kmol Fe ha⁻¹yr⁻¹, 95 kmol Al ha⁻¹yr⁻¹, and >200 kmol SO₄-S ha⁻¹yr⁻¹ at the younger sites. At the older sites these flux rates are considerably decreasing indicating the termination of pyrite oxidation and advanced leaching of soluble salts. Nevertheless, output rates of most elements measured are clearly increased even after 50 years compared to non-mined sites of the region.

The lignite components of these substrates seems to constitute an interesting feature in long-term site quality, especially it's role in water retention, nutrient availability, and nitrogen cycling. All these effects together may explain the long-term success of site restoration. In comparison the element fluxes at the lignite- and pyrite-free sites are manifold lower and show much less temporal dynamics.

The chronosequence approach to study "false-time series" of post-mining sites has proven to be a very useful tool to evaluate trends and rates of development on the ecosystem level. The results reveal fundamental differences in element cycling between the two substrate types due to their different geochemistry.

Introduction

In Lusatia, an area of more than 80,000 ha is affected by open-cast lignite-mining activities (Hüttl, 1998). Above that an area of 2,500 km² is affected by groundwater lowering due to large-scale pumping measures before the opening of a mine creating a groundwater deficit of 7*10⁹ m³ in the region. Once the groundwater level is lowered beneath the depth of the lignite seam (around 70 m below surface) huge amounts of overburden have to be translocated (eg. 309 Mio. m³ in 1997). The dumping of these overburden substrates result in largely devastated landscapes with disturbed or destroyed soils, flora, and fauna.

In the post-mining landscapes two main types of substrates can be identified: lignite- and pyrite-containing substrates stemming from Tertiary sediments and lignite- and pyrite-free substrates from Quaternary sediments. The majority of

these substrates are pure sands and loamy sands. Due to the mining technology using overburden-conveyer bridges (Häge, 1996) about 60 % of the land surface today consist of at least partially lignite- and pyrite-containing substrates and are characterized by low nutrient content and poor water retention capacity (Katzur, 1998). The pyrite content in these substrates exposed to the atmosphere leads to a high potential for acid production and consequently very phytotoxic site conditions. To reclaim or recultivate these sites, high amounts of ashes from lignite power plants were used for amelioration and neutralization of actual and potential acidity (Katzur and Haubold-Rosar, 1996). Since reclamation measures lagged behind mining activities during GDR times, an area of about 30,000 ha remains for recultivation. In this context, "recultivation" is defined as supporting "the development of the

soils, the vegetation, the wildlife, the water balance and water quality in order to allow future land uses such as agriculture and forestry” (Hüttl, 1998). Due to the poor substrates forestry is the dominating land use in the post-mining landscape covering about 60 % of the area. These forest ecosystems virtually start very close to the “point zero” of development, especially with regard to soil development, plant-soil interactions, and establishment of biogeochemical cycles.

The establishment or reconstruction of forest ecosystems as they dominated the Lusatian landscape before mining requires the definition of target or optimum conditions. Following (Bradshaw 1987) the re-establishment of the budget type of an ecosystem with respect to its element turnover and output can be defined as a long-term recultivation target. To evaluate recultivation success in this context therefore requires an ecosystem-oriented approach (cf. Ulrich 1991).

Materials and Methods

Seven sites on comparable substrate representing the two prevailing site types were chosen as chronosequences covering periods of up to 60 years of development (Tab. 1). The lignite- and pyrite-containing substrates (LPCS) were ameliorated with different amounts of lignite ash depending on their calculated potential lime requirements (Katzur, 1998). The different incorporation depths represent the available technology at the time. The lignite- and pyrite-free substrates (LPFS) were either left unameliorated or had been limed. All sites received an initial mineral NPK-fertilization before afforestation. For comparison, element cycling data from a 45-year old Scots pine stand on non-mined glacial outwash sands (Spoddystric Cambisol) were used (site name: TA; for detailed description see Schaaf et al., 1995 and 2001)

Detailed information on methods used for soil and soil solution analysis are described in Schaaf (2001) and Wilden et al. (2001). All sites were intensively instrumented for water and element flux measurements with meteorological stations, bulk and throughfall samplers (10 each), ceramic suction cups (P80 material) for soil solution sampling in 2 - 4 soil depths (6 cups per depth), pressure transducer tensiometers (5 per depth) and TDR/FDR probes (2 per depth) for continuous registration of soil tension and volumetric water content.

