A history of lignite coal mining and reclamation practices in Lusatia, eastern Germany

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[1]Brandenburg University of Technology, Konrad-Wachsmann-Allee 6, 03046 Cottbus, Germany (e-mail: kruemmel@tu-cottbus.de); [2]Helmholtz Centre Potsdam, GFZ German Research Centre for Geosciences, Telegrafenberg, 14473 Potsdam, Germany; and [3]Department of Renewable Resources, University of Alberta, Edmonton, Alberta, Canada T6G 2H1. Received 13 December 2010, accepted 30 August 2011.

Krümmelbein, J., Bens, O., Raab, T. and Naeth, M. A. 2012. **A history of lignite coal mining and reclamation practices in Lusatia, eastern Germany**. Can. J. Soil Sci. **92**: 53–66. Germany is the world's leading lignite coal producer. The region surrounding the towns of Cottbus and Senftenberg in Lusatia, Eastern Germany, is one of the largest mining areas in Germany, and has economically been strongly dependent on lignite mining and lignite processing industries since the middle of the 19th century. We introduce the area, give a brief historical overview of lignite mining techniques and concentrate on post-mining recultivation (reclamation) to agricultural and forestry dominated landscapes. An overview of the physical and chemical limitations for reclamation of the Tertiary and Quaternary substrates due to their natural composition and the technical processes of mine site construction is provided. We introduce some recultivation practices and end with a display of land uses before and after mining and an outlook on the future use of the reclaimed landscape. This review serves as a defined perspective on long-term coal mine reclamation from which to address global similarities and contrasts.

Key words: Recultivation, brown coal mining, pyrite, soil properties, amelioration, reclamation

Krümmelbein, J., Bens, O., Raab, T. et Naeth, M. A. 2012. **Historique de l'extraction de la lignite et pratiques de restauration des sols en Lusace (Allemagne de l'est)**. Can. J. Soil Sci. **92**: 53–66. L'Allemagne est le plus grand producteur au monde de houille brune ou lignite. La région qui entoure les villes de Cottbus et de Senftenberg, en Lusace (Allemagne de l'Est), est l'une des principales zones minières du pays et son économie dépend lourdement de l'extraction et de la transformation de la lignite depuis le milieu du XIX[e] siècle. Les auteurs présentent la région et donnent un bref historique des techniques d'extraction minière de la lignite avant de se concentrer sur la remise en valeur des terres pour l'agriculture et la foresterie après exploitation du sous-sol. Ils offrent un aperçu des contraintes physiques et chimiques associées à la restauration des substrats du Tertiaire et du Quaternaire attribuables à la composition des sols et aux techniques d'aménagement des mines. Les auteurs présentent quelques pratiques de remise en valeur et concluent par une présentation sur la vocation des terres avant et après l'exploitation minière, en donnant un aperçu de l'usage futur des sols restaurés. Cet examen donne une perspective précise de la restauration à long terme des mines de charbon, de manière à faciliter la restauration dans des conditions similaires ou différentes dans le monde.

Mots clés: Remise en valeur, extraction de la houille brune, pyrite, propriétés du sol, amélioration, restauration

Although Germany's output of brown coal has declined significantly in the past 20 yr (Statistik der Kohlewirtschaft e.V. 2009; Bundesanstalt für Geowissenschaften und Rohstoffe 2009), it is still the leading lignite producer in the world. In 2007, the year for which the most recent data are available, Germany had mined 180 million tons of brown coal, over twice as much as the next highest producer (Table 1).

Coal mining in Germany is distributed over the three main areas of Rhineland, Central Germany and Lusatia, The region surrounding the towns of Cottbus and Senftenberg in Lusatia, eastern Germany, is one of the largest mining areas in Germany and has been strongly economically dependent on lignite mining and lignite processing industries since the middle of the 19th century, after lignite deposits were discovered at the end of the 18th century (Großer 1998; Schulz 2000) (Fig. 1). The total mined area is approximately 85 000 ha (Statistik der Kohlewirtschaft e.V. 2009), with zan additional 30 000 ha (Vattenfall Europe AG 2009) approved for mining. These former and ongoing mining areas present a tremendous challenge for recultivation (reclamation).

Several German terms will be used in this review. Recultivation is the literal translation of the German word *Rekultivierung* and is used synonymously with the term reclamation in Canada. Forestal is the literal translation of the German word *forstlich* and refers to a return to forested areas or afforestation. Recultivation does not rely on natural succession of an area. Forestal recultivation includes planted forest systems in which the trees are harvested and used as timber or as an energy source. Agroforestry systems, such as alley cropping, are part of the forestal reclamation scenario. The wood from these systems is mostly used as woodchips for heat, energy and paper production.

Table 1. Annual production of brown coal in 2007 (modified from Bundesanstalt für Geologie und Rohstoffe 2009)

Country	Million tons
Germany	180.0
Australia	72.3
Russia	71.3
USA	71.2
Turkey	70.0
China	70.0
Greece	64.4
Poland	57.5
Czech Republic	54.4
Serbia	36.5

Fig. 1. Lusatian lignite mining district surrounding Cottbus: Geographical position within Europe, Germany and the Federal German State of Brandenburg.

Agricultural recultivation includes agricultural crops such as forages and cereals.

PHYSIOGEOGRAPHIC CHARACTERISTICS OF LUSATIA

Geology, Geomorphology and Climate

The Lusatian lignite developed about 15 to 20 million years ago from the subtropical bog forests of the early Tertiary (Miocene) (Großer 1998). At this time, abundant peat deposits built up on lignite free Tertiary layers. During the following ice age those deposits were covered by glacial till of advancing glaciers and sediments originating from melting processes. The thickness of this covering layer varies from approximately 10 to 150 m. Lignite developed under the pressure of this overburden.

