AMELIORATION AND REFORESTATION OF SULFUROUS MINE SOILS IN LUSATIA (EASTERN GERMANY)

J. KATZUR and M. HAUBOLD-ROSAR

Forschungsinstitut für Bergbaufolgelandschaften e.V. Finsterwalde (FIB) Brauhausweg 2, 03238 Finsterwalde, Germany

Abstract. In Germany nearly 1.550 km^2 have been claimed by brown coal mining until now. Mine soils formed of carboniferous and sulfurous overburden are classified as "sulfurous mine soils". They remain vegetation-free for decades and may be cultivated only after soil amelioration. The objective of amelioration is a sustained improvement of soil reaction. Lime requirement for the achievement of a certain pH-value is calculated from acid-base-balance (SBB). Lime fertilizers and base-rich brown coal ashes are used for amelioration. As ashes have serveral advantages,their application is recommended. The ameliorative application of lime fertilizer or brown coal ash should be incorporated intensively into the soil to a depth of 60 cm, better 100 cm. Amelioration includes a mineral fertilization with N, P and K.

Afforestations with Pinus sylvestris, Pinus nigra, Larix decidua, Larix eurolepis, Tilia cordata, Quercus rubra and Quercus petraea on ameliorated mine soils show surprising good results. Multi-species stands have very positive effects on soil formation. Raw humus is formed under pine and larch, and under deciduous trees moder and mull with higher bioactivity and better development of water and nutrient balance in the topsoil are found.
Key words. lignite mining, recultivation, sulfurous mine soils, soil amelioration, reforestation, soil development.

1. Introduction

In Germany nearly 1.550 km^2 have been claimed by brown coal mining until now. Brown-coal deposits have exclusively been extracted in open-cast mines. Often Tertiary overburden were dumped at the surface. Tertiary deposits mostly contain carboniferous additions and considerable amounts of sulfur.

Mine soils formed of carboniferous and sulfurous overburden are classified as "sulfurous mine soils" (Katzur, 1971). This group includes mine soils of different texture and composition; thus, nutrient contents and fine-spread coal vary within a wide range. Fertility limiting soil properties are very similar, impeding revegetation by complex effects on plant growth. Sulfurous mine soils remain barren of vegetation for decades if man does not interfere (Figure 1).

Reclamation of sulfurous mine soils is either achieved by depositing a cultivable soil layer of at least 100 cm thickness (Illner and Sauer, 1974) or by soil amelioration (Brüning, 1959 and 1962; Illner and Katzur, 1964 a and b; Katzur, 1971 and 1977 a; Knabe, 1954 and 1959 a and b). Successful amelioration requires an exploration of the site (Wünsche *et al.*, 1972 and 1981) and the identification of its fertility limiting soil properties. The latter characterize the necessity for amelioration which is marked very differently depending on soil parameters.

Fertility of sulfurous mine soils is limited by acidity, lack of humus and insufficient nutrient supply. A modification of fertility limiting soil properties is the objective of soil amelioration as well as of biological recultivation. The results of amelioration and recultivation steps are especially improved by setting parameters for optimum capacities

Water, Air, and Soil Pollution **91:** 17–32.

of mine soils in regard to their later utilization (Katzur and Zeitz, 1985; Katzur, 1988). According to this, soil amelioration and recultivation form a unity and have to be adjusted to later utilization (e.g. agriculture, forestry or nature preservation).

Fig. 1. Sulfurous and carboniferous mine soils remain barren of vegetation for decades (conveying bridge dump in the open cast mine "Kleinleipisch"), picture: Hanschke (1993).

2. Fertility Limiting Soil Properties

Considering aspects of soil amelioration, specific characteristics of "sulfurous mine soils" are high sulfur content (> 0,2 % SO_3), fine-spread carboniferous additions (total carbon (C_t) > 0,5 - 30 %) and low base saturation (BS < 25 - 0 %). In general, soils with extremely low pH (1,7 - 3,5), lack of plant-available P, K and Mg (each < 1 mg/100g soil) and very wide C/N ratio (> 40 - 170) predominate. In case of higher contents of coal and/or elutriatable constituents, small portions of macropores are found as a result of compaction (Thomas, 1969).

A further property of Tertiary carboniferous and sulfurous mine soils is their periodic and long lasting wetting resistance. Consequences are the increased surface run-off leading to considerable damages by water erosion. As a reason for this phenomenon colloidally distributed wax residues of Tertiary reed grasses (Kraemer, 1953) and other alcohol soluble substances (Knabe, 1959a) are presumed. As wetting resistence is only relevant in the summer term after intense drying of mine soils, it is probably also caused by hydrophobic reaction of iron- and aluminium-humates. Wetting resistance increases susceptibility of mine soils rich in fine sand to wind erosion. That is why sandstorms are almost daily events on vegetation-free dumps.

The unusual high acidity of sulfurous mine soils is caused by chemical weathering of ferric sulfides (pyrite, marcasite) (Arkesteyn 1980; Stumm and Morgan, 1981; Kleinmann *et al.*, 1981; Pugh *et al.*, 1984;Caruccio *et al.*, 1988). Hereby sulfuric acid and ferric sulfate arise, which again may hydrolyze to FeOOH and H_2SO_4. If sulfuric acid is not neutralized, the pH drops into the extreme acid range. This fact had already been suggested by Knabe (1959a). The process of pyrite weathering starts immediately when brought into contact with atmospheric oxygen and is considerably accelerated by sulfur bacteria. In model experiments Thiobacillus ferrooxidans turned out to be quite insensitive to a pH of 7,0 (Schwartz, 1964), so that biochemical oxidation of pyrite sulfur may not be affected by higher pH values. Moreover it could be shown, that pyrite weathering in the zone of aeration is an irreversible process. Therefore acid release in the upper, 100 cm of the soil is probably lasting longer than 60 years (Katzur, 1970).