Table 1: Sites of the chronosequence studies sites on tertiary substrates (LPCS)

Weissagker Berg (WB)	
dumped in:	1991
substrate:	lignite + pyrite containing sand
melioration:	1996, 28 t CaO/ha-60-80 cm
stand age:	2 years (<i>Pinus sylvestris</i>)
Baerenbrueck (BB)	
dumped in:	1977
substrate:	lignite + pyrite cont. loamy sand
melioration:	1978, ca. 190 t CaO/ha-40 cm
stand age:	16 years (<i>Pinus nigra</i>)
Meuro (MR)	
dumped in:	1970
substrate:	lignite + pyrite cont. loamy sand
melioration:	1971, ca. 160 t CaO/ha-60 cm
stand age:	20 years (<i>Pinus sylvestris</i>)
Domsdorf (DD)	
dumped in:	ca. 1946
substrate:	lignite + pyrite cont. loamy sand
melioration:	1963, ca. 50 t CaO/ha-30 cm
stand age:	34 years (<i>Pinus sylvestris</i>)
sites on quaternary substrates (LPFS)	
Seeblick (SB)	
dumped in:	1994
substrate:	sand
melioration:	1995, 7.5 t CaO/ha 100 cm
stand age:	2 years (<i>Pinus sylvestris</i>)
Schipkau (SK)	
dumped in:	no data
substrate:	sand
melioration:	no data
stand age:	20 years (<i>Pinus sylvestris</i>)
Plessa (PL)	
dumped in:	1924
substrate:	sand
melioration:	none
stand age:	62 years (<i>Pinus sylvestris</i>)

Results and Discussion

The geochemistry of the substrate types is very different as reflected in soil solution compositions. Gast et al. (2001), Schaaf et al. (1998), and Wilden et al. (1999) described and discussed soil solution chemistry of the sites in detail. Ion pairs and complexes play an important role in highly concentrated solutions (Knoche et al., 1999; Schaaf, 1999a). At the LPCS-sites the solutions show high concentrations with electrical conductivities (EC) up to 16 mS cm⁻¹. pH values vary from 4.3 - 5.5 in ameliorated topsoils down to 2.3 - 3.3 in the subsoils (100 - 130 cm depth). Dominating mean element concentrations are calcium (up to 12.5 mmol Ca_T L⁻¹), magnesium (up to 13 mmol Mg_T L⁻¹), aluminium (up to 105 mmol Al_T L⁻¹), iron (up to 50 mmol Fe_T L⁻¹), and sulfate (up to

160 mmol $\text{SO}_{4\text{T}} \text{L}^{-1}$). With increasing site age these high values decrease and clear depth gradients are observed with higher concentrations in the subsoils (Schaaf et al., 1998). After amelioration and the induced pH increases in the topsoils especially, Al_{T} and Fe_{T} concentrations are reduced considerably. Despite high total carbon contents due to lignite in the substrate, the DOC concentrations are relatively low (10 – 30 mg L^{-1}). Elevated values up to 100 mg DOC L^{-1} paralleled by high ammonium concentrations (up to 2.5 mmol $\text{NH}_{4\text{T}} \text{L}^{-1}$) were found in extremely acid layers (pH 2.2).

At the LPFS-sites the mean total elemental concentrations are manifold lower compared to LPCS-sites. Mean pH values are 4.0 – 6.6, and EC varies between 0.2 and 1.0 mS cm^{-1} (Schaaf et al., 1998). Soil solution composition is dominated by calcium and sulfate at these sites also, but at very much lower levels (0.5 – 3.8 mmol $\text{Ca}_{\text{T}} \text{L}^{-1}$, 0.5 – 5.6 mmol $\text{SO}_{4\text{T}} \text{L}^{-1}$). Due to the higher pH, aluminium and iron concentrations are below 10 $\mu\text{mol L}^{-1}$. Only the youngest site (SB) shows higher concentrations than the two older LPFS-sites. No clear depth gradients can be identified in the soil profiles.

