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Perspectives of lignite post-mining landscapes under changing environmental conditions: what can we learn from a comparison between the Rhenish and Lusatian region in Germany?

Werner Gerwin¹ , Thomas Raab² , Klaus Birkhofer³ , Christoph Hinz⁴, Peter Letmathe⁵ , Michael Leuchner⁶ , Martina Roß-Nickoll⁷ , Thomas Rüdert⁸ , Katja Trachte⁹ , Frank Wätzold¹⁰ and Frank Lehmkuhl^{11*}

Abstract

Background The decision of the German federal government to cease lignite mining until 2038 or—if possible—already earlier until 2030, will cause manifold transition processes in the remaining lignite mining districts of Germany. The two largest districts are located in geographically opposite regions: The Rhineland in the western part and Lusatia in the east of Germany. As particularly these two mining districts will experience severe changes in their socioeconomic as well environmental conditions, the federal government has adopted comprehensive economic support measures. However, the environmental changes will also cause altered ecosystem functions and services to be provided by the future post-mining landscapes.

Results In this paper, the two main lignite-producing regions of Germany are compared with regard to their natural and cultural settings. The economic situation and its history are reflected and differences are outlined. Part of the disparities in the cultural development can be explained by very different natural conditions, especially edaphic factors and climatic situation. Because of dissimilar geological settings, different mining technologies were developed and are in use in the two regions with distinct effects on the resulting post-mining landscapes.

Conclusion The long-standing and manifold lignite mining activities have radically restructured the landscapes in Lusatia and the Rhineland. With the ongoing decline of the mining industry and its complete cessation, presumably within the next decade, both regions will alter their faces significantly. These changes offer both challenges but also opportunities with respect to the post-mining landscapes and their ecosystem services they are going to provide. The prerequisites for a positive socioeconomic development and for sustainable land-use concepts that also consider ecological aspects are different for both regions. However, or especially because of these differences, the knowledge exchange and experience transfer between both mining regions are pivotal for the success of this extensive transformation process.

Keywords Lignite mining, Ecosystem services, Post-mining landscapes, Transformation processes

*Correspondence:

Frank Lehmkuhl

flehmkuhl@geo.rwth-aachen.de

Full list of author information is available at the end of the article

Introduction

Even if the recent geopolitical situation in Europe raises many questions with regard to future energy supply, the German federal government still adheres to its political goal to cease lignite mining until 2038 or—if possible—already earlier until 2030. Associated with this political decision, a massive socioeconomic structural change will occur in Germany's two largest lignite mining districts. The closure of mines offers numerous opportunities, but also challenges, to overcome the severe ecological disturbances caused by long-lasting and large-scaled mining operations. Solutions for these challenges are manifold and touch several scientific disciplines. Effects and effectiveness of reclamation or restoration measures have to be verified. Traditionally, environmental economics often emphasized the source function (source of raw materials) and the sink function (absorption of pollutants) of the natural environment. Today, this view is widely seen as outdated. For the last 15 years, much more emphasis has been placed on the provision of ecosystem services, and assessing ecosystem services might be a suitable interdisciplinary approach to validate the success of measures related to the ongoing structural change in both regions, which basically includes the creation of sustainable and multifunctional post-mining landscapes.

The concept of ecosystem services comprises supporting, providing, regulating, and cultural services supplied

by ecosystems to the benefits of humans and other species [1] (Fig. 1). Services in these categories are provided through markets (e.g., food) and, more often, without organized markets (e.g., climate regulation). In particular, these services are, in the absence of adequate pricing, often neglected in political and economic decision processes. This way of operating has not only resulted in severe overexploitation of the natural environment, overdevelopment of land, resource scarcity, worsening global environmental problems such as climate change and a sharp decline in biodiversity, but also negatively affects the livelihood opportunities of future generations.

Spatial transformation processes, in particular, offer the opportunity to rethink patterns of land use and to better integrate ecosystem services methodically into decision-making processes [2]. In principle, economic research can contribute to make better decisions in two ways:

- (1) The economic valuation of ecosystem services, i.e., their assessment in monetary terms, can help to give those ecosystem services equal consideration in policy processes, whose value is usually not considered in markets, and, as a consequence, are often not given adequate attention and equal consideration in policy processes.
- (2) In case certain policy targets exist with respect to ecosystem services, e.g., the provision of a certain

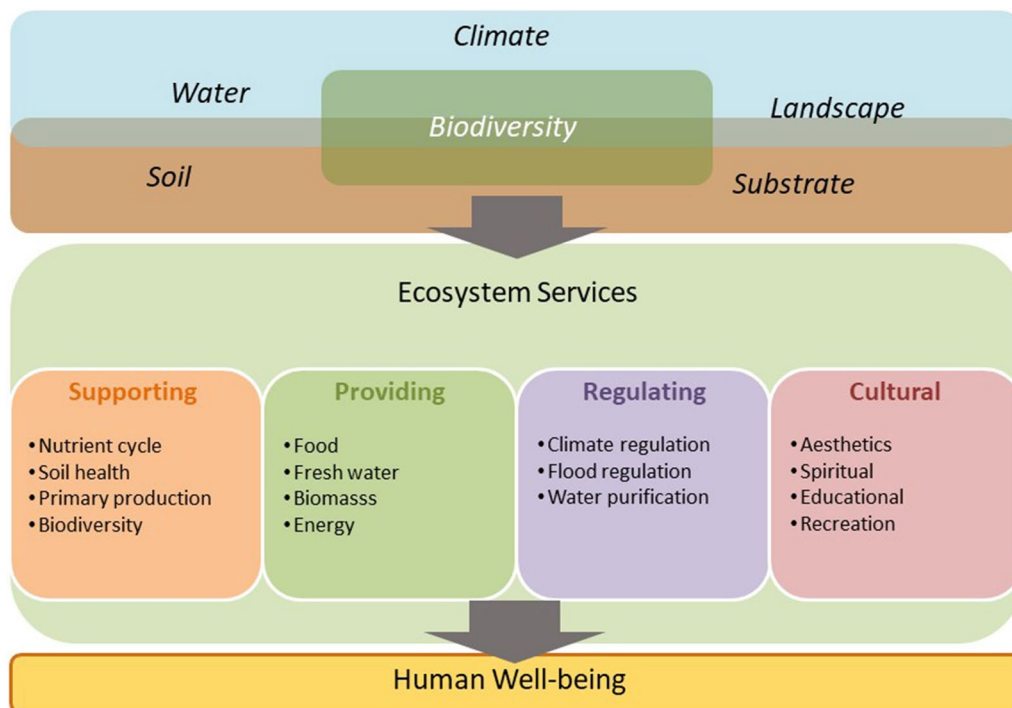


Fig. 1 Ecosystem services (with selected examples for each category) as connectors between vivid ecosystems and human well-being

level of water supply, economics can help identifying the cost-effective way to achieve that level. Cost-effectiveness is here reached when a mix of certain land use or other measures achieve certain ecosystem services at a low-cost level.