The natural appearance of the Lusatian landscape is mainly due to Quaternary processes. In the north the branches of the second Lusatian lignite seam reach the terminal moraines and outwash plains of the Brandenburg stage of Weichselian glaciation (Nowel 1992; Pflug 1998). In the south and southeast, the lignite seam reaches areas of older moraines (Saale I and Saale 2 glaciations) of western and southern Lower Lusatia. The central geomorphologic element of the region is the terminal moraine of Saale III glaciation, also called the Lusatian Land Ridge. The Lusatian Land Ridge is accompanied by a complex of moraines, plateaus and reservoirs of earlier Saale glaciations. Streams of melt water shaped two glacial valleys, one north of the Lusatian Land Ridge (Baruth Glacial Valley), and one south of it (Lusatian or Breslau-Magdeburg Urstromtal) (Fig. 2). Periglacial and post-glacial development induced formation of dune and sand drift areas up to 30 km^2 in size. In the Lusatian Glacial Valley some larger fens developed. The highest elevation of the area, 138 m above sea level, is situated east of the Lusatian Land Ridge (Döbern). The bottom of the Baruth Glacial Valley has an elevation of about 50 m above sea level, the Lusatian Glacial Valley between 145 and 92 m above sea level (Großer 1998).

The lignite layer that is mined today is approximately 10 to 20 m thick and is covered by 40 to 120 m of Tertiary and Quaternary substrates, consisting of sands and gravel interspersed with silts, clays and glacial till. The relatively small amounts of cohesive Quaternary material such as silt and glacial till are usually mined selectively to be used later to recultivate (reclaim) the post-mining areas (Pflug 1998).

The Lusatian lignite-mining area belongs to the warm continental areas of the lowlands of northeastern Germany. Due to the general north hemispheric circulation pattern the main wind direction is west (Graf 1994), but strong east winds can occur, caused by quasi stationary high-pressure areas located on the Eurasian land mass. Especially in winter the Siberian High forms a relatively stable pressure, building for weeks to months, and can produce cold and dry winds with high erosive capacity. Mean annual temperature is 8.5°C, mean annual precipitation (1990 to 2008 long-term mean) is 707 mm (Deutscher Wetterdienst 2011). About half of the precipitation occurs during the growing season from March to September. Summers can have weeks or even months with hot and dry periods because most precipitation occurs as short convective rain showers. Thus, climatic conditions, in combination with the widely distributed sand-rich substrates, enhance the natural risk for edaphic drought. Opencast mining influences the regional climate. For example, at relatively low wind speeds, these huge areas, which are generally free of vegetation, lead to lower temperatures during the night and higher temperatures during the day (Regionaler Planungsverband Oberlausitz-Niederschlesien 1994).

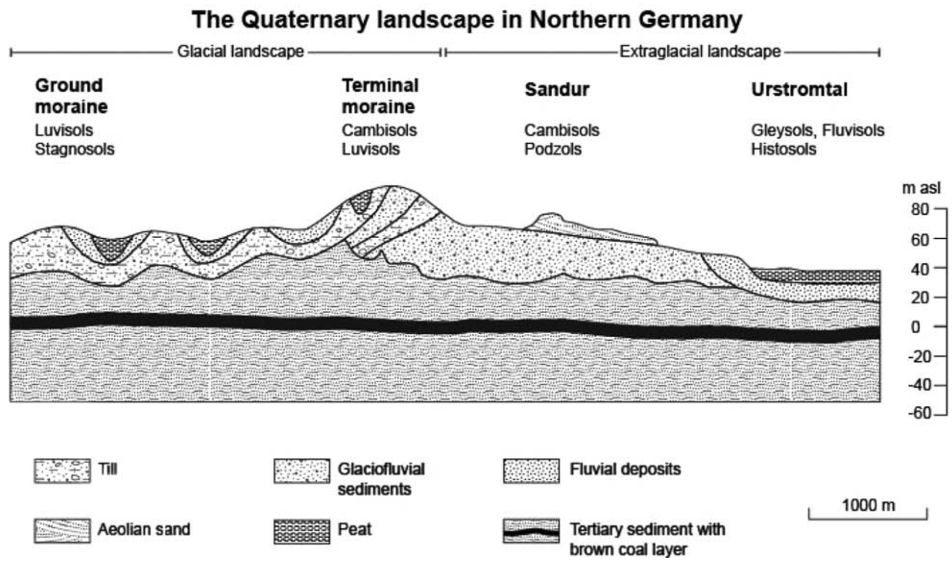

Fig. 2. Glacial sequences of Northern Germany. Modified figure according to Schmidt (1991).

Soils and Potential Natural Vegetation

The Slavic word *Lusatia*, roughly translated, means swampland. Accordingly, in Lusatia various extensive bogs with comparatively small peat depths can be found. Fens within the ground moraines and dead ice areas are smaller but numerous and have comparatively high peat depths. Most of the former fens and bogs have been intensively degraded by human activities, especially by ground water lowering and drainage to enable agriculture. Of the former 300 000 ha of fen meadows in Brandenburg, only 210 000 ha remain and are mostly used as extensive grassland (Landesumweltamt Brandenburg 2009).

In lowland areas where no fens developed, different gleysols can often be found, mostly in the glacial valleys where ground water is only a few decimetres below the surface. Transitional luvisolic and podzolic soils are common. With lowering of the ground water table by mining, many fens, bogs and gleysols were degraded. *Relictische* soils formed; these are soils subjected to current conditions, but which historically developed under different conditions. In this case relict gleysols which developed under the influence of ground water are no longer influenced by ground water and will undoubtedly change with time.

Most of the soils in Lusatia are located on melt water sand areas and are characterized by intense drought, especially in summer. They are rich in quartz and feldspar, which, in combination with the dryness, induces a very low supply of nutrients due to weathering. Soils that developed were mainly luvisols with podzolic features. The low amounts of precipitation mostly prevented the formation of podzols, except in dune and pine forest areas. In comparison with the soils described above, soils of ground moraine areas with glacial till as parent material are relatively fertile. Soils with stagnic or gleyic features are common (Lippstreu et al. 1997; Stackebrandt and Manhenke 2002).

The potential natural vegetation in Lusatia covers various moor types according to the original water and nutrient supply (Großer 1998). Today, most of the fens and bogs are severely degraded and no longer reflect the former natural vegetation. Only relict parts of the former flood plain and marshland forests can be found. At drier locations, different oak forest types are present, according to the nutrient and water supply of the soil. Oak pine forests are most common. On very sandy locations, such as dunes, natural pine forests have developed.