The substrates also differ in a number of other important soil chemical parameters. The lignite content results in higher C_{T} and N_{T} contents in the LPCS-sites compared to the LPFS-sites (Tab. 2). The higher lignite contents of the LPCS also increases the cation exchange capacity (CEC) of the sandy substrates, with CEC values 10- to 30-fold higher than both the LPFS-sites and the non-mined site (Tab. 2). Iron and Al contents, as determined by oxalate and dithionite extraction, were clearly elevated also throughout the profiles. The Fe_{o} and Fe_{d} values especially were 2- to 5-fold higher even when compared to the contents found in the Bh horizon of the Cambisol. The low values at the LPFS-sites are comparable to those found for the BC horizon of the non-mined site and are characteristic of low weathering and early stages of pedogenic processes.

Despite the low water fluxes through the soil profiles, very high element fluxes are calculated for the LPCS-sites as a consequence of the high soil solution concentrations. Output fluxes are generally 10 times higher at the LPCS-sites compared to the LPFS-sites and the non-mined site.

Calcium fluxes in the soil show two trends: the fluxes from the topsoils at the LPCS-sites

(ameliorated layers) decline with site age whereas the outputs from the subsoils reflect the amount of water fluxes quite well (Fig. 1). Despite the high fluxes, the Ca outputs (up to 30 $\text{kmol Ca ha}^{-1}\text{yr}^{-1}$) are generally below 1% of the total stores within the substrates. At the LPFS-sites, Ca outputs are only elevated at the youngest site SB. At the older sites the fluxes are at levels comparable to the non-mined site (TA). Although the Ca budgets are negative for all sites, outputs at the sites SK, PL and TA are much closer to the level of actual inputs compared to all LPCS-sites.

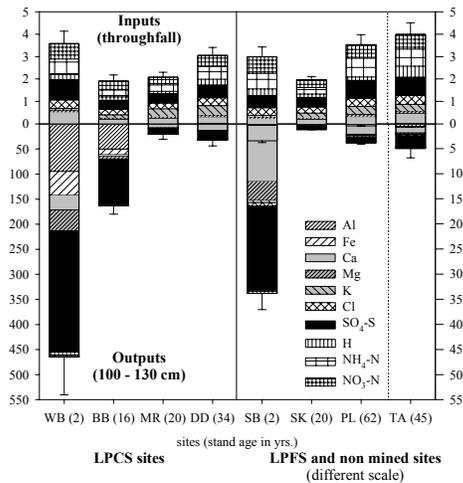


Figure 1: Budgets of the major elements at the chronosequence sites on lignite and pyrite containing substrates (LPFS-sites: WB – BB – MR – DD), on lignite and pyrite free substrates (LPFS-sites: SB – SK – PL), and at a non-mined site (TA); Inputs: throughfall deposition, except at WB and SB: bulk deposition; Outputs: fluxes in 100 cm (BB, MR, DD, SK, PL, and TA) or 130 cm (WB and SB) soil depth; all fluxes are mean values of 2 years in $\text{kmol ha}^{-1} \text{yr}^{-1}$ (but note different scales), error bars indicate variation between single years

The S fluxes in the soils show a similar pattern. LPCS-sites are characterized by extremely high S outputs up to $>200 \text{ kmol ha}^{-1}\text{yr}^{-1}$ (Fig. 1). Despite decreasing water fluxes, the S fluxes are increasing with soil depth. At the youngest site (WB) S outputs are more than 300-fold above actual deposition inputs. These figures decrease with site age, but at the oldest site (DD) the outputs are still 25-fold above inputs. The S budget is also negative at all LPFS-sites (especially at SB) and at the non-mined site (TA), but on much lower levels.