The low acid buffering capacity of these soils causes contents of free acid of 1 to 40 mmol (eq)/100 g. Extreme cases show values up to 150 mmol (eq)/100g soil. In case of extreme soil acidity (pH < 3,0) FeOOH is dissolved, silicates are destroyed, Fe^{3+}- and Al^{3+}-ions are released and heavy metals are mobilized. Salt loads and heavy metal contents of seepage waters are high (Katzur, 1992).

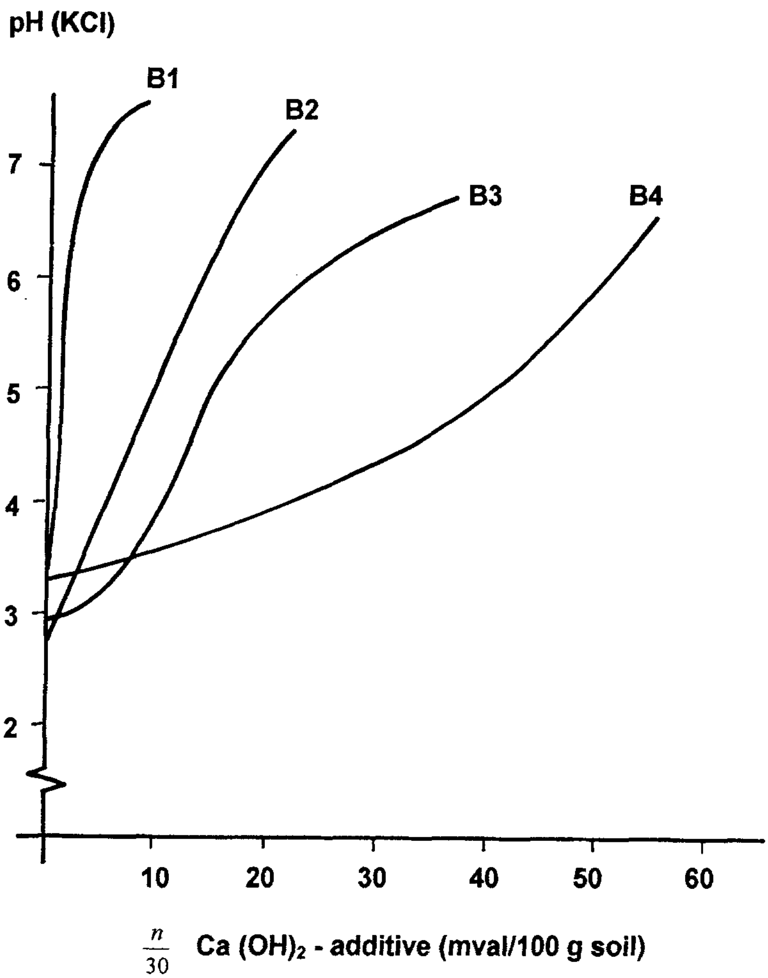
According to the contents of clay and coal, potential cation exchange capacity (CEC_{pot}) of sulfurous mine soils is 10 - 50 mmol (eq)/100g, sometimes up to 60 mmol (eq)/100g soil. Base neutralization capacity is very high (Figure 2), 80 - 100 % of the exchangeable cations are Al^{3+}-ions and to a lower percentage H^+- and Fe^{3+}-ions.

Besides a generally very high lime requirement Tertiary mine soils mostly have low quantities of hydrochloric acid soluble nutrients (Wünsche *et al.*, 1972). Since part of the nutrient reserves is fixed in fossil humus substance, nutrient contents rise with carbon content and reach a medium degree of supply (Kopp, 1960) in case of strongly carboniferous mine soils (C_t > 5 %). However, plant availability of macronutrients is limited because of the very unfavorable soil reaction.

Another consequence of extremely low pH-values is low bioactivity (Brüning, 1959; Lorenz, 1967a). After sustained amelioration of soil reaction carboniferous additions are microbially decomposed and transformed (Katzur, 1987). Because of partly mineralization of fossil organic substance mine soils rich in carbon (C_t > 2 %) show higher degrees of nutrient supply than mine soils free from or poor in carbon (C_t < 1 %). This has also been proved by investigations concerning forest growth on ameliorated dump sites.

3. Amelioration

The objective of amelioration is to achieve a sustained improvement of pH in sulfurous mine soils and to affect nutrient supply in a way that the following recultivation may be carried successfully. Recultivation contributes to further improvement of



	pH (KCl)	soil-texture	CECpot (in mval/100 g soil)	H-value	C_t (%) JACKSON	lime requirement (dt CaO/ha) for pH 5,5 SCHACHTSCHABEL	JENSEN
B1	3,5	S	3,1	3,5	0,3	12	8,0
B2	2,8	lS	17,7	23,3	2,2	62	83,1
B3	2,9	lS	28,5	46,0	4,3	131	127,6
B4	3,3	lS	44,1	67,1	9,4	243	382,4

Fig. 2. Buffer curves of selected mine soils.

soil properties and to the restoration of soil functions. In the former GDR (Germasn Democratic Republic) amelioration of sulfurous mine soils was of great economical importance because these soils covered 40 - 60 % of the reclamation area in the different mining districts.

Acids released by weathering of sulfides and low acid buffering capacity in sulfurous mine soils are considered in order to find out the total lime requirement. Otherwise, a second lime treatment becomes necessary, which in certain circumstances has to be repeated several times until optimum-pH is reached. This procedure is hardly practicable in case of forestal utilization of dump areas and is associated with considerable economical disadvantages in case of agricultural recultivation. Therefore it was proposed to calculate the lime requirement of sulfurous mine soils on the basis of "acid-base-balance" (SBB) (Illner and Katzur, 1964a and b; Illner, 1966; Katzur, 1965 and 1971). The SBB records and calculates on one side total sulfur, a certain portion of CEC_{pot} and on the other side mono- and bivalent bases measured in a HCl-extract. (Table I).