Both approaches need to take temporal (e.g., considering the time of the year when groundwater is used) and spatial (e.g., considering where a certain biodiversity conservation measure is carried out) aspects explicitly into account. The reason is that the benefits as well as the costs of land use and other measures (often) differ depending on where and when they are carried out [3]. However, specifically land-use measures and their related impacts on the provision of ecosystem services often unfold only over longer periods of time and, therefore, require long-term planning horizons. Therefore, different land-use options (residential, industrial, infrastructure, natural ecosystems) should be defined in a long-term manner so that the dynamics of ecosystem services can develop in the desired direction and path dependence and lock-in effects are avoided [4]. In this regard, regional planning and land-use planning instruments exist in both lignite mining regions (*Braunkohlepläne*) and define the basic framework of the post-mining landscapes and specific ecosystem services to be provided. A land-use budgeting approach implies to designate spatial areas to ensure the provision of specific ecosystem services. Related cost–benefit analyses can not only promote cost-efficient decisions, but they also clarify where society incurs particularly high damages and what causes them. The resulting increased levels of transparency make it possible to charge the originators for the (external) costs incurred [5].

However, the question of evaluating ecosystem services is still largely unresolved. Evaluation approaches that focus, in particular, on damage costs, restoration costs, prevention costs, and willingness to pay are scientifically controversial. Moreover, empirical and market studies that evaluate different ecosystem services often lead to contradictory results, which at least limit their use and acceptance for political and economic processes. It is also important to consider aspects which are specifically relevant for (former) mining areas, which include:

Mining and its impacts on landscapes and society involves transient or non-stationary processes operating at different temporal and spatial scales interacting with climate change impacts and society. This non-stationary behavior should be detectable through changes of ecosystem services in space and time [6, 7].

Ecosystem services in post-mining landscapes cannot be expected to be similar to pre-mining land uses. In fact, biophysical and biogeochemical properties and constraints of the post-mining substrates force land managers to specifically tailor land-use systems to those constraints [8].

Against this background, the objective of this paper is to provide a comprehensive, interdisciplinary overview of similarities but also distinct differences of both natural and economic capacities in the two lignite mining regions of the Rhineland and Lusatia. This comparison starts with an overview of general settings of both regions and of changes of these settings related to mining and global change. Potentials but also limitations for the provision of specific ecosystems services are highlighted. The findings from literature are presented in a chronological order from pre- to post-mining time. Conclusions are drawn with respect to specific, but also common, challenges both mining regions will face in the future. Challenges in terms of ecosystem disturbances by mining activities, the ongoing structural change, and the creation of large-scale post-mining landscapes are discussed with an emphasis on the expected ecosystem services to be provided by the post-mining landscapes. These challenges are related to mining closure and landscaping, effects of climate change, land-use change after mine closure, and impact on the socioeconomic systems of both regions. Emerging perspectives and scientifically based demands for a successful structural change are suggested in the end of this paper.

General settings: similarities and differences

Basic facts and figures

After the German reunification, four lignite mining districts existed in Germany. The mining district of Helme-Stedt was already closed in 2002 and also in Central Germany, mining was stopped in several open cast mines until the turn of the millennium. Today, active lignite production in Germany is mainly concentrated on the two districts in the Rhineland and Lusatia as well as on some remaining mines in Central Germany (Table 1).

The western lignite mining district in the Rhineland extends over an area of 2500 km² [11] and represents today the largest lignite district in Europe and the main focus of lignite mining today in Germany (lignite production in 2021: 62.6 Mt; see Table 1). The total area directly affected by mining operations is 338.4 km² and the recent operating area is 99.1 km² (see Table 1). Groundwater lowering has affected areas of 1500 km² in the upper groundwater storey [12] and of approx. 2900 km² in the second one [13]. Even if traditional elements of the former cultural landscapes (arable land, pastures

Table 1 Mining affected and reclaimed areas in the main lignite mining districts of Germany, data as of 2021 [9, 10]

	Lignite production [Mt]	Total utilized area [km ²]	Operating area [km ²]	Reclaimed area									
				Total area		Arable land		Forest area		Water bodies		Others	
				[km ²]	(%)	[km ²]	(%)	[km ²]	(%)	[km ²]	(%)	[km ²]	(%)
Rhineland	62.6	338.4	99.6	238.8	100	130.5	54.6	88.0	36.9	8.2	3.4	12.1	5.1
Lusatia	46.8	899.5	308.0	591.5	100	106.9	18.1	318.9	53.9	89.8	15.2	75.8	12.8
Central Germany	16.9	490.3	124.3	366.0	100	94.2	25.7	116.6	31.9	124.2	33.9	31.4	8.6
Helmstedt	0.0	25.3	9.8	15.5	100	7.0	45.2	7.2	46.5	0.4	2.6	0.9	5.8

and forests) are still present, distinct structural changes are visible (see Fig. 2). Particularly, the Rhenish district is characterized by massive urbanization processes in a developed economic region in direct vicinity of expanding cities like Cologne, Düsseldorf or Aachen.

Although Lusatia is part of the German capital region, it is comparatively far away from Berlin (about 100 km) and, thus, urbanization is less advanced there. The second largest lignite mining district covered at the beginning of the 1990s an area of up to 2100 km² which had been affected by groundwater lowering [14]. As an effect of the different geological situations and mining technologies,

the total directly influenced area (899.5 km²) is much larger than in the Rhenish district, whereas the annual lignite production in 2021 of 46.8 Mt lignite was lower (see Table 1). However, during the 1970s and 80 s, the Lusatian district was by far the most important lignite-producing region of the former German Democratic Republic (GDR) [15]. In 1989, the lignite production in Lusatia of 195.1 Mt still clearly exceeded the production of the Rhenish district (104.2 Mt) [16]. The political and economic transformation in the 1990s resulted in an unplanned and rapid process of extensive mine closures and led to a social and economic crisis which is still



Fig. 2 Operating lignite mining in the Rhineland. (1) Panoramic view of the open cast mining area of Garzweiler. Photo from the viewpoint 2011. (2) Sophienhöhe as artificial mountain of the Hambach open cast mine with Inden open cast mine in the foreground. Photo taken from the Indemann. (3) Indemann: View platform for tourists south of the Inden open cast mine. Photos: F. Lehmkuhl, 2011 (1), 9.7.2022 (2, 3)

deeply rooted in the local public awareness. Symptoms of this crisis were exceptional high unemployment and massive population losses due to migration of younger people to western parts of Germany. Figure 3 gives exemplary insights into the mining landscapes of Lusatia.