The differences between the two substrates are even larger for Al and Fe. Both the LPFS-sites and TA show very low input and output fluxes for both elements due to low concentrations that are often below the detection limit. In contrast, Al and Fe fluxes at the LPCS-sites can reach extremely high amounts at the younger sites (up to 95 kmol Al ha⁻¹yr⁻¹ and 50 kmol Fe ha⁻¹yr⁻¹). Iron fluxes decline very rapidly with site age, especially in the ameliorated topsoils, whereas Al outputs are elevated at the two youngest sites WB and BB. Aluminium fluxes from the topsoils of the older sites show reductions similar to Fe and from the subsoils they are comparable to the non-mined site (TA).

Nitrogen budgets show interesting differences between the sites. In deposition inputs, inorganic N is found in almost equivalent amounts as NH₄-N and NO₃-N at all sites. Generally, N outputs are well below inputs, and at some sites almost zero (Fig. 1). With two exceptions, the dominating N_{inorg.}-form in soil solution at all sites is NO₃ (usually > 90 % of N_{inorg.}). Elevated NH₄ fluxes from the subsoils (2.4 – 3.4 kmol NH₄-N ha⁻¹yr⁻¹) that exceed deposition rates are found only at the younger LPCS-sites. At the site DD, high NO₃ fluxes are detected, especially in the topsoil (1.7 kmol NO₃-N ha⁻¹yr⁻¹), resulting in N outputs at the level of deposition inputs.

The high element concentrations in soil solutions from LPCS-sites are similar to those reported by Knoche et al. (1999) at lignite and pyrite containing sites under oak and by Katur and Liebner (1995) in lysimeter studies with LPCS. Concentrations of comparable magnitudes are also found in soil solution samples from the mining area around Leipzig (Feldhaus and Wilczynski, 1998). Low pH and high SO₄ and metal concentrations in surface and ground waters from pyritic dumps and tailings are frequently reported in literature related to acid mine drainage (Evangelou, 1995).

The temporal development of soil solution composition along the “false-time series” can be explained as a combined effect of intensive “weathering” processes (including pyrite oxidation, transformation and precipitation processes) and leaching. Additionally, ash amelioration affects soil chemical properties, at least in the topsoils. Pyrite oxidation as the major source for Fe, SO₄, and acidity is completed within the time frame of the chronosequence as could be shown by the

declining pyrite-S contents in the subsoils (Heinkele et al., 1999). Intensive weathering of primary minerals within the substrates explains the high Al and Si concentrations (Gast et al., 2001) and could be verified by microscopy e.g. for feldspars (Heinkele et al., 1999). In the ameliorated layers of the profile, Fe and Al precipitate in the form of oxides and hydroxides (e.g. goethite, gibbsite or copiapite) due to the elevated pH (Miller, 1995). This is supported by the elemental composition of precipitates detected by scanning electron microscopy (Schaaf et al., 1999b) and explains the low Fe and Al concentrations in the topsoils. Other precipitates of secondary salt and mineral phases found at the LPCS-sites include gypsum, Fe- and Al-sulfates, and K-jarosite (Heinkele et al., 1999; Schaaf et al., 1999b). Gypsum, found at all sites and all soil depths, controls the Ca concentrations in soil solution which are frequently at the level of maximum gypsum solubility (Schaaf et al., 1998). Formation of gypsum as a result of pyrite oxidation and primary mineral weathering is commonly found in acid mine drainage, but also in naturally formed acid sulfate soils (Boulet and Larocque, 1998; Dent, 1986; Evangelou, 1995; Karathansis et al. 1990; van Breemen 1973). Sulfates like alunite, basaluminite, jurbanite or schwertmannite could also occur as possible solid phases (Bigham et al., 1996; Lin, 1997). This is supported by results from geochemical equilibrium modeling (Schaaf et al., 1999a), but could not be clearly identified by scanning electron microscopy (Heinkele et al., 1999). These transformation processes for Fe and Al from primary to secondary minerals is further supported by the high amounts of oxalate and dithionite soluble Fe and Al throughout the LPCS profiles.

The lower elemental concentration in soil solutions from the LPFS-chronosequence are comparable to results from oak ecosystems on mine sites derived from Quaternary sediments reported by Knoche (1998).