HISTORICAL OVERVIEW: LIGNITE MINING IN LUSATIA

Lignite, or brown coal, was discovered in eastern Germany at the end of the 18th century. First it was mined in open pits, which developed into small scale under ground mines. Around 1900 the first large-scale opencast surface mines were established (Pflug 1998). This technique is still used, with the mines continuously increasing in size (Weber et al. 1999). In the 1940s lignite became the most important primary energy source of the German Democratic Republic and the region around Cottbus became an economically important centre for lignite mining and electricity production (Großer 1998).

Until the 1970s mining activities were in pace with recultivation capacity of the German Democratic Republic. Later, as mining production constantly increased, total recultivation of the mined areas was no longer possible, which lead to large-scale unreclaimed areas. After 1996, the total annually reclaimed area was considerably larger than the annually mined area (Drebenstedt 1998).

Mining and recultivation areas, depending on the origin (Tertiary, Quaternary) and on the constituents (lignite, pyrite) of the substrates, had negative effects on soils, water, air, flora and fauna (Hüttl 1998; Pflug 1998). Mining induced a dramatic increase in land consumption and created huge areas with a lowered ground water table (Pflug 1998; Weber et al. 1999). The area affected by ground water lowering was about 2100 km^2 in 1992 (Möckel 2002). At the outer edge of the cone of depression in a mine site, the ground water level is about 1 m below surface. In the middle of the area, ground water reaches depths below the brown coal seam; in Lusatia this is between 60 and 100 m. The ground water discharges into the river Spree and artificially raises its water level (Arnold and Kuhlmann 1993). In 1998 approximately 80 000 ha of arable and forested land were affected by mining activities (Hüttl 1998).

The conveyor bridge technology was invented in the Lusatian lignite mining district in 1924 and induced the complete mechanization of mining. Conveyor bridges are still used today and the transport capacity of the systems has increased constantly (Katzur and Böcker 2010). With this method, sandy overburden sediments covering the coal seam are generally excavated and dumped in one step. In the three active mines around Cottbus (Jänschwalde, Welzow South, Nochten), the conveyor bridge can take 60 m of overburden at a time, which is then dumped on a spoil pile at the rear end. During this procedure, the various Quaternary and Tertiary overburden substrates are mixed and aerated, resulting in oxidation, particularly of pyrite (Hüttl and Weber 2001). It has not been technically feasible to separate pyrite containing and pyrite-free substrates from each other, thus the recultivated sites constructed during those times often consist of a mixture of the substrate types (Katzur 1998). Since 1990, the recultivation sites must be covered with 2 m of lignite- and pyrite-free substrate according to German law (Wilden 2000).

CHEMICAL AND PHYSICAL RECULTIVATION SUBSTRATE LIMITATIONS

Tertiary Pyrite Containing Substrates

The carbon content of lignitic and pyritic substrates is due to the brown coal and not recent organic matter (Gast 2003). Carbon content is highly variable within and between sites in Lusatia and is positively correlated with nitrogen and sulphur concentrations. The brown coal fragments induce uncommonly high cation exchange capacities. During excavation of the pyrite-containing sediments, and later due to their deposition, the pyrite is oxidized, leading to iron (II) ions and sulphuric acid. Pyrite oxidation can be divided into chemical, microbial catalyzed chemical and microbial. Due to these processes, pH can drop to below 2 (e.g., Weber et al. 1999). Pyrite oxidation leads to severe acidification of substrate surfaces and creates a hostile environment for plants if it is not ameliorated, such as by liming. Pyrite oxidation takes place not only at the surface of the dumped substrates, but also inside the deposited structures (Weber et al. 1999).

Hangen (2003) investigated preferential flow patterns that developed at afforested lignitic sites. He applied multitracer infiltration experiments in 10-cm increments and determined parameters of the substrate that may influence flow paths, such as root density, water repellency and bulk density. He found that water infiltrated preferentially at distinct spots and redistributed at a depth of 10 cm. At 20 cm, preferential flow fingers developed and persisted to a depth of 150 cm. Among the parameters investigated he could not determine one prevailing factor for development of the described preferential flow patterns. The flow patterns showed a high temporal variability. This was partly attributed to stationary factors (e.g., dumping structures within the profile) and partly to variable factors (e.g., soil water content), which influenced the prevailing water repellency.

The amount of acidification and acid drainage production depends on the pyrite content in the substrate (Neumann 1999) and on precipitation and hydraulic conductivity. The acid drainage of these sites frequently contains high concentrations of iron and heavy metals (Vanberk and Wisotzky 1995), which can limit the establishment of a sustainable ecosystem in the recultivated area. Pyrite oxidation is the main pedogenetic process at reclaimed sites where Tertiary pyritic substrates have been used for site establishment (Neumann 1999). Percolation of acidic oxidation products can lead to severe ground water acidification and acidification of the lakes which remain as relicts of the open cast mines (Weber et al. 1999).

Quaternary Substrates

Quaternary substrates do not contain lignite or pyrite and, thus, there is usually no acid drainage developing from these substrates. They are therefore often used to cover Tertiary substrates or mixes of Tertiary and Quaternary substrates that have been deposited at the base of the recultivation site. The Quaternary substrates are mostly sandy and have comparatively high concentrations of calcium carbonate (Stock et al. 2007a; Krümmelbein et al. 2010). Substrates with cohesive properties can only be found in areas of former terminal and ground moraines and in smaller and isolated lenses. With the excavators and stackers used in Lusatia, it is generally not feasible to separate cohesive material from the sandy substrates for systematic formation of an upper layer suitable for agriculture or forestry. The Quaternary sandy substrates used to cover lignitic and pyritic substrates and to create a surface suitable for agricultural and forestal recultivation tend to severe hard setting (Stock 2005). Due to increasing pore water suction during dry periods, mechanical stability of the soil can be so high that penetration of the soil by plant roots or soil tillage operations is restricted and sometimes impossible. This hard-setting behaviour is attributed to soil particle size (texture); the fine sand and silt allow quite high tensile stresses to be transferred between mineral soil particles by concave water menisci. Another reason for the very high mechanical stability in a dry state is cementation of coarser soil particles with calcium carbonate and silt and clay particles.

Quaternary and Tertiary substrates have very low mechanical stabilities in a wet state. Stock et al. (2007a) showed that especially with Quaternary substrates, stability is so low that water saturation provokes a consolidation of the substrate only by forces induced by water menisci between particles and the weight of the water. Krümmelbein et al. (2010) showed that an agricultural recultivation site constructed with Quaternary substrates exhibited relatively low precompression stress between 40 and 60 kPa even at very high bulk densities up to 1.9 Mg m^{-3}.