In Helmstedt as well as in Central Germany mining areas, reclamation is already advanced and examples of established infrastructure for tourists are visible in all mining districts. Figure 4 provides examples from Helmstedt and the new cultural landscape with lakes in the Central German mining district.

Natural settings

These two largest German lignite districts are both located in the southern part of the Northern German lowlands but in opposite regions: In the far west of Germany, the Rhenish district is laid in the State of North Rhine-Westphalia, whereas the Lusatian district is part of the States of Brandenburg and Saxony near the German–Polish border.

The climate of both target regions reveals a humid regime with a comparable annual course of precipitation totals and mean temperature. However, the Lusatian region is among the driest regions in Germany [17] with a negative climatic water balance due to a more continental character, while the Rhenish region in the western

part experiences maritime influences from the Atlantic. Climate indices [18] for the climate normal period 1971–2000 (calculated by arithmetic means from four (Rhenish) and three (Lusatian) counties in the lignite mining areas) indicated this by the higher annual precipitation totals. With the exception of the summer months, the Rhenish region receives considerably higher totals than the Lusatian region. The temperature in 2-m height reflects these conditions with lower daily maximum ($-2.4\text{ }^{\circ}\text{C}$) and minimum ($-12.5\text{ }^{\circ}\text{C}$) values on average in the eastern part of Germany caused by less cloud cover as a precondition for precipitation and thus, stronger radiative cooling. To further assess the differences, particularly, dry days as well as frost days confirm the two aforementioned climate regimes. The eastern region experienced more days without precipitation (22.6) over the considered time period and almost twice as many frost days per year (49.5 compared to 82.1). The gradient in the precipitation fields can also be observed by means of the spatial distribution of the mean annual totals with an obvious decrease from the West (600–700 mm, North Rhine-Westphalia) to the East (450–600 mm, Brandenburg).

The Lower Rhine Embayment (LRE) is one of the largest groundwater regions in Germany. Data from the Erftverband [19] indicate for its area of activity, which covers the so far discussed section of the LRE, a groundwater



Fig. 3 Operating lignite mining in Lusatia: (1) Active mining operations in the Jänschwalde open cast mine with overburden conveyor bridge F60; (2) emerging new mining lake: The future Cottbus Ostsee as the currently largest artificial lake of Germany is flooded in the former Cottbus-Nord open cast mine. (3) The developing Bergheider See as part of the Lusatian chain of artificial mining lakes. (4) The artificial Hühnerwasser catchment in the Welzow-Süd open cast mine as source for a re-established stream in the post-mining landscape and a scientific research platform for ecosystem research. Photos: F. Lehmkuhl (1, 2013), K. Birkhofer (2, 2018 and 3, 2017), and R. Nenov (4, 2022)

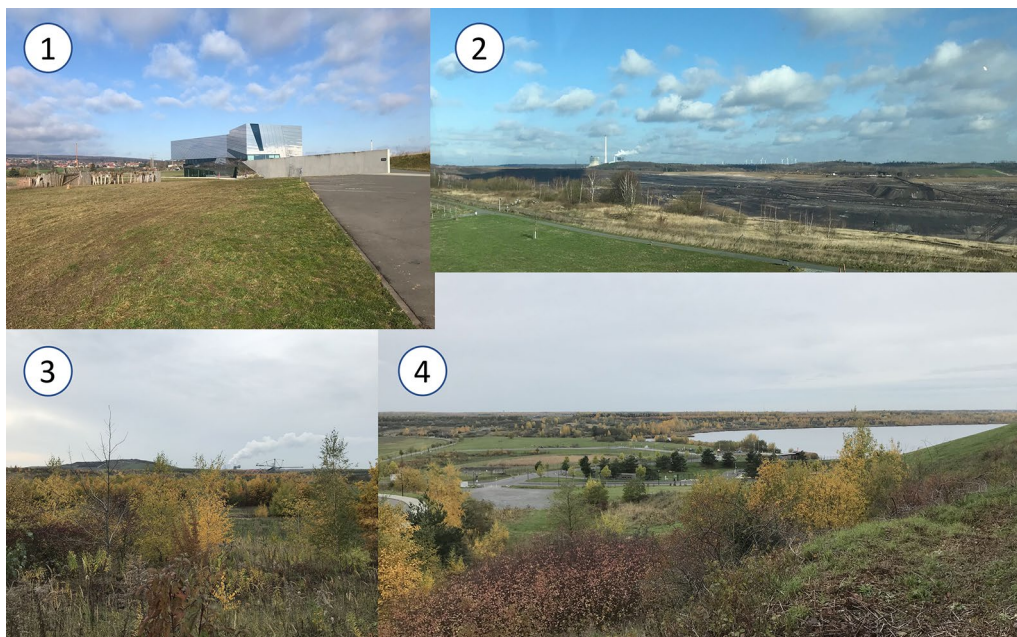


Fig. 4 Examples from two abundant mining areas: (1) Research institute and museum Schöningen (former *Paläon*) in the abandoned Helmstedt mining district. (2) Former mining area Schöningen and power plant Buschhaus. The area will be flooded until approximately 2032 creating a 400 ha and 100 m deep lake. (3) and (4) Reclaimed areas in the Central German mining district with hills and the lake Markkleeberger, See southeast of Leipzig. Photos: F. Lehmkuhl, 4.3.2020 (1, 2) and 8.11.2019 (3, 4)

withdrawal of 940 Mill m³ in the year 2019/2020. A population of about 2.8 Mill. people are supplied with 551 Mill m³ of water taken from groundwater and to a minor extent from surface water (22 Mill m³). Also, Lusatia naturally offered large groundwater resources. Particularly, the broad ice marginal valley in Lusatia (Lusatian and Baruth *Urstromtal* in the south and north, respectively) are characterized by shallow groundwater levels less than 5 m below surface. A great example for such a semiterrestrial landscape at the northwestern edge of the mining district is the Spree Forest (Spreewald), an inland delta of the Spree river with extensive bog lands and a unique cultural landscape, that is protected as UNESCO Biosphere Reserve since 1991.