The elevated C_T and N_T content of the LPCS-sites underline the high stability of lignite. Investigations by Rumpel et al. (1997) enabled the separation of pedogenic and geogenic carbon in these soils. They showed that pedogenic organic matter derived from recent litter fall contributes to C_T only in the uppermost centimeters of the profile. Although lignite decomposition is much lower compared to pedogenic organic matter due to its composition

and high C/N ratio (Rumpel et al., 1998), it may play an important role in long-term nutrient cycling. The positive influence of lignite on (potential) CEC is reported by Katzur and Haubold-Rosar (1997). This increase is of high importance for soil ecological functions in these sandy and nutrient poor substrates. The extraordinary high CEC in the topsoil of the oldest site may be a result of the high ash amount used for amelioration.

Changes in the N fluxes in the topsoils indicate differences in mineralization and nitrification. Whereas at most sites both $\text{NH}_4\text{-N}$ and $\text{NO}_3\text{-N}$ fluxes at 20 cm soil depth are very low, the oldest LPCS-site shows elevated nitrate fluxes resulting in an internal proton production of $1.8 \text{ kmol H}^+ \text{ ha}^{-1} \text{ yr}^{-1}$ that is more than 5-fold above actual deposition input and exceeds by far all other measured proton fluxes at that site. The elevated $\text{NH}_4\text{-N}$ outputs from the subsoils at the younger LPCS-sites can not be connected to input or topsoil processes and can only be explained by NH_4 release from lignite under very acid conditions. With regard to plant nutrition it is important that most sites on both substrate types act as a sink for N and K. Increasing amounts of both nutrients are moving within a “small cycle” between plant uptake, growing biomass, accumulating organic surface layer, and the ameliorated top soil as stands grow in age. However, the exception at the oldest LPCS-site (DD) with clear net N losses makes it difficult to predict future development and long-term ecosystem stability.

Conclusions

The chronosequence approach to study “false-time series” of post-mining sites has proven to be a very useful tool to identify dominating processes at the ecosystem level. The results reveal fundamental differences of element budgets between the two substrate types due to their different geochemistry. The fluxes of almost all elements under investigation at the LPFS-sites are similar or even lower compared to a non-mined site which can be explained by low weathering rates of the dumped material consisting mainly of quartz and low atmospheric input rates. In contrast, the LPCS-sites show very high dynamics of initial development induced by substrate composition and are characterized by high element flux rates and intensive transformation processes, i.e. changes and redistribution of element pools.

With regard to transformation processes, the development starts before the actual mining and dumping activities. Pumping of groundwater and leveling of the groundwater table below the lignite seam leads to an aeration of the pyritic sediments resulting in initial pyrite oxidation and partial in-situ buffering of produced acidity, e.g. by feldspar weathering (Heinkele et al., 1999). This is important, because it shows that initial processes of transformation have already taken place when the substrate is dumped. At the well aerated dump sites the major processes are:

- Continued pyrite oxidation resulting in the release of large amount of acidity, sulfate, and iron, intensive weathering of primary minerals within the substrate releasing considerable amounts of Al, Ca, Mg or K depending on the specific mineral composition of the substrate, and precipitation of secondary salt and mineral phases like gypsum or oxides, hydroxides and sulfates of aluminum and iron. Since pyrite oxidation can be a rather fast process depending on its control by chemical or microbial oxidation (Evangelou, 1995), a pyrite-free zone is developing from the surface to increasing soil depths over time.
- Leaching of easily soluble or labile secondary salt and mineral phases like gypsum, anhydrite or epsom salt. Over time this zone develops down the profile, too, forming a zone free of pyrite and salts.
- Both processes are affected by the amelioration measures undertaken as a part of the recultivation practices. Large amounts of lignite ash are incorporated in the topsoils resulting in an input of high amounts of Ca and Mg, but also to a lesser extent sulfur. This introduces a large acid neutralization capacity compared to the substrate-internal buffering and also enhances formation of gypsum and other sulfate salts like MgSO_4 that is leached very fast in high amounts from the profiles (Schaaf et al., 1999b). The raising of soil pH on the other hand induces precipitation of Fe - and Al - oxides/hydroxides.