Mixtures of Tertiary and Quaternary Substrates

Until the beginning of the 1990s, the substrates used for recultivation of post-mining landscapes were very heterogeneous mixtures of Tertiary and Quaternary substrates. Due to the high contents of pyrite in Tertiary substrates, they tended to be severely acidic. The dumped soils or substrates were characterized by a random dumping of different substrates and different chemical and physical properties depending upon the proportion of Tertiary and Quaternary contents (Böhm 1994).

General Substrate Properties

The lignite- and pyrite-containing substrates and substrates free of those materials mostly have a sandy texture, low recent organic matter content and low nutrient status (Wilden 2000). All substrates used for recultivation are structureless, have no soil development and have undergone several treatments, such as excavation, transport deposition, dumping and levelling, which induced large mechanical stresses (Krümmelbein et al. 2010). Stock (2005) showed that the technical processes described above led to modification of the original coherent structure of the substrates before they were excavated to a single grain structure. The single mineral particles are far more movable than before when they had a cohesive structure. Due to drying processes and increasing forces transferred by water menisci, soil particles rearrange spatially, which enhances mechanical stability of the matrix. The hard-setting behaviour of a soil or substrate is enhanced by intense drying. This can be due to climate conditions and/or water consumption by plants. In contrast with the behaviour of the soil or substrate under dry conditions, Stock et al. (2007b) showed that recultivation substrates are very unstable in wet conditions and tend to compact even by water menisci and the weight of the water.

Similar behaviour is reported for typical hard-setting soils in Australia and Africa (Mullins et al. 1987, 1990), which are also mechanically very stable and hard during dry periods and very unstable and soft in a wet state. This behaviour is attributed to textural composition of the substrate, which contains swelling and shrinking clay too small to induce crack and structure formation. However, the silt and clay particles, which fit into the voids between the sand grains, are high enough to cement the sand grains without forming a continuous fine-textured matrix.

Due to the processes of substrate formation by mining described above, the recultivation sites display very heterogeneous physical properties. Depending on substrate water content during excavation, transport, deposition and levelling and the number of wheelings (passes with machinery) during surface levelling, the mechanical forces induced are spatially very heterogeneous. Krümmelbein et al. (2010) showed that soil bulk density, saturated hydraulic conductivity and air permeability of an agricultural recultivation site are highly variable. They found that especially on reclaimed anthropogenic post-mining sites, bulk density did not explain precompression stress, saturated hydraulic conductivity and air permeability. The varying physical properties lead to heterogeneous water-holding and infiltration capacity. Thus, preferential flow patterns developed with known effects on ground water recharge and ground water pollution (Buczko 1999). The assumption that dense soils are mechanically stable is a simplification for most soils and Krümmelbein et al. (2010) showed that this is especially not true for recently established recultivation sites. They even found a negative correlation between bulk density and precompression stress in some cases.

SUBSTRATE AMELIORATION

Soil Physical Property Amelioration

Construction of recultivation sites in Lusatia includes heaping dam-like structures with heights up to 4 m, which are later levelled with heavy crawlers. Depending on substrate water content during these procedures and contact area pressure of the crawler (between 33 kPa and 97 kPa) serious substrate compaction can occur (Krümmelbein et al. 2010). Bulk densities up to 1.9 Mg m^{-3} can induce very low saturated hydraulic conductivity and air permeability.

In Lusatia, recultivation practices include deep ploughing or deep ripping (50 cm soil depth) to reduce the compaction induced by dumping and levelling the substrate (Katzur and Haubold-Rosar 1996). The very low mechanical stability of the recultivation substrates, especially under wet conditions (Stock et al. 2007a; Krümmelbein et al. 2010), requires rapid root growth into the newly created pore space for long-term stability and revegetation success. The fact that Gunschera (1996) recommends a second deep ploughing after approximately 3 yr in addition to the primary deep ploughing clarifies the low persistence of such loosening actions. Haubold-Rosar (1994) summarized the success and persistence of deep loosening tillage for soils and substrates with clay contents $>25\%$ by mass; deep loosening had a positive, persistent effect on the substrate, if the tillage was conducted under optimum substrate water contents out of the plastic range. Significant recompaction occurred in soils and substrates with lower clay contents. For silty soils, he concluded that water contents during deep loosening should be between 20 and 22%; for the investigated soils this corresponded to pF values between 3.2 and 3.5 (Haubold-Rosar 1994).

Soil Chemical Property Amelioration

Recultivation substrates containing pyrite have acidic pH and require chemical amelioration to increase pH and to prevent percolation of acidic water into ground water and lakes. Based on field research, ameliorative methods were developed for forestal reclamation even on substrates with high pyrite concentrations (Weber et al. 1999). In this context the acid-base balance introduced by Illner and Katzur (1964) and Illner and Lorenz (1965) is of great importance.

For amelioration of sulphuric substrates, lime, and, until 1990, brown coal ash, by-products of combustion of lignite for energy and heat production, have been used (Illner and Lorenz 1965). The thickness of the upper, ameliorated layer, which consists of either Tertiary substrate with additions of lime or ashes or of Quaternary substrates determines the depth of the rooting zone. Consequently, the quality of the basic amelioration is crucial for future agricultural and forestal productivity (Katzur and Hanschke 1990). Gunschera (1996) suggests a minimum depth of 100 cm for this arable and rootable layer. This means that 120 to 130 cm of material must be applied, considering settlement of the substrates. The depth of the arable layer can be reduced to about 60 cm if the material below that zone is of Quaternary origin or has been ameliorated with lime or similar substances. The short-term success of such ameliorative measures can be assessed by drill seeding a test crop, such as forest bush rye (wild rye, *Secale multicaule* L.).