TABLE I

Acid-base balance (SBB) and lime requirement (for pH 5.0) of a sulfurous mine soil

soil parameters:			
pH_{KCL}	2.25		
CEC_{pot}	34 mmol (eq)/100g soil		
total sulfur	1.34 % SO_3		40.03 mg SO_3 = 1 mmol (eq)
CaO (HCl-extract)	0.205 %		28.04 mg CaO = 1 mmol (eq)
MgO (HCL-excract)	0.008 %		20.16 mg MgO = 1 mmol (eq)
dry bulk density	1.27 g/cm^3		
acid-base-balance (SBB)			
"acids":		1340 mg SO_3/100g soil	= 33.47 mmol (eq)/100g soil
	+	50 % of CEC_{pot}	= 17.00 mmol (eq)/100g soil
		sum 1	= 50.47 mmol (eq)/100g soil
"bases":		204 mg CaO/100g soil	= 7.28 mmol (eq)/100g soil
	+	8 mg MgO/100g soil	= 0.40 mmol (eq)/100g soil
		sum 2	= 7.68 mmol (eq)/100g soil
balance:		sum 1 - sum 2	= 42.79 mmol (eq)/100g soil
lime requirement for pH 5.0 (45 cm working depth):			
42.79 mmol (eq)/100g soil		= 1.2 g CaO/100g soil	
		= 90 dt CaO/ha (dry bulk density = 1.27 g/cm^3)	

Since pH is clearly related to base saturation (BS) (Lorenz, 1967a), that portion of CEC_{pot} which corresponds to the aspired pH is included in the SBB. Depending on the buffering capacity of the soil, BS-values vary within a wide range. For practical use consideration of 50 to 70 % of CEC_{pot} (and of bivalent bases Ca and Mg only) is sufficient. In most cases a base saturation of 50 % corresponds to pH 5,0, which is required for reforestation.

The calculation of the SBB is demonstrated (Table I) by an example, which has already been laid out in 1958. This experiment examines the effects on soil and plant growth by sewage sprinkling, occasionally combined with the use of lime fertilizer or base-rich brown coal ash.

According to the SBB, the lime requirement of the examined minesoil is about 690 dt CaO/ha for a 45 cm thick soil layer. This is almost equivalent to a CaO application given with base-rich brown coal ash (590 dt CaO/ha) and sewage (49 dt CaO/ha). Hence, changes of soil reaction achieved by amelioration with ash (500 m^3/ha) remained above pH 5,0 in 35 cm soil depth since 1962. PH values in the underlying soil layer gradually increased (Figure 3). The correctness of SBB as a method to determine the lime requirement of sulfurous mine soils has been proved within numerous field experiments (Illner and Katzur, 1968; Katzur, 1971; Lorenz, 1967a; Haubold *et al.*, 1993).

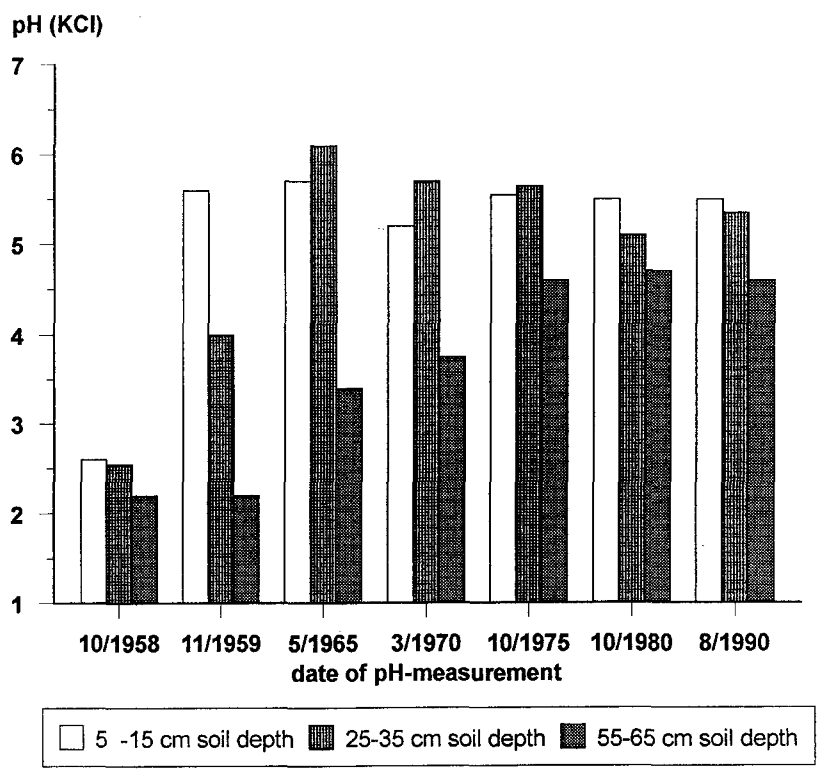


Fig. 3. Development of pH values after sewage sprinkling on a minesoil ameliorated with brown coal ash to a depth of 20 cm.

The success of post mining reforestation further depends on the thickness of the ameliorated soil layer. During the first years of recultivation roots of most tree species only penetrate the ameliorated horizon (Lorenz, 1967b). Therefore, a deep amelioration has positive effects on forest growth and stability of forest ecosystems. The enlargement of the root zone improves nutrient and water supply, reduces root competition, diminishes susceptibility to windbreak and multiplies the possibilities of silvicultural design.

The ameliorative application of CaO is given as lime fertilizers or base-rich brown coal ash. Application of ashes is recommended if more than 400 to 500 dt CaO/ha are necessary in order to ameliorate a 100 cm thick soil layer. Even a very high lime requirement may be covered with one ash application. Slow weathering of the ash (especially if it contains Ca-silicates) and a lasting release of bases cause a sustained liming effect. Moreover, ashes contain considerable amounts of magnesium and potassium and therefore, improve the nutrient supply of mine soils. Additionally they cause meliorative effects on soil structure. Disadvantageous is the considerably changing composition of ashes and its sometimes high boron content. Therefore, the decision to apply a special ash for amelioration should only be taken after its complete examination.