Within the time frame of the chronosequence a trend at least in the topsoils towards “undisturbed” conditions can be found, but for the prediction of future soil and ecosystem development there are still some important question marks left.

First, even after complete pyrite oxidation and leaching of salts, the geochemistry of the LPCS remains quite different from LPFS-sites as well as from non-mined sites of the region. The lignite particles show a high stability and resistance to microbial or fungal decomposition. They will therefore resemble a long-term constituent of the soil with the effects discussed above. Secondary minerals may be stable or labile in further soil development. The stability of some of them, like aluminium hydroxosulfates, is strongly pH-dependent. Reaction kinetics of amorphous forms but also of the incorporated ashes are very difficult to predict. The formation of Fe and Al oxides and hydroxides due to intensive weathering provides increased sorption capacity. Although actual base saturation is high only in the ameliorated topsoils, the potential for sorption of base cations available for plant uptake is clearly elevated compared to the LPFS-sites.

Second, to fully understand processes and to enable reliable predictions it is necessary to know the real “zero point” of geochemistry – that is the mineral composition at the pre-mining state before ground water leveling and aeration.

Finally, it should be stressed that the chronosequences are indeed “false” time series and the approach is limited by site-induced differences like substrate composition, amounts, incorporation depths, and composition of amelioration ashes, micro-meteorological conditions, and seasonal or stand induced differences in water fluxes. A number of processes discussed above have to be investigated in more detail both in quality and quantity. In addition, despite the high dynamics that are observed especially at the LPCS-sites, the time frames of our chronosequences obviously are too short to reliably predict long-term soil and ecosystem development. However, at the very least, the chronosequence approach on an ecosystem level provides a very useful tool to find the right questions.

The results of this chronosequence study show that the post-mining landscape will have a completely different pattern of completely different soil and site qualities compared to the situation before disturbance, and that it is extremely difficult to estimate the long-term development of these site qualities.

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Table 2: Soil chemical parameters of the sites

site/depth (horizon)	type	pH (H ₂ O)	C _T %	N _T mg g ⁻¹	S _T mg g ⁻¹	CEC mmol _c kg ⁻¹	Fe _o mg g ⁻¹	Fe _d mg g ⁻¹	Al _o mg g ⁻¹	Al _d mg g ⁻¹
WB 20 cm*	LPCS	3,7	1,44	0,6	4,4	32,8	3,1	3,9	0,4	0,4
WB 100 cm*		2,8	1,64	0,40	5,6	22,0	4,1	4,4	0,6	0,6
BB 20 cm	LPCS	4,0	5,38	1,0	9,8	97,2	7,5	8,9	1,5	1,0
BB 100 cm		2,5	6,20	1,2	13,6	72,1	7,0	6,5	1,9	1,5
MR 20 cm	LPCS	5,3	3,11	0,7	2,3	99,7	4,2	6,3	0,6	0,6
MR 100 cm		2,8	4,46	1,0	3,0	68,3	3,6	4,2	0,3	0,3
DD 20 cm	LPCS	5,5	5,25	1,1	1,5	203,8	7,1	10,9	0,6	0,7
DD 100 cm		2,9	5,80	1,3	2,3	73,5	7,1	9,4	0,4	0,4
SB 20 cm	LPFS	5,4	0,08	< 0,1	< 0,1	6,5	0,5*	1,0*	0,2*	0,2*
TA (Bhs) **	non	4,2	0,55	0,5	< 0,1	25,1	1,6	2,4	1,0	n.d.
TA (Bw) **	mined	4,4	0,25	0,5	0,1	14,9	0,7	1,7	1,9	n.d.
TA (BC) **		4,4	0,05	0,2	< 0,1	7,0	0,1	0,4	0,3	n.d.

* data from Heinkele and Weiß (BTUC 1999, pers. comm.);

** data from Schaaf et al. (1999c);

n.d. = not detected, Fe_o/Al_o = oxalate extractable iron/aluminium, Fe_d/Al_d = dithionite extractable iron/aluminium