Typical horizons which develop in a pyritic substrate ameliorated with lime or ashes are amelioration horizon, a horizon with finished pyrite oxidation and a horizon with ongoing pyrite oxidation (Neumann 1999). The thickness of the ameliorated horizon depends on the amount and depth of liming or application of ashes. Katzur and Haubold-Rosar (1996) recommend incorporating lime fertilizer or brown coal ash to a depth of 60 cm. Compared with the lower horizon, the ameliorated horizon had higher pH and higher potential cation exchange capacity (Neumann 1999). Gast (2003) showed that pyrite oxidation and pH reduction strongly influenced mineral weathering processes and significant differences in solution chemistry between ameliorated and unameliorated horizons developed. Heterogeneity of pH and other chemical properties in the subsoil is greater than in the ameliorated topsoil. In younger ameliorated horizons Neumann (1999) found that secondary iron formations were mainly jarosite and in older ones mainly goethite. The secondary soluble salt was mainly gypsum. No relationship between depth of desalinization and soil age was detected. Rumpel et al. (1999) found an initial salty A horizon developed within one year after recultivation and development of a desalinized initial topsoil horizon occurred after 16 and 19 yr. In the ameliorated horizon and in the horizon below (zone with completed pyrite oxidation) no pyrite crystals are left. Horizons with pyrite oxidation completed are generally characterized by acidic pH, high salt concentrations and high Fe_o/Fe_d quotients ($Fe_o =$ oxalate soluble iron; $Fe_d =$ dithionite soluble iron). Acidic conditions lead to a strong feldspar weathering, clay mineral destruction and high gibbsite contents in these zones. Due to low pH, aluminum becomes mobilized and can reach phytotoxic concentrations. A second soil horizon with completed pyrite oxidation had not developed after one year of amelioration; after 34 yr it reached a depth >1 m (Neumann 1999).

When pyrite- and lignite-containing sites are ameliorated well and revegetated with trees, pedogenesis and overall water and elemental budgets eventually approach normal development after several decades, which is reflected in adjacent unmined forest areas, as shown by chronosequence studies with pine forest ecosystems on typical Lusatian mine sites (Hüttl 2000; Hüttl and Weber 2001). However, this takes considerable time and ecosystems that develop on lignitic and pyritic substrates are dominated by substrate-induced processes for decades (Hüttl 2000). Even after more than 50 yr, lignitic pyritic sites have strong quantitative and qualitative differences in water and element fluxes with imbalances through the system compared with unmined sites. The main amelioration objective is sustainable improvement of soil reaction (Katzur and Haubold-Rosar 1996). Gast (2003) found that lignite-containing recultivation sites were characterized by extraordinary high fluxes of aluminum, iron, calcium and sulphur (as SO_4), which acted as sources of elements. The elements transferred to deeper soil layers can reach several tons per hectare per year.

Soil solution chemistry is very much influenced by liming or application of fly ash and by acidic atmospheric inputs (Wilden et al. 1999). Schaaf et al. (1998) investigated development of soil solution chemistry of lignitic substrates in the field and in microcosm experiments. They showed that application of sufficient amounts of alkaline materials to buffer acid production due to pyrite oxidation in the long term is necessary to enable recultivation and reduce the risk of ground water pollution. Neumann (1999) showed that sites recultivated with brown coal ashes still displayed a high acid neutralization capacity after 34 yr of recultivation, and explained it with the high buffering capacity of calcium cations from calcium silicates contained in the ashes. Development of a closed cycling of nutrients such as nitrogen and potassium are thus essential to create a sustainable ecosystem (Schaaf et al. 1998).

Amelioration with Fertilizer

The substrates that are used for recultivation require applications of fertilizer with nitrogen, phosphorus and potassium. The amount and type of fertilizer depends on substrate composition and future land use (Katzur and Haubold-Rosar 1996; Weber et al. 1999). Wilden et al. (1999) studied the difference between organic and mineral fertilizer applications. They showed that application of mineral fertilizer led to an immediate but short-term (about 1 mo) increase in nitrate, ammonium and potassium concentrations in the soil solution to a depth of 130 cm. Application of sewage sludge caused a longer-term (>1 yr) increase of nitrate in the topsoil. Compared with the sites with mineral fertilizer application the nitrate content in the subsoil was significantly lower. Compost application resulted in a strong longer-term increase of potassium in the soil solution, whereas nitrate concentration did not increase. Phosphate concentration in the soil solution depended strongly on pH and not on the kind of fertilizer applied.

As an alternative, and/or in addition to mineral fertilizers, organic residues can provide additional benefits to soil structure formation and water-holding capacity (Tester 1990). As an added benefit, use of these materials will remove them from the waste storage system. In Lusatia, until 1990 organic fertilizer applications were not made due to the risk of nitrate and heavy metals leaching in sandy substrates (Wilden 2000).

Emmerling et al. (2000) applied organic waste materials in lysimeters and mesocosms to study the short-term stimulation of microbial and enzyme activity in mine soils. Soils consisted of Tertiary and Quaternary substrates, which were ameliorated with brown coal filter ash and lime. In the first 2 yr after application a low level of microbial activity was determined. The microbial and substrate-induced respiration and enzyme activities increased significantly with increasing amounts of organic materials. This was attributed to increased organic matter and nutrient concentrations and improved soil physical properties, such as water and nutrient retention capacities. Constituents of the coal fragments in Tertiary deposits were mineralized or converted by soil microorganisms. Tertiary substrates ameliorated with brown coal ash showed high microbial and enzyme activities after application of nitrogen-rich sewage sludge or very high amounts of mature compost mainly consisting of green waste. The stimulating effects of composted sewage sludge were lower than those from sewage sludge.

In forestal recultivation, Fettweis et al. (2005) investigated the accumulation of recent organic matter on lignite-containing pine stands. They used a ^{14}C method to distinguish between recent and geogenic carbon. The content of organic matter increased with stand age, and carbon contents in the substrate were mainly classified as geogenic (brown coal fragments). They found that brown coal with its ability to store water and nutrients could replace some of the recent functions of organic matter. They showed that water-holding capacity increased with increasing contents of geogenic carbon (brown coal).

Amelioration with Soil Organic Matter or Topsoil

The unstructured and mostly sandy substrates used for recultivation in Lusatia are relatively free of recent organic matter; therefore the application of soil organic matter and topsoil on reclaimed sites has been studied. Dageförde (1998) investigated development of vegetation at reclaimed sites in Lusatia, where topsoil (0 to 50 cm) from an adjacent forest had been applied. This process is known as topsoiling. Lime and nitrogen, phosphorus and potassium were applied to the topsoil and 1-yr-old *Pinus* trees (likely Scots pine, *Pinus sylvestris* L.) were planted. Topsoiled plots consistently had higher species numbers and plant cover than plots without topsoil. Wüstrich (2000) found similar results for a topsoiled site. The denser plant cover, which developed on the subsoiled plots, prevented water erosion (Dageförde 1998) and protected the soil from evaporation.