The rate of the ameliorative ash application depends on the lime requirement of the minesoil and on the soil affecting base content of the ash. The bas-active substance of the ash is calculated from HCl-extract (CaO and MgO) and sulfur content and is specified in % CaO (Illner and Raasch, 1967). Comparable results are achieved with the HCl-hydrolysis-method (Illner *et al.*, 1970). Also, the ash should be analysed for free and easily hydrolyzable CaO in order to estimate the mode of action of the ash.

The applied ash or lime fertilizer has to be mixed with the minesoil as intense as possible down to the aspired soil depth. Since success of reclamation also depends on the distribution of ash or lime fertilizer in the cultivated soil layer, technical execution of soil amelioration requires the same attention as the determination of lime requirement. Newer investigations show that amelioration horizons of 100 cm thickness may be produced with nowadays disposable soil working tools.

Amelioration of sulfurous and carboniferous mine soils is always combined with mineral fertilization. In case of reforestation of ash ameliorated mine soils, basic fertilization is 100 - 150 kg N/ha, 25 - 50 kg P/ha and 100 - 150 kg K/ha, according to the carbon content of the soil. In case of amelioration with lime fertilizers application of K has to be raised up to 150 - 200 kg/ha. Nitrogen fertilizer has to be applid twice. The second application is spread in June of the planting year or in April of the following year. Mineral fertilizer is worked into the topsoil to guarantee its uptake by the woody plants.

4. Reforestation

Analysis of tree species distribution and age structure of forest stands on dump sites in the Lower Lusatia (Kleinschmidt, 1994) reveals developments, which are in clear relation with perception progress achieved by ameliorating sulfurous mine soils. First experiments aiming in reforestation of sulfurous mine soils trace back to Copien (1942), Heusohn (1928, 1930, 1935 and 1947), Eichinger (1931), Kraemer (1935) and Mampel (1929). First of all liming was practiced (Eichinger, 1931; Copien, 1942), but the results differed strongly. Best recultivation results were found after treating plant holes with brown coal ash (one or two shovels per plant hole) (Heusohn, 1935 and 1947; Copien, 1942; Kraemer, 1935; Peters, 1930; Teumer, 1931). Soils treated in that way were mainly afforested with weeping birch (Betula pendula), grey and black alder (Alnus incana, A. glutinosa) and sometimes with northern red oak (Quercus rubra). Thus the "birch phase" of post mining reforestation was started. It nearly lasted until 1960, so that almost 75 % of the birch forests on dump sites belong to the age class of 31 to 60 years (Figure 4).

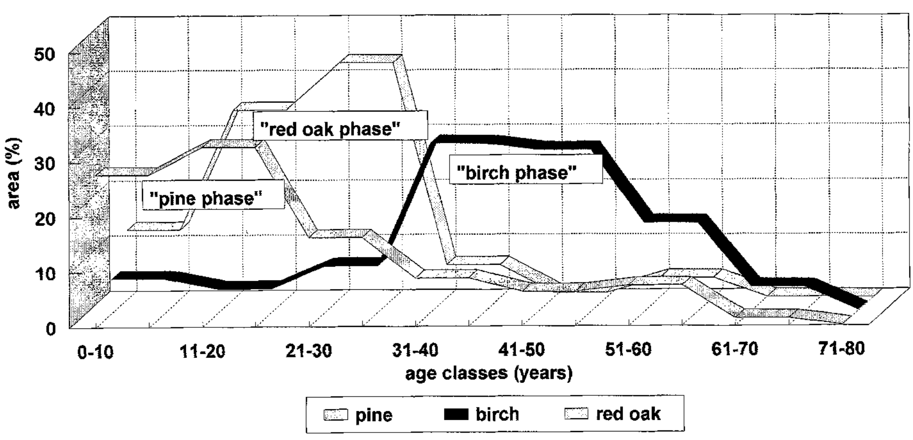


Fig. 4. Age class distribution of main tree species on dumps in the Lusatian lignite mining district.

In the 1950's Knabe (1954, 1959a and b, 1960) developed the so called "Schwarzkollmer" and "Domsdorfer Verfahren" as useful methods for reforestation of sulfurous mine soils, using brown coal ash (300 - 700 m^3/ha) for large-area amelioration. Dump sites fertilized with N, P an K and ameliorated with ash could be afforested without big difficulties although distinct guiding-lines for the calculation of ash application were missing. Afforestation experiments with northern red oak and poplar (Populus spec.) and admixtures of black alder, small-leaved lime and many shrub species turned out to be very successful. As a consequence afforestation areas with northern red oak increased very quickly and therefore, the area percentage of the age classes of 11 - 20 and 21 -30 years among northern red oak stands on dumps is 75 %. The "northern red oak phase" nearly lasted until 1980 and was slowly replaced by the "pine phase" since 1970. After the problem of amelioration of sulfurous mine soils had been solved, first afforestation experiments with red pine (Pinus sylvestris) were carried out. The pines showed good or very good growth even continuing in the pole stage. Since in the meantime a considerable backlog demand for the recultivation of sulfurous mine soils occured, so that these areas were intensively afforested with red pine since 1970. At the same time cultivation experiments with larch (Larix eurolepis, L. decidua), small-leaved lime (Tilia cordata), sessile oak (Quercus petraea) and European black pine (Pinus nigra) were carried out (Figure 5).