The LRE is characterized by a generally flat topography with the only exception of the Ville hills west of the Rhine, which are around 50 m above the lowlands of the loess landscapes. There are only a few rivers that form the Eifel Mountains crossing the LRE from south to north, such as Rur and Erft and their tributaries. The whole relief was leveled by intensive agricultural use since the Neolithic period about 7500 years ago. In the floodplains, Pleistocene river terraces and loamy Holocene floodplain deposits were accumulated. In contrast, the Lusatian lignite mining district is located in a landscape that was directly affected by Pleistocene glaciers. Most of the numerous former and recent lignite mines are located

in glacial meltwater valleys (both Bremen and Baruth *Urstromtal*). The sediments are dominated by sandy substrates and loamy material in basal till and in terminal moraine ridges. With the rivers Spree and Schwarze Elster as part of the Elbe catchment and the Neisse as a tributary of the Oder River, only few small rivers flow through.

Geological settings, although both regions are mainly determined by Tertiary to Quaternary dynamics, are different with significant impact on mining technologies applied. The Rhenish lignite mining district is located in a transitional landscape between the northern foothills of the Eifel-Ardennes-massif and the lowlands of the LRE (Fig. 5). Figure 6 provides a geological cross-section of the LRE. The region is part of the Neogene trans-European rift system and its rock sequence and groundwater resources are subdivided into several major units by normal faults of NW–SE strike and subsidiary WNW–ESE [20]. Rock sequence, rock thickness, and groundwater conditions can change greatly along the main faults that bound these blocks. The up to 1200 m thick sedimentary sequence includes terrigenous and marine clastics and begins in the latest Lower Oligocene stage. A Lower Seam Group was formed at the same time in the southern section of the LRE. From Miocene on, paralic and fluvial, siliciclastic sediments dominate the sedimentary sequence of the LRE. This series is characterized by

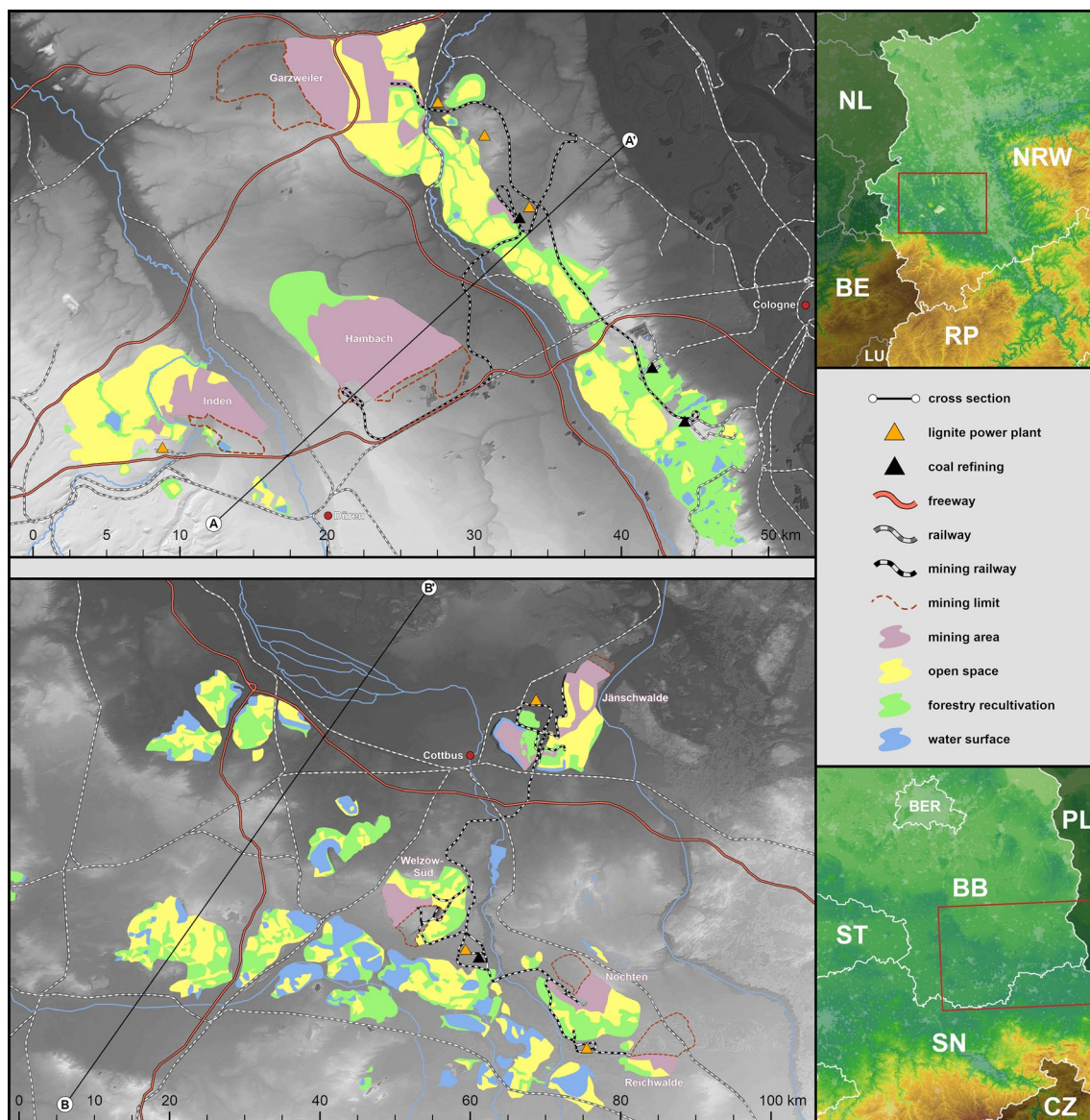


Fig. 5 (above) Overview of the Rhenish lignite mining district between Aachen and Cologne; (below) overview of the Lusatian lignite mining district southeast from Berlin (cross sections are shown in Fig. 6); note the different scales for both mining districts. Data sources: [24–31]. Draft: F. Lehmkuhl, W. Gerwin and D. Stawinoga

extensive marshlands, which led to today's lignite seams of the Main Seam Group and became the basis for mining. The thickness of some seams can be up to 100 m [21]. The Upper Seam Group is mined in the Inden open cast mine. Finally, in Pliocene time, some pelitic units (*Rot-tone*, *Reuvertone*) were deposited among further sand layers which are important aquicludes protecting the deeper groundwater bodies against anthropogenic contaminants. These Tertiary sediments including the lignite were covered by Quaternary sediments, mainly terrace sequences of the River Meuse and Rhine and covering

loess sequences. High subsidence supported high sedimentation rates of Pleistocene deposits and the highest subsidence occurs in the eastern part of the major geological blocks [22, 23]. In the central part of the district, lignite seams lie in a depth of up to 300–600 m below surface as a result of the still ongoing tectonic processes (Fig. 6).