Topsoiling led to an accumulation of organic substances, which were used as a nutrient source for microbial activity (Dageförde 1998; Klem 1998, 2000). Accordingly, topsoiled treatments had greater microbial biomass and higher carbon mineralization rates compared with those without topsoil application (Kolk 1998). Dageförde et al. (1998) found that topsoiling improved pore functions and thus water balance.

Wüstrich (2000) investigated the effects of a 60-cm-thick layer of humic substrates (2 to 6% carbon) and highly humic substrates (16% carbon) on reclaimed sites. Organic carbon content increased from below 1% by mass up to 5.7% by mass, and nitrogen concentration increased. Total porosity and compressibility increased, while bulk density decreased. This induced higher field water contents on topsoiled sites (7 to 30% by volume) compared with sites with no humic application (1 to 15% by volume) and an increase in effective root space. Application of highly humic material induced more intense root growth and higher root density compared with the control. She detected more intense aggregation and higher aggregate stability with wet sieving of the topsoiled sites. She measured precompression stress values between 50 and 100 kPa, with no typical increase of precompression stress with depth, which is supported by results from an agricultural reclamation site in Lusatia (Krümmelbein et al. 2010). Accumulation of organic substances induced increasing water repellency of soils and substrates

(Hallett et al. 2001). This must be considered when the content of organic matter is to be increased during recultivation, because the water balance can be severely affected by water repellency of the substrate by influencing water infiltration (Wessolek et al. 2008) and evaporation (Doerr et al. 2000). Water repellency is known not only to depend on the kind of organic matter but also on its composition (Ellerbrock et al. 2005). However, Buczko et al. (2006) showed that in their investigation of wetting properties of Lusatian recultivation sites, the influence of soil water content was stronger than the influence of different forest stands, thus different soil organic matter compositions. For a macroscopic homogenous and unstructured soil, Buczko and Bens (2006) found preferential flow patterns and attributed them to varying soil repellency features.

Amelioration with Rhizosphere Bacteria and Mycorrhizae

Höflich et al. (2001) found application of selected rhizosphere bacteria (especially *Pseudomonas fluorescens*, *Rhizobium trifolii*, *Agrobacterium rhizogenes* and *Stenotrophomonas maltophilia*) and ectomycorrhizal fungi to recultivation substrates stimulated seedling growth of pine (shoot and root dry mass) in undisturbed landscapes and in the disturbed substrates of post-mining landscapes in Lusatia. They found co-inoculations of effective bacteria with ectomycorrhizal fungi increased the reproducibility of positive inoculation effects. Positive interactions among stimulated mycorrhiza formation, higher root tip numbers and better shoot and root growth were demonstrated repeatedly. Most bacteria produced phytohormones (especially auxins), cellulase or pectinase and reacted antagonistically against phytopathogenic fungi. *Pseudomonas fluorescens* isolated from the rhizosphere of wheat from arable soil survived on pine roots in forest soils and stimulated mycorrhizal formation. Rhizosphere bacteria from arable soils can thus likely improve afforestation success of former arable land and highly degraded sites.

RECULTIVATION PRACTICES

Agricultural Recultivation

Depending on the type of substrate used for agricultural recultivation, several practices have been developed (Table 2). Seven different substrate classes that are used to determine the revegetation treatment to be applied are defined in reclamation recommendations, which are used as a basis for recultivation by mining companies (Gunschera 1996). Table 3 shows values that should be reached within recultivation, which Katzur and Böcker (2010) summarized according to recultivation practices. After basic substrate amelioration, a suitable crop rotation must be developed. The crops should utilize the substrate, have no high demands on substrate structure (e.g., peas; lupines, *Lupinus*; field beans) and nutrient cycling (e.g., nitrogen fixing plants such as *Medicago sativa* L, alfalfa or *Trifolium*, clover), use water efficiently (e.g., *Melilotus*, sweet clover or *Gramineae*, grass mixes), develop deep root systems (e.g., alfalfa) and produce high amounts of above- and below-ground biomass to be incorporated into the substrate. Plants producing biomass with a carbon: nitrogen (C:N) ratio as small as possible are favourable to enable uncomplicated decomposition of the organic matter by microorganisms. Decomposed components of organic matter promote aggregation and aggregate stability and development of a stable and functioning soil structure (Gunschera 1996). All cultivated crops generally increase organic matter content of the soil or substrate and improve soil structure, thus improving water balance and soil mechanical properties.

Table 2. Substrate classes in agricultural recultivation (modified according to Katzur and Böcker 2010)

Substrate class	Substrate description
1 and 2	Quaternary, strongly cohesive
3	Quaternary and/or Tertiary mixtures, strongly cohesive
4	Tertiary, strongly cohesive
5	Quaternary, cohesive
6	Quaternary and/or Tertiary mixtures, cohesive
7	Tertiary, cohesive

Crop rotations have been successful on reclaimed sites. One such rotation is 1 yr of sweet clover and grass, 1 yr of winter rye (*Secale cereale* L.), 4 yr of alfalfa and grass, 1 yr of winter wheat (*Tritium aestivum* L.) or winter rye, 1 yr of winter barley (*Hordeum vulgare* L.) or rapeseed (*Brassica napus* L.), 1 yr of grass, 1 yr of winter wheat, 1 yr of winter barley, 4 yr of alfalfa and grass (Gunschera 1996).

Since the substrates used for recultivation are very low in biological activity, structure development and mechanical stability they are subject to more frequent and intense compaction than natural soils (Krümmelbein et al. 2010). Thus, soil tillage operations should be minimized to avoid further compactive and structure homogenizing impacts on the substrate (Gunschera 1996). Deep plowing at the beginning of reclamation and again after approximately 3 yr is recommended. Although the persistence of such measures is mostly low and may require repetition.