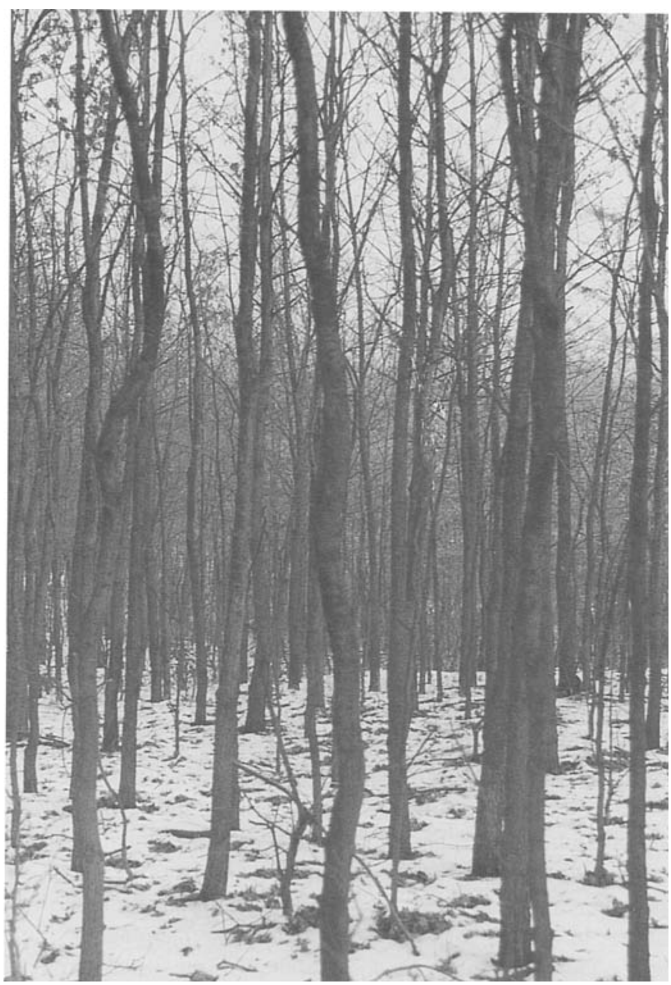


Fig. 5. 25 years old sessile oak stand (I growth class) on a carboniferous mine soil (loamy sand) ameliorated with ash to a depth of 60 cm.

Research work on reforestation of mine soils came to a temporary end in 1974 after 15 types of growing-stock objectives had been elaborated for the brown coal district of Lusatia (Lorenz and Kopp, 1968). Afforestations aimed in covering the soil surface as quickly as possible, protecting it from erosion, making soil deeply accessible for intense rooting and enriching it with high-grade humus substance thus advancing bioactivity. Planting multi-species stands with two or more tree species and especially mixtures of coniferous and deciduous tree species complementing each other is advantageous. It is now the task of the forester to choose those tree species and mixtures which are best adapted to the special site conditions on dumps and tips and may fulfil the multiple functions of growing forests.

5. Soil Development under Forest

Without measures of amelioration and reclamation, sulfurous mine soils from Tertiary parent material remain barren of vegetation for decades and are subject to continuous acid release, mineral destruction and nutrient or salt leaching into the subsoil.

After amelioration and afforestation, soil development first leads to formation of Regosols. Thereby direction and velocity of pedogenesis are mainly determined by soil texture, soil reaction, sulfur and carbon content and mineral composition of substratum as well as by planted tree species and tree species compositions.

Amount and quality of the litter are controlling the development of humus. Under pine and especially larch thick organic surface layers are formed with initially little shares of fine organic substance and indistinctly marked Oh-horizon indicating the formation of raw humus. Products of litter decomposition are mainly low-molecular organic acids which are leached. There are only few earthworms. In general, fine organic substances are not noticeably incorporated into the topsoil. As a consequence under coniferous trees high percentages of C_t and N_t are accumulated in the organic surface layer (Table II). This tendency is strongest in soils which are dry and poor in clay, silt, coal, minerals and nutrients. In ameliorated mine soils which are more cohesive, richer in coal and which have a better water retention capacity and nutrient availability, conditions are more favourable for the formation of stable humus substances and clay-humus complexes. An improvement of litter decomposition and humus development is the establishing of multi-species stands (e.g. larch and small-leaved lime). Often the C/N-ratio is atypically low (20 - 25) because of immissions (power plants, traffic, agriculture) and fertilization; so the formation of organic surface layers may also be caused by the extreme phosphorus deficiency of sulfurous mine soils.

In hardwood stands bioactivity in the topsoils is higher, litter decompostion and formation of stable humus substances are better. Under lime, poplar or birch more favourable conditions are found than under sessile oak or northern red oak. The organic surface layer is richer in fine humus, the Oh-horizon turns into the Ah-horizon without clear deviding line. In 30 year old stands the tendency of moder or mull formation is clearly perceptible.The Structure of topsoils shows transitions from single-grain to subpolyhedron structure. Crumb structure and worm pellets occur more often.

After amelioration, additions of coal have a positive effect on the percentage of plant-available moisture and on the nutrient exchange capacity.

TABLE II

Carbon and nitrogen accumulation as well as bioactivity in organic surface layers and topsoils of forest stands on dump sites in Lower Lusatia

		Tertiary substratum, amelioration with ash				Quaternary sub.
tree species:		P.sylvestris	Q.rubra/ T.cordata	Populus nigra	P.sylvestris	P.sylvestris
age [years]:		27	31	29	22	35
clay + silt [m.-%]:		15-30	15-30	15-30	2-10	2-10
skeleton [m.-%]:		2-15	2-15	2-15	2-15	15
C_t [m.-%]:	Of/Oh-hor.	35.9	28.9	20.5	30.2	31.5
	Ah-hor.	8.0	6.0	10.4	4.3	2.9
	jY_1-hor.(-30 cm)	5.8	5.5	6.3	2.8	0.2
N_t [m.-%]:	Of/Oh-hor.	1.66	1.27	0.97	1.4	1.19
	Ah-hor.	0.29	0.23	0.36	0.14	0.10
	jY_1-hor.(-30 cm)	0.17	0.13	0.13	0.07	0.01
accumulation [kg x ha^{-1} x a^{-1}]:						
C	Of/Oh-hor.	610	510	450	330	530
	Ah-hor.	450	450	750	280	300
	sum	1060	960	1200	610	830
N	Of/Oh-hor.	28	22	21	15	20
	Ah-hor.	22	21	35	7	10
	sum	50	43	56	22	30
maximum rate of substrate induced respiration, MIR [µg CO_2 x g^{-1} x d^{-1}][1]						
	Of/Oh-hor.	2259	2870	3350	1870	1350
	Ah-hor.	250	820	1770	210	107
	jY_1-hor.(-30 cm)	95	177	485	95	78
catalase index[2]						
	Of/Oh-hor.	135	145	164	120	91
	Ah-Hor.	18	33	33	9	11
	jY_1-Hor.(-30 cm)	3	2	6	3	3

([1]MIR accord. to ANDERSON und DOMSCH 1978, [2]catalase index accord. to BECK 1971)

At the same time they serve as a substrate for the soil microflora and are mineralized and synthesized to new humus substances (Katzur, 1987; Laves *et al.*, 1993). Therefore, after amelioration humus balance and soil bioactivity of carboniferous and sulfurous mine soils are at least just as good as in carbon- and sulfur-free Quaternary soils with the same texture (Schwabe, 1970; Thum, 1978; Heinsdorf, 1992). Plant growth and thus litter fall and humus accumulation may be better.

Amelioration with brown coal ashes has a sustained positive effect on soil reaction and nutrient status of sulfurous mine soils. In ameliorated layers of stands examined up to now pH, CEC_{eff}/CEC_{pot}-ratio and base saturation remain improved even 30 years after ash incorporation (Table III). Soil reaction is in the carbonate buffer range and still buffering Ca- and Mg-ions are released out of the ash. As a consequence of dislocation of basic-active cations initially low pH-values (2 - 3) of the deeper subsoil are also improved. Thus the Al-concentration in the soil solution, which is typically high in sulfurous mine soils, disappears in favour of a higher Ca/Al-ratio. That explains the depth of root penetration beyond the ameliorated layer which could be observed in older stands. However, intensity of rooting is low, so that sufficient growth mainly of fastidious tree species is only achieved by amelioration to a depth of 60 cm. Amelioration depths of 20 - 30 cm e.g. have the consequence, that afforested poplar with low competitive ability is gradually replaced by natural seeding of birches (Figure 6). Therefore the creation of stable forest ecosystems demands an amelioration depth of at least 60 cm, better 100 cm.

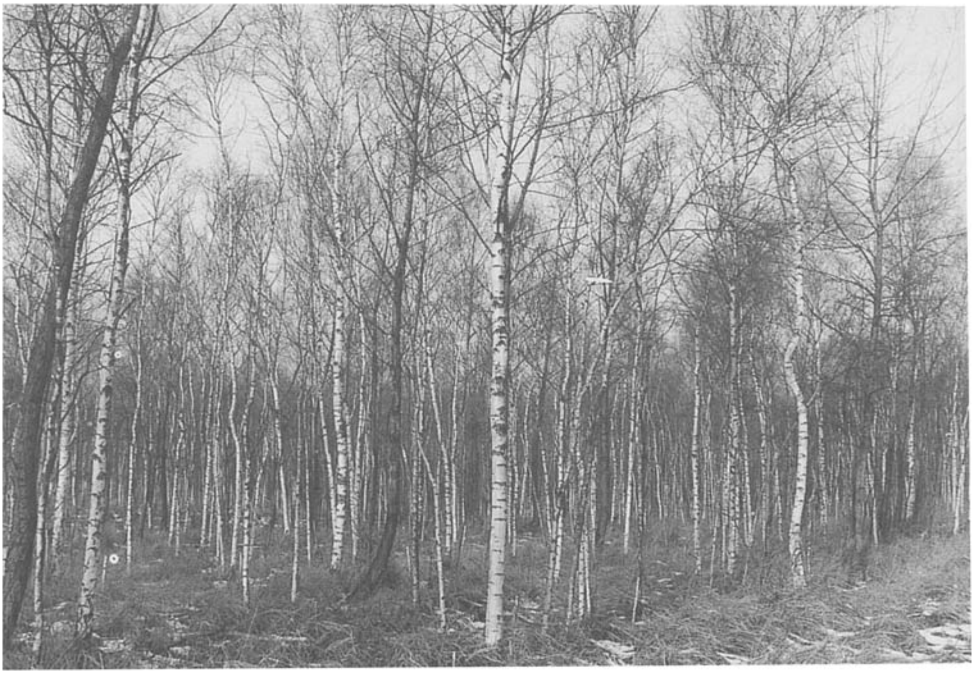


Fig. 6. Poplar stands (first afforestation in 1961) on mine soils ameliorated with brown coal ashes to a depth of 20-30 cm are replaced by gradual natural seeding of birches.

TABLE III

Soil chemical properties of ameliorated (incorporation of ash to a depth of 30 cm), sulfurous mine soils after 30 years of forestal land use

horizon	depth [cm]	CEC_{pot}	CEC_{eff} Σ [mmol (eq)/100g]	Na	K	Mg	Ca	base saturation [%]
Of-Oh	0 -+3	92.5	56.2	0.2	0.7	4.0	50.2	98
jAh	0 - 5	33.5	30.6	0.1	0.4	2.0	27.3	97
jY1	-30	25.7	14.8	0.2	0.1	0.4	13.1	92
jY2	-60	18.5	5.0	0.2	0.1	0.1	2.6	54
jY3	-90	18.2	6.6	0.1	0.1	0.1	3.3	51

horizon	depth [cm]	CEC_{eff} Mn [mmol (eq)/100g]	Fe	Al	H	pH (KCl)	pH	GBL Ca/Al
Of-Oh	0 -+3	0.20	0.0	1.0	0.0	5.5	6.7	40
jAh	0 - 5	0.04	0.1	0.8	0.0	6.0	7.3	30
jY1	-30	0.04	0.2	0.9	0.0	4.7	6.0	100
jY2	-60	0.04	0.4	0.7	0.9	3.6	4.0	40
jY3	-90	0.04	0.6	1.0	1.4	3.5	3.9	25

horizon	depth [cm]	Zn [ppm]	Cu	Cr	Ni	Cd
Of-Oh	0 -+3	74.1	22.4	12.2	13.1	0.635
jAh	0 - 5	17.3	14.0	8.3	8.0	0.160
jY1	-30	5.3	4.0	5.6	1.6	0.055
jY2	-60	7.4	4.0	4.1	2.6	0.060
jY3	-90	5.6	4.3	4.1	2.3	0.045

(CEC_{pot} accord. to MEHLICH; CEC_{eff} and equilibrium soil solution (GBL) accord. to MEIWES et al. 1984; heavy metals in aqua regia extract)

Beyond that, in the case of post mining reforestation the loosening effect of tree roots and the missing of field traffic result in lower bulk density and penetration resistance and in higher water and air permeability than in the case of agricultural land use (Table IV).

TABLE IV

Soil physical properties of sulfurous mine soils (total carbon: 3 - 5%).

horizon	depth [cm]	texture	R_t [g/cm^3]	pore vol. [%] Σ PV	>50µm	pen. res. [MPa]	k_a [µm^2]
a) after 30 years of forestal land use, n=2							
jAh	0-5	Sl3	0.92	63.4	28.9	1.0	61.1
jY1	-30	Sl2	1.15	54.3	23.0	1.7	22.7
jY2	-60	S	1.19	49.2	24.6	2.6	33.9
jY3	-90	S	1.18	53.7	25.4	2.5	30.2
b) after 25 years of agricultural land use, n=2							
jAp	0-30	Sl3	1.36	46.3	13.5	2.4	6.8
jY1	-60	Sl2	1.53	40.5	9.7	4.0	3.2
jY2	-90	Sl3	1.34	47.9	15.8	3.3	4.9

(R_t = dry bulk density; pen. res. = penetration resistance measured in soil sampling cylinders of 100 cm^3 at pF 2.5, probe diameter = 0.6 cm; k_a = air permeability accord. to KMOCH 1962)

The example of the examined sites shows furthermore (Table III), that there is no danger of heavy metal contamination if suitable brown coal ashes are selected.

6. Conclusion

Sulfurous and carboniferous mine soils remain vegetation-free for decades and may be cultivated only after soil amelioration. The objective of amelioration is a sustained improvement of soil reaction. Lime requirement for the achievement of a certain pH-value is calculated from the "acid-base-balance" (SBB). For amelioration lime fertilizers and base-rich brown coal ashes are used. In comparison with lime fertilizers brown coal ashes bear serveral advantages, so that their application is recommended for amelioration of sulfurous mine soils. The ameliorative application of lime fertilizer or brown coal ash should be incorporated intensively into the soil to a depth of 60 cm, better 100 cm. Amelioration includes a mineral fertilization with N, P and K. For reforestation, fertilizers are merely incorporated into the upper soil layer.

Afforestations with Pinus sylvestris, Pinus nigra, Larix decidua, Larix eurolepis, Tilia cordata, Quercus rubra and Quercus petraea on ameliorated mine soils show surprising good results. Multi-species stands have very positive effects on soil formation. Under pine and larch raw humus is formed and under deciduous trees moder and mull with higher bioactivity and better water and nutrient balance is found.

References

Anderson, J.P.E. and Domsch, K.H.: 1978, *Soil Biol.Biochem.*, **10**, 215.

Arkesteyn, G.J.M.W.: 1980, *Plant and Soil*, **54**, 119.

Beck, Th.: 1971, *Z. Pflanzenernähr. Düng. Bodenkd.*, **130**, 68.

Brüning, E.: 1959, *Untersuchungen zu Fragen der Begrünung tertiärer Rohbodenkippen des Braunkohlentagebaues, dargestellt am Beispiel der Hochabsetzerkippe 18 Böhlen*, Diss., Leipzig.

Brüning, E.: 1962, *Wiss. Zeitschr. K.-M.-Univ. Leipzig. Math.-Nat. Reihe*, H. **2**, 325.

Carruccio, F.T., Hossner, L.R. and Geidel, G.: 1988, *Reclamation of surface mined lands*, Vol. **1**, CRC Press, Boca Raton, 159.

Copien: 1942, *Zeitschr. f. Forst- u. Jagdwesen*, 74, 43 and 81.

Eichinger: 1931, *Gutachten über die bei Lauchhammer gelegenen Kippenflächen, Pförten/NL*, unpublished.

Haubold, W., Kästner, S., Markmann, N. and Rascher, J.: 1993, *Glückauf - Forschungshefte*, H. **1**, 35.

Haubold-Rosar, M., Katzur, J., Schröder, D. und Schneider, R.: 1993, *Mitteilgn. Dtsch. Bodenkundl. Gesellschaft.*, **72/II**, 1197.

Heinsdorf, D.: 1992, *Untersuchungen zur Düngebedürftigkeit von Forstkulturen auf Kippböden der Niederlausitz*, Habil.-Schrift, Dresden.

Heusohn, R.: 1928, *Braunkohle*, **27**, 985.

Heusohn, R.: 1930, *Bergbaul. Rundschau*, **4**, 113.

Heusohn, R.: 1935, *Praktische Kulturvorschläge für Kippen, Bruchfelder, Dünen und Ödländereien*, Neumann, Berlin.

Heusohn, R.: 1947, *Die Kultivierung roher Mineralböden*, Siebeneicher Verlag, Berlin - Charlottenburg.

Illner, K.: 1966, *Bergbautechnik*, **16**, 31.

Illner, K. and Katzur, J.: 1964 a, *Zeitschr. f. Landeskultur*, **5**, 287.

Illner, K. and Katzur, J.: 1964 b, *Bergbautechnik*, **14**, 522.

Illner, K. and Katzur, J.: 1968, *Bergbautechnik*, **18**, 423.