Germany's easternmost lignite mining district in Lusatia (Fig. 5) is part of the northeastern lowlands and was, in comparison to the Rhenish district, directly influenced by Pleistocene glaciations. They left behind typical glacial

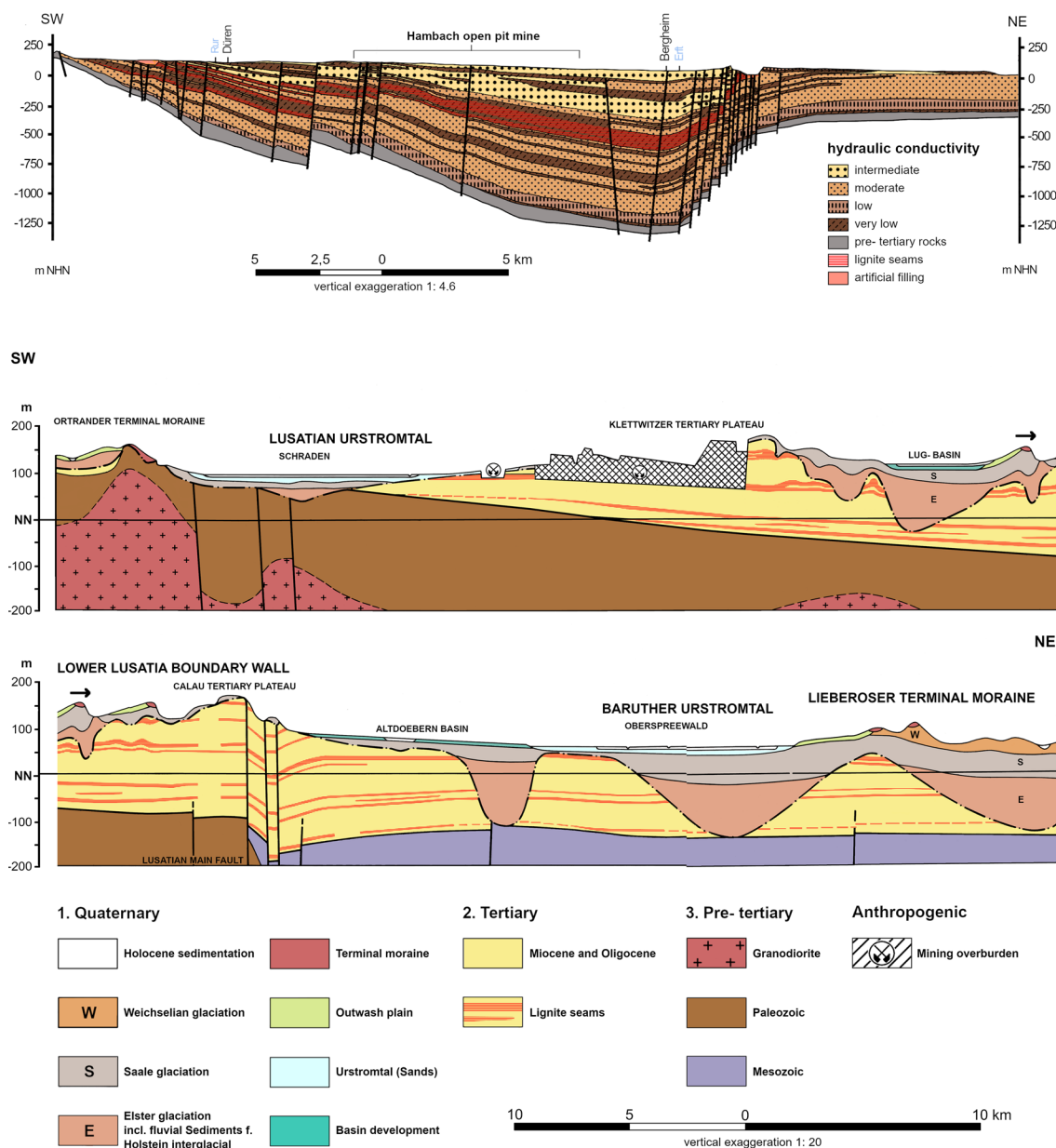


Fig. 6 (above) Geological cross-section (SW–NE, see Fig. 5: A–A') of the Rhenish lignite mining district with hydraulic conductivity of Tertiary and Quaternary deposits and main coal seams; (below, divided into two parts) geological cross-section (SW–NE, see Fig. 5: B–B') of the Lusatian lignite mining district with Tertiary and Quaternary deposits; note the different horizontal and vertical scales of both profiles (sources: redrawn from [32, 33]. Draft: F. Lehmkuhl, T. Rüde, and D. Stawinoga

series with ice marginal valleys (*Urstromtal*), outwash plains, terminal moraines, and basal tills. Paleozoic and Mesozoic sediments are, therefore, covered by thick Cenozoic layers. The Tertiary layers in Lusatia reach a thickness of up to 200 m. In contrast to the Rhenish region, existing recent tectonic processes are of minor importance [34]. Youngest faults within superficial layers developed during the Pleistocene caused by glacial

deformation in terminal moraines. These glaciotectonics locally dislocated Tertiary layers with lignite seams near to the surface allowing for early small-scale mining in these areas (e.g., Muskauer Faltenbogen). Four major lignite seams can be distinguished (Fig. 6). The oldest and deepest seam (fourth Miocene seam complex) originates from the earliest Miocene and its exploitation is only of subordinate importance. The active lignite production

today mainly relies on the second seam complex deposited during the Middle Miocene [35]. The uppermost seam was already widely mined in the first half of the twentieth century. Lignite seams can be found in depths of up to 100 m below surface level with a thickness of up to 20 m. Due to the mentioned subordinate relevance of neotectonic processes, lignite seams are mostly maintained in their original horizontal stratification which allows for the use of overburden conveyor bridges as a very efficient mining technology. The open cast mines do not reach comparable depths as in the Rhenish district but cover large areas. The ratio between overburden removal and lignite production, however, is in a similar range of values for both mining districts with some slight changes over the years (2020: Rhineland: 6.0: 1, Lusatia: 6.1: 1/2021: Rhineland: 4.0: 1, Lusatia: 5.9: 1; data from [36]).