Forestal Recultivation

For forestal recultivation, the available geotope, including the soil substrate, is classified similarly to that in agricultural recultivation (Thomasius et al. 1999). Classification of the subtrate is based on texture and contents of brown coal and lime. Emissions of fly ash from the brown coal combusting industry are classified and combined with the substrate classification to obtain degrees of nutritional status. The geotope classification is completed by considering plant-available water.

Table 3. Target values to be reached within the upper 30 cm during agricultural recultivation (modified according to Katzur and Böcker 2010)

	Substrate class					
	1 and 2	3	4	5	6	7
Phosphorus (mg g^{-1} soil)	8	7	7	7	7	7
Potassium (mg g^{-1} soil)	15	14	12	11	12	9
Magnesium (mg g^{-1} soil)	9	8	6	6	6	5
pH (potassium chloride)	6.8–7.2	6.5–7.0	6.0–7.0	6.0–7.0	6.0–6.5	6.0–6.2
Total carbon (%)	0.5–1.5	1.0–1.5	1.5–2.0	0.5–0.9	1.0–1.5	>0.5–1.0
Bulk density (Mg m^{-3})	1.65	1.60	1.65	1.60	1.50	1.50

Tree species for economical stand development under prevailing ecological conditions are chosen (Thomasius et al. 1999). The current dominant tree for recultivation in the Lusatian district is pine (*Pinus*); since the 1980s efforts to establish oak (*Quercus*) in Lusatia have increased (Thomasius et al. 1999). Since 1994 it has been planned to decrease the proportion of broadleaf trees from 16 to 25% to minimize forest fires, insect catastrophes and soil degradation and to increase the ecological value of the forest stands (Preußner 2008).

Forestall recultivation in Lusatia can be structured into three phases with different main tree species. From 1930 to 1960 mainly birch (*Betula*) trees were planted, after 1960 mainly red oak (*Quercus rubra* L.) were planted and after 1990 mainly pine (*Pinus*) species were planted (Preußner 1998). However, multi species stands had very positive effects on soil formation (Katzur and Haubold-Rosar 1996). Under pine and larch (*Larix*) trees, mostly raw humus developed, while under deciduous trees organic matter was mostly well decomposed and showed a higher bioactivity and better water and nutrient balance in the topsoil.

Besides the planned recultivation, the sites are also recolonized by several plants that can be used to classify the trophic level of the site if no precipitation of ash has occurred (Thomasius et al. 1999). The different geotopes with their different abiotic properties induced the development of varying types of forest floors, ranging from poorly to well decomposed. The different humus types led to different accumulation rates of organic matter into the substrate and different soil development rates (Thomasius et al. 1999; Bens et al. 2004; Ertle and Knoche 2008).

Thomasius et al. (1999) suggested deep loosening if compacted areas were encountered. According to the trophic level of the site, fertilizer application may be necessary. They also suggested cultivation of nitrogen-fixing plants such as alfalfa. The trees are normally planted as seedlings; only oak and birch species are seeded. Protective plant covers against erosion and extreme climatic impacts are often applied. That such protective plant covers can also act as competitors (nutrients, water, light) to the tree seedlings is considered (Thomasius et al. 1999).

In Lusatia the forestal recultivation occupies about 60% of the post-mining area. Forest stands reflect the given site conditions and demands of the site owners and operators and at the same time act as controlling factors for soil, water and climate protection and for wood production, recreation purposes and nature conservation (Bungart 1998). In contrast to agricultural recultivation, forest sites can only be ameliorated during site construction and before or while the trees are planted.

Bungart et al. (1998) investigated forestal recultivation in Lusatia and determined the above-ground biomass production in relation to nutrient contents in a pine chronosequence. They compared planted stands with those of natural succession and found that limiting factors for tree growth were dense forest stands and nitrogen deficiency. Basic fertilizer, which was applied when the trees were planted, released sufficient amounts of potassium, magnesium and calcium for 60 yr. Knoche et al. (2002) examined water and element fluxes in reclaimed red oak (Q*uercus rubra* L.) stands of different ages on both Quaternary pure sands and Tertiary, pyritic loamy sands. They compared the fluxes with those of an adjacent location unaffected by mining. Due to increasing interception and evapotranspiration, the deep percolation rates of red oak forests declined dramatically within 30 yr after site establishment. The initial annual ground water recharge was about 45% of precipitation. Deep drainage of the older stands decreased to <15% of precipitation, independent of substrate type. Tertiary substrates were characterized by intensive leaching of hydrogen, iron, aluminum, magnesium, calcium, ammonium and sulphate sulphur due to pyrite oxidation and therefore enhanced silicate weathering. Aged stands acted almost completely as a sink for nitrogen, phosphorus and potassium. Compared with adjacent oak forests on unmined locations, the stands on reclaimed sites showed very similar patterns for nitrogen, phosphorus, potassium, calcium and magnesium turnover (Knoche et al. 2002).

It is important to control the density of the forest stands to avoid competition among single trees for water and nitrogen (Bungart 1998). Ectomycorrhizal communities were assessed by Gebhardt et al. (2007) along a chronosequence of red oak stands on a forest reclamation site. The number of ectomycorrhizal morphotypes increased with stand age along the chronosequence. However, the number of morphotypes was lower in stands with disturbed soil than with undisturbed soil.

All stands showed site-specific ectomycorrhizal communities with low similarity between the chronosequence stands. Gebhartd et al. (2007) suggested an artificial inoculation with site-adapted mycorrhizal fungi to increase the colonization rate of red oak stands, and thus tree growth and survival in the first years after planting.

Agroforestry Recultivation

Agroforestry is an expression for a system that integrates trees with agricultural crops and/or livestock at the same time or sequentially on the same field (Alavalapati et al. 2004). The combination of different management systems can create a variety of benefits (e.g., optimized water and nutrient cycles, microclimate and a high biodiversity) for the cultivated plants and/or animals. Both economic yield and environmental protection receive overall sustainable benefits (Grünewald et al. 2007; Quinkenstein et al. 2009a).