Illner, K., Katzur, J. and Raasch, H.: 1970, *Bergbautechnik*, **20**, 46.

Illner, K. and Raasch, H.: 1967, *Zeitschr. f. Landeskultur*, **8**, 171.

Illner, K. and Sauer, H.: 1974, *Neue Bergbautechnik*, **4**, 34.

Katzur, J.: 1965, *Untersuchungen über die Rekultivierung von schwefelhaltigen Tertiärkippen unter Verwendung phenolhaltiger Kokereiabwässer*, Diss., Berlin.

Katzur, J.: 1970, *Die Wiedernutzbarmachung der durch die Industrie devastierten Territorien*, IV. Internationales Symposium, II., Leipzig, 238.

Katzur, J.: 1971, *Die Bodenmelioration extrem saurer Kipprohböden*, Diss. (B)., Berlin.

Katzur, J.: 1977 a, *Technik und Umweltschutz*, H. **18**, 52.

Katzur, J.: 1987, *Arch. Acker-Pflanzenb. Bodenkd.*, **31**, 239.

Katzur, J.: 1988, *Schutz und Nutzung des Bodens*, Kolloquium des Institutes für Pflanzenernährung Jena, H. **3**, 147.

Katzur, J.: 1992, *Stoffrachten der Sickerwässer und Entwicklung des Entsorgungspotentials landwirtschaftlich genutzter Kippböden*, BMFT Förderprojekt 0339392A (Teil-Abschlußbericht). Forschungsinstitut für Bergbaufolgelandschaften e. V. Finsterwalde.

Katzur, J. and Zeitz, J: 1985, *Arch. Acker-Pflanzenb. Bodenkd.*, **29**, 195.

Kleinmann, R.L.P., Crerar, D.A. and Pacelli, R.H.: 1981, *Mining Engineering*, **33**, 300.

Kleinschmidt, L.: 1994, *Ermittlung, Darstellung und Bewertung der Standortgrundlagen der forstlich genutzten Kippenflächen der Niederlausitz*, Forschungsinstitut für Bergbaufolgelandschaften, unpublished.

Kmoch, H.G.: 1962, *Die Luftdurchlässigkeit des Bodens. Ihre Bestimmung und ihre Bedeutung für einige ackerbauliche Probleme*, Gebr. Borntraeger, Berlin.

Knabe, W.: 1954, *Forst und Jagd*, **9**, 229.

Knabe, W.: 1959 a, *Zur Wiederurbarmachung im Braunkohlenbergbau*, VEB Deutscher Verlag der Wissenschaften, Berlin.

Knabe, W.: 1959 b, *Bergbautechnik*, **9**, 173.

Knabe, W.: 1960, *Hilfe durch Grün*, H. **9**, 27.

Kopp, E.: 1960, *Der Einfluß der organischen kohlehaltigen Beimengungen auf den Kulturwert der pleistozänen und miozänen Deckgebirgsmassen der Niederlausitzer Tagebaue*, Diss., Berlin.

Kraemer, C.: 1935, *Kultivierung von Abraumkippen der Braunkohlengruben der Nieder-lausitz*, Diss., Breslau.

Laves, D., Franko, U. and Thum, J.: 1993, *Arch. Acker-Pflanzenb. Bodenkd.*, **37**, 211.

Lorenz, W.-D.: 1967 a, *Untersuchungen über die Wiederurbarmachung von kulturfeindlichen Kippen nach dem Domsdorfer Verfahren*, Diss., Berlin.

Lorenz, W.-D.: 1967 b, *Veröff. d. Inst. f. Landschaftspflege der Humboldt-Univ. Berlin*, H. **1**, 44.

Lorenz, W.-D. and Kopp, D.: 1968, *Veröff. d. Inst. f. Landschaftspflege*, Humboldt-Univ. Berlin, H. 1968/II, 1.

Mampel, W.: 1929, *Braunkohle*, **28**, 596.

Meiwes, K.J., König, N., Khana, P.K., Prenzel, J. and Ulrich, B.: 1984, *Berichte des Forschungszentrums Waldökosysteme/Waldsterben*, 7, Göttingen.

Peters: 1930, *Zeitschr. f. Berg-, Hütten- und Salinenwesen*, **78**, B 191.

Pugh, C.E., Hossner, L.R. and Dixon, J.B.: 1984, *Soil Sci.*, **137**, 309.

Schwabe, H.: 1970, *Ergebnisse der forstlichen Rekultivierung auf vorwiegend kultur- feindlichem Abraummaterial des Braunkohlenbergbaues in der Niederlausitz*, Diss., TU Dresden, Tharandt.

Schwartz, W.: 1964, *Gutachten über das Vorkommen von Thiobacillus-Arten im Kippengelände und über die Beziehungen zur Rekultivierung*, Greifswald, unpublished.

Stumm, W. and Morgan, J.J.: 1981, *Aquatic chemistry*, Wiley & Sons, New York.

Teumer, TH.: 1931, *Der geologische Gebirgsaufbau im Niederlausitzer Braunkohlenrevier in seiner Bedeutung für die Profilangaben der Bohrmeister und bei der Wiedernutzbarmachung der Abraumkippen*, Mitteilgn. d. Senftenberger Heimatmuseums.

Thomas, S.: 1969, *Untersuchungen über die Feuchtigkeitsverhältnisse von Kipprohböden des Braunkohlenbergbaues in der Niederlausitz*, Diss., Berlin.

Thum, J.: 1978, *Arch. Acker-Pflanzenb. Bodenkd.*, **22**, 615.

Wünsche, M., Lorenz, W.-D., Oehme, W.-D. Und Haubold, W.: 1972, *Die Bodenformen der Kippen und Halden im Niederlausitzer Braunkohlenrevier*, Mitteilung Nr. **15**/72 aus dem VEG GFE Halle, BT Freiberg, Senftenberg.

Wünsche, M. *et al.*: 1981, *Neue Bergbautechnik*, **11**, 42.