Very different soil landscapes developed in both districts. In the Rhenish lignite district, soils are developed on Pleistocene fluvial and/or aeolian sediments. While, the sandy or gravelly terrace sediments deposited by the rivers Rhine, Meuse, and Rur as well as their tributaries are widespread in the topmost sediment sequences. In the vicinity of larger rivers, the aeolian sediments, mainly loess and loess derivatives, cover larger areas of the LRE [37]. Luvisols and Stagnosols developed at the loess covered surfaces and they offer a huge agricultural potential as they provide optimum water and nutrient supply for crops. Traditionally, wheat and sugar beets are intensively cultivated on these sites. In Lusatia, however, parent rock material for soil development is predominantly poor and consists primarily of glacial sands and loamy substrates from glacial till are only of secondary relevance. Therefore, Brunic Arenosols, Cambisols, and Podzols are frequent in Lusatia. These soil types with mainly sandy texture provide only poor water and nutrient holding capacities and poor soil quality for agricultural land use.

Whereas the fertile Luvisol sites of the Rhineland have been in agricultural use since the Neolithic and especially Bronze Age, larger areas with Stagnosols were covered by deciduous tree forests since the Middle Ages (Hambacher Forst). The potential natural vegetation in this region would be forests dominated by European beech (*Fagus sylvatica*) with oak (*Quercus robur*) and European hornbeam (*Carpinus betulus*) as further important tree species. In contrast, agricultural utilization of soils in Lusatia is limited by generally poor soil qualities. Yield potentials for agricultural crops can be considered as low. Large parts of the region are, therefore, covered by forests adapted to the poor soil quality and naturally occurring water stress [38]. Today, these forests are dominated by pine trees (*Pinus sylvestris*) as the result of long-term forest management. The potential natural vegetation in

this landscape would be oak-dominated forests (*Quercus petraea* or *robur*). Pine (*Pinus sylvestris*) would be mixed in at very dry or extremely acidic sites.

Cultural landscape development and mining history

Of major importance for the development of the traditional cultural landscapes were the potentials for agricultural food provision. These traditional cultural landscapes have been massively transformed during the twentieth century by mining operations. However, already during pre-industrial times, both regions have been changed by humans and, therefore, recent landscapes must be seen as a result of complex human–environment interactions since the earliest settlements. The general timeline is summarized in Table 2.

The use of lignite in the Rhineland is an old tradition reaching back to the sixteenth century [51]. Mining activities increased during the eighteenth and nineteenth centuries with numerous small-scale lignite mines [52]. At the end of the nineteenth century, first bucket-chain excavators came up and supported the development of larger open cast mines. The lignite seams are in very different depths due to the Cenozoic faulting and block formation with the highest seams in the most eastern, the Ville unit (Fig. 6). Industrial lignite mining started in this part of the district southwest from Cologne where lignite seams could be easily reached in shallow depths. This situation allowed for easy access to lignite seams by means of small pits [53]. In the following decades, mining activity moved to the north along the Ville unit west of the river Rhine. With the depletion of these lignite resources in minor depths, mining activities had to be adapted. In the second half of the century, new areas for mining were established west of the Ville between Cologne and Aachen. Using large-scale bucket-wheel excavators, lignite is now mined in a depth of up to 400 m below surface [54].

In Lusatia, lignite was used for the first time in 1789 [16]. However, lignite mining in larger scales started not before the middle of the nineteenth century. In the beginning, small underground mines were opened where the geological situation allowed for easy access. One of these regions was the Muskauer Faltenbogen, a folded ridge of the Saalian (Warthe) terminal moraine range where lignite reaches the surface due to glacial tectonic processes. Therefore, the early lignite production started in the nineteenth century in this area. An important step for a very efficient coal production was the invention of the overburden conveyor bridge technology. The first overburden conveyor bridge worldwide was put into operation in 1924 [55]. The latest development of this technology was the construction of the overburden conveyor bridge type “F60”. In 1989, 300 Mt lignite were produced in Eastern

Table 2 Historical timeline of Rhineland and Lusatia with reference to main eras of European history (Database [39–50])

Age		European history	Rhineland	Lusatia
BCE	5300–2200	Neolithic	Farming in the forest Clearing islands	Funnelbeaker Culture First farming activities starting mainly in Northern Brandenburg
	2200–1300	Early and Middle Bronze Age	Farming in the forest Clearing islands Expansion of the cultivated land New: meadows and pastures	
	1300–800	Late Bronze Age	Urnfield Culture	Lusatian Culture Fortified settlements
	800–475	Iron Age Hallstatt C/D	Iron ore extraction and processing Expansion of arable land, meadows and pastures	
	475–27	Iron Age Latène	Extensive clearings Expansion of the arable land, meadows and pastures	Settlement of Germanic tribes Iron melting centers
CE	27 BCE–284 CE	Roman Empire (early and middle)	Villae rusticae Surplus agriculture	
	284–450	Late Antiquity	Abandonment of settlements and deforestation	Immigration of Slavic tribes Iron production
	450–919	Early Middle Ages	New settlements and clearings	
	10th–13th c	High Middle Ages	Greatest expansion of cultivated land	German colonization and Slavic minority (Wends and Sorbs) Agricultural landscape (mainly poor soil quality)
	14th–15th c	Late Middle Ages	Agricultural crisis	Iron works of Peitz
	16th–19th c	Early Modern times	Industrialization	Glass and textile factories
	20th c.–today	Modern times	Large-scale lignite mining	

Germany (in both mining districts of Lusatia and Central Germany) and Lusatia was the clearly dominating mining district of the GDR [15]. Large areas were devastated but a proper reclamation was often neglected. With the end of the GDR in 1990, only three mines in the State of Brandenburg (Jänschwalde, Cottbus-Nord and Welzow-Süd) and two in the State of Saxony (Nochten and Reichwalde) were continued and privatized and are still active (Cottbus-Nord had its scheduled closure in 2015). In total, 32 open cast mines were closed in the last decades in both Eastern German lignite mining districts (Lusatia and Central Germany) [15]. In this context, the *Lausitzer und Mitteldeutsche Bergbauverwaltungs-gesellschaft mbH* (LMBV) was founded in the 1990s as a federally owned company responsible for restoring these huge post-mining areas.

Changes and disturbances of the cultural landscapes

Today, the cultural landscapes of both investigated regions are influenced by complex disturbance regimes and undergo significant changes. Parallel to the ongoing disturbances caused by mining, additional effects of global change processes become obvious, too. In land-use maps “mineral extraction sites” are present in both regions to a large extent representing the large-scale open cast lignite mines. These vast areas have been completely

transformed by mining operations. Existing ecosystems have been destroyed and also the surrounding landscapes have been severely affected. These disturbances influence the ability of the respective cultural landscapes to provide traditional ecosystem services.

Climate

In the context of the recent climate changes, alterations of the atmospheric conditions determining the precipitation and temperature behavior are to be expected as reported by various studies. Werner and Gerstengarbe [56] showed that the occurrence of zonal circulation patterns in the winter months significantly increased, which was confirmed by Hoy et al. [57] and Szymanowski et al. [58]. The consequences are more frequent cyclones passing over central Europe associated with an increase in the precipitation totals in the winter season. Concerning the maximum daily precipitation, [59] demonstrated a statistically significant increase for the upper Lusatian Neisse River basin. However, during the summer months of the past years, Germany suffered from extreme drought events with considerable impacts on the soil–vegetation–atmosphere interactions [60, 61] and resulting in a massive increase of forest fire activities particularly in Brandenburg [62]. Furthermore, Brandenburg experienced notable water shortages, which are associated with an increase in the summer days. As shown by [63],

trends in the drought conditions over Central Europe are dependent on season as well as season definition. The authors found the strongest drying trend in spring rather than in summer, while autumn and winter showed a wetting effect, but an even stronger effect considering the early vegetation period (April–June). A driving factor of drought conditions is evapotranspiration, which increases with rising air temperatures. In lignite mining areas as the Rhenish and Lusatian region, the scarcity of water is further fostered due to low groundwater level as well as sparse vegetation. Lusatia is characterized by a negative climatic water balance with a high potential evapotranspiration of around 600–650 mm/year [64], which leads to the estimated low annual groundwater recharge ranges between 28 and 440 mm/year [65].

Hydrology

The mining company RWE Power in the Rhineland has pumped off 512 Mill m³ for mine dewatering in the year 2019/2020. Beside water supply to the power plants and some water suppliers, 132 Mill m³ were used for managed aquifer recharge. Especially in areas north of the Garzweiler open cast mine (Nordraum), groundwater conditions are significantly controlled by managed aquifer recharge, particularly to support groundwater-connected wetlands, even some decades after mining has ceased. At the peak, up to 1.3 billion m³/year of groundwater was pumped for dewatering [13]. At the same time, controlled groundwater rise is taking place in several areas as part of the rolling mining system. Due to the long mining history, measures for controlled groundwater rise will last until the 2080s/2090s. By then, the three future mining lakes will be the largest artificial lakes in Germany. They will cover a total area of approx. 7000 ha and will hold a water volume of approx. 6.8 billion m³ [66]. The future lake Hambach will be up to 360 m deep. Original plans for this mining lake assumed a volume of 4.6 billion m³, which exceeds the volumes of all natural lakes in Germany, with the sole exception of the Lake Constance (Bodensee) [67]. Due to the planned earlier stop of lignite production in the Rhenish district in 2030, the plans for these lakes have to be reconsidered and their final dimensions are still subject to public discussions. The future lake levels should be balanced with the groundwater level and they will also be connected to rivers (Inde, Erft, Niers).

With the closure of several Lusatian mines since 1990, groundwater tables are rising again but the discharge of mining water into the regional rivers is decreasing substantially. Serious effects of these contrasting processes on the cultural landscape, particularly on protected wetlands, became already during the last decades [68] and are subject of current debates. Already today, several

large artificial mining lakes exist in the Lusatian lignite mining district as a direct result of mine closures in the 1990s. Naturally, in this region, only few smaller lakes occurred, so that these new lakes generally offer potentials for new ecosystem functions and services. Part of them form the currently largest artificially created lake area in Europe with 14 interconnected large mining lakes and a total area of 7000 ha [69]. The total number of mining lakes in Lusatia is higher and Grünewald and Schoenheinz [14] report on 26 larger mining lakes that have been analyzed with regard to their water quality. The temporarily largest artificial lake of Germany will be the Cottbuser Ostsee with an area of 1,900 ha filled—according to current schedules for the flooding process—approximately until the mid of 2020s, which is recently formed in direct vicinity of the city of Cottbus in the northern part of the Lusatian lignite mining district [70]. These lakes can be regarded as mostly nutrient poor and clear. Nixdorf et al. [69] mention that half of the mining lakes in Lusatia differ significantly from natural lakes as they show very high acidity with low pH values between 2 and 4. These very acidic lakes offer extreme habitats mainly for microorganisms [71].

This strong acidification is the effect of pyrite weathering processes in the subsurface of mine sites, also known as acid mine drainage (AMD). In a few sedimentary layers, disulfide contents of on average 0.2 wt% sulfur (S) occur as pyrites also in the Rhenish district [72]. For the anthropogenic use of the subsurface, the disulfide-bearing rocks have significant meanings. Aeration of the rock in the course of the regional dewatering has led to an oxidation of the sulfidic minerals causing a sulfate load of the groundwater. Sulfate load to the groundwater has been caused by lignite mining and partly by agriculture. Sulfate is mainly conservatively transported and diluted by groundwater recharge and groundwater inflow. In accordance with predicted sulfate plumes, water extraction areas for public water supply have been and will be relocated especially east of Hambach [73]. In Lusatia, the recent hydrological situation is not only characterized by effects of excessive groundwater lowering during the last decades but also by a significant alteration of the chemical composition of both ground and surface waters [14]. Particularly, the high sulfur load in the river Spree becomes a clear obstacle for the provision of drinking water in the capital region around Berlin [74]. In their study, the authors [74] show several ecological effects of high sulfate loads in the river Spree (e.g., eutrophication due to release of phosphate from sediments). In addition, iron hydroxides from AMD are responsible for severe ecological issues in the rivers of the mining district and endanger nature reserves like the Spree Forest. Solving such AMD-related problems requires special measures,

e.g., lime addition (blending) [73–75], for the deposition in the overburden dump sites. On the other hand, pyrite oxidation may cause a substantially reduced nitrate loading from agriculture of deeper groundwater resources by chemoautotrophic nitrate reduction [76]. However, the sulfate load in specific areas have to be observed in all intended groundwater uses for several decades after mining has ceased.

Geomorphology

Most obvious changes due to mining operations are visible in the landscape's topography. Huge overburden masses had to be removed and transported to overburden dumping sites where hills or larger artificial mountains were formed. Conversely, deep hollows remained at excavation areas of the mining districts due to the removal of overburden material and the extraction of lignite. After mine closure, these hollows are subjected to flooding and develop into artificial lakes. In case of the Rhenish Ville, mining resulted in massive changes of the surface topography as shown exemplarily by Henselowsky et al. [54]. Several of the artificially created mountains have large dimensions. For example, the outer overburden dumping site of Hambach (Sophienhöhe, see Fig. 2) with a volume of about 2 billion m³ resulted in the largest artificial height of the LRE up to 200 m above the flat natural landscape, covering an area of 1000 ha [77]. Several other heaps have been dumped during the last decades in the Rhenish district, some of them also with heights of up to 100 m above the original landscape surface [78]. Future giant artificial lakes with wide stretched water surfaces and very great depths will be formed after closure of the still active Hambach, Garzweiler and Inden large-scale open cast mines. Also running waters have been affected by mining processes. Between 1998 and 2005, a 4-km long and straight section of the Inde River has been relocated resulting in a 13-km long new river (New Inde River) around the Inden open cast mine due to the eastward extension of the lignite mining [79]. The new artificial river section is still geomorphologically "naïve" and characterized by temporary, highly energetic morphodynamic processes resulting in strong erosion processes in the river bed and the surrounding area. Extreme precipitation and resulting extraordinary discharge on July 15th 2021 caused serious flooding and erosion in the Inden open cast mine. After heavy rainfall, bankfull discharge of the Inde River resulted in a spillover into the open cast mine. As the lignite mining is more than 200 m below the surface, rapid erosion of the old channel and fast backward erosion created a 540-m long gorge which was about 5 m deep. More than 500,000 m³ of material were eroded and subsequently accumulated in the open cast area. A similar event happened at the Erft River close

to the settlement Erftstadt-Blessem flooding a 60 m deep gravel pit [80]. In both areas, erosion and sediment transport occurred, showing the high risk and strong geomorphological processes in flooded open cast mining areas with large base-level changes on short distances. However, due to the spillover of water, the flood in the lower reaches of both open cast mines was reduced. In future, the open cast mine can store water and could be used as retention basins for flood protection.

The Lusatian lignite mining district is characterized by massive changes of the original geomorphology, too. Small-scaled hollows occur in many parts of the district where lignite was produced in subsurface mines in the nineteenth and early twentieth century [81]. Similar to the Rhenish district, the ongoing open cast mining caused large-scale translocation of overburden material. The heaps in Lusatia are generally smaller with lower heights as most of the overburden material is transported by the conveyor bridge technology over short distances and is dumped within the same pit. In contrast to the Rhenish district, a large number of mining lakes is already finally flooded or close to finalization—many of them with huge dimensions.

Soil conditions

With the translocation of overburden material, initial soil development starts at post-mining sites. Generally, the dumped substrate can be classified as loose sedimentary material deriving from Quaternary and Tertiary layers. Mining companies are legally obliged according to state regulations in North Rhine-Westphalia and Brandenburg to dump the most fertile substrates to the surface of the post-mining landscapes. For this reason, loess is used for the formation of the new surface morphology in the Rhenish region. As a result, Calcaric Regosols can be found on these post-mining sites as young (initial) anthropogenic soils. Such soils offer a high potential for agricultural land use. Future forest sites in the post-mining landscapes of the Rhineland are covered by a mixture of loess and fluvial substrates called forest gravel (*Forstkies*) [82]. Schulte et al. [83] investigated initial soil formation in the morphodynamically active artificial river valley of the New Inde River constructed with this restoration substrate.

In contrast, loess is not available for reclamation in the Lusatian lignite mining district. Parts of the surface of the Lusatian post-mining landscapes are covered by mixed substrates from Tertiary and Quaternary layers. Tertiary substrates frequently contain larger amounts of pyrite which results into extreme soil acidification with pH values below 3 due to AMD processes. Such soils have a massive demand for amelioration by applying large amounts of calcareous material [84]. Especially during

early years of large-scale mining, this was a major issue as Tertiary and Quaternary substrates were not deposited separately. In recent decades, more attention has been paid to placing the more cultivable Quaternary substrates free of pyrite in greater thickness as a near-surface cap to the dumps to avoid this extreme acidification. Gerwin et al. [85] offer an overview of soil types developing at post-mining sites in Lusatia. Arenic and Dystric Regosols are typical soil types in Lusatian post-mining landscapes with non-calcareous substrates. The soil quality of such sites is mainly limited so that the main part of the post-mining landscape is used for forestry. Agricultural land use can also in Lusatia be re-established at sites with better cohesive properties, e.g., from glacial till [86].

Biology

Mining activities can be regarded as one of the most severe disturbances in terrestrial ecosystems and particularly open cast mines completely destroy formerly existing ecosystems. In recent years, this destruction of landscapes and natural habitats became subject of intense political debates in both districts. Especially, the excavation of the Rhenish Hambach forest brought the debate about lignite mining into the public consciousness. On the other hand, post-mining landscapes represent important case studies for severely disturbed ecosystems and offer manifold opportunities for studying the regeneration and redevelopment of ecosystems starting from a well-defined point in time [87, 88]. Comprehensive ecological research on faunistic and floristic colonization has been carried out particularly in the Lusatian lignite mining district but to some extent also in the Rhineland. A large part of the research in the Rhineland has been performed by a mining company owned research center (*Forschungsstelle Rekultivierung*) and results are only partially published in scientific papers [11]. With regard to forest development, it could be shown for the Sophienhöhe dump, that it was possible to transfer more than half of the species inventory of vascular plants of the near-natural forest community to the reclamation areas and to establish them there [89]. Greater attention was laid on soil fauna and ground-dwelling beetles as indicators for ecosystem development [90, 91], but also the interactions between plants and soil properties have been reflected [92]. The state of biodiversity in the landscape of the Rhenish mining area before and after the mining activities, including an assessment of the deficits, is summarized by Imboden and Moczek [93]. Plant communities in former open cast mines in Lusatia under passive restoration (natural succession) are predominantly characterized by colonization from the