Alternative forestal land use options, such as short rotation plantations, allow establishment of a sustainable and environmentally friendly utilization of the land and additionally improve socio-economic and cultural welfare without competing with traditional agriculture or forestry. In the future, this will enable society to use forestry more as an integrated production system for wood, which can be used as timber and for energetic utilization (Bens and Hüttl 2001). The aims of agroforestry systems are adaption to (changing) climatic conditions, protection of abiotic and biotic resources (e.g., water, soil, biodiversity), high rentability due to low input management and utilization of the soil to act as a sink for carbon and nitrogen (Grünewald et al. 2007; Freese 2008). Freese (2008) summarized interactions in agroforestry systems as high protection against erosion (wind and water), improved microclimatic conditions (wind protection, shadowing), accumulation of organic materials (tree litter) and the role of trees to pump water and nutrients from greater soil depths. Quinkenstein et al. (2009a) described alley cropping as a sustainable land use system for post-mining landscapes with low input needs of fertilizers, pesticides and human power. Higher biodiversity is induced and a well-structured system of hedgerows may further support the connection of meta-populations at a regional scale.

Cultivation of perennial woody plants also contributes to carbon sequestration in the soil and supports the formation of soil organic matter. The simulation of carbon sequestration of a short rotation system (poplar, *Populus*) in Lusatia showed that at least for the first 20 yr such a site can act as a carbon sink (Quinkenstein et al. 2009b). As a part of the recultivation research activities in 1995, a 2.5-ha short-rotation plantation was established on clayey, sandy, nutrient-poor substrates in the Lusatian mining area to study the yield potential of fast-growing tree species under the prevailing site conditions (Bungart and Hüttl 2001). Even under unfavourable soil conditions with a low nitrogen and phosphorus supply, above-ground biomass production was significant. Bungart (1998) investigated the performance of a short-rotation plantation to assess the potentials of fast-growing tree species as affected by nutrient and water supply. All species showed the highest biomass production in the third growing season. Further investigations showed that clones with higher shoot hydraulic conductivity and transpiration rate had significantly higher yields (Bungart et al. 2000). Cultivation of hybrid poplar (*Populus*) clones in a short-rotation plantation was an adequate tool for establishing alternative land use systems in the Lusatian post-mining landscape as a potential source of biomass energy (Bungart and Hüttl 2004).

OUTLOOK: FUTURE LAND USE OPTIONS

In the Lusatian lignite mining district, the proportion of forestal land use before and after mining is relatively equal; agricultural use decreases, while water areas increase (Fig. 3). This is mainly due to the remaining voids of the opencast mines, which are supposed to be filled by water and is proposed in the future to form the largest area of connected lakes in Germany (Zweckverband Elstertal 2006; Vattenfall Europe AG 2009). The design of the post-mining landscape is part of the regional planning and has the status of a federal state law (Hüttl et al. 1999).

In Lusatia the landscape has undergone strong modifications due to mining, and the whole region has changed dramatically during the past few decades according to economic, social and demographic issues. After German reunification in 1990, industrial production, which formerly consisted mainly of brown coal processing, textile and energy production industries, decreased drastically, and with it the population of the area. The future prospect of the connected lakes is expected to attract tourists and generate new sources of income.

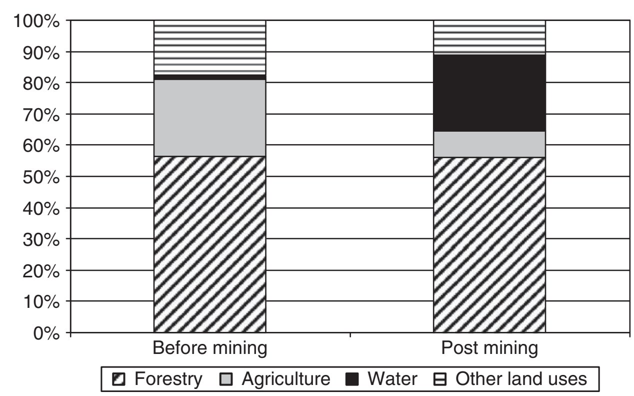

Fig. 3. Proportion of land uses before and after mining. Figure according to Vattenfall Europe AG (2009). Horizontal stripes, other land uses; black, water areas (lakes etc.); grey, agriculture; diagonal stripes, forestry.

The economic and social aspects of recultivated and rehabilitated areas are a growing concern to be addressed in planning procedures for post-mining landscapes. They may include new permanent employment possibilities and new sources of energy, such as wind energy and agroforestry systems (Bungart et al. 2000; Bens and Hüttl 2001; Grünewald et al. 2007; von Bismarck 2010). The introduction of bioenergy production in agriculture offers new economic perspectives, providing a multitude of societal benefits and contributing to new employment in agriculture and rural areas, especially in post-mining landscapes. Biomass production for energy purposes is an innovation that meets with little reservation among farmers compared with other renewable energy sources, such as wind and solar power plants. However, investigations of suitable biomass production are necessary. Therefore, different biomass production, processing and conversion technologies need to be compared and assessed for their complex ecological, economic and social impact (Plieninger et al. 2006; Grünewald et al. 2007). Meanwhile it is quite commonly accepted that it is not possible to rebuild the same landscape that existed before mining, more than 100 yr ago (Gräbe 2010). There is an ongoing social process and political discussion to decide which post-mining landscape is most desired and how the recultivated areas can be best used for the benefit of the region (Gräbe 2010). In post-mining regions it is essential to improve public and private partnerships and networks to interconnect the regional innovation system in all areas and to create channels for knowledge flow that can induce innovative activities to manage environmental impacts and post-mining development. Future research needs to combine social, economic and ecological issues. There is a need to increase and communicate an understanding of basic environmental, technical and social processes and to find strategies to determine which landscapes and which types of land use can be implemented after mining and which can offer the most benefits for society and the environment (Martinez-Fernandez 2010). New methods need to be developed that allow evaluation of the decisions concerning landscape development in terms of social, economic and ecologic benefits (van der Heide 2010).

Much research on reclamation or recultivation in Lusatia has been done to investigate past and ongoing reclamation practices and their outcomes. The basic physical (e.g., compaction, substrate homogenization, preferential flow patterns, stagnic features, etc.), chemical (e.g., acidification due to pyrite oxidation, lack of nutrients, contents of phytotoxic substances, etc.) and biological (e.g., lack of microbial activity due to chemical and physical properties) limitations of the substrates in the post-mining region are known and ways to address them have been and are being developed. It becomes increasingly important to link this knowledge and to merge the conceptions of the various scientific disciplines to receive a holistic view on all issues of restoring a landscape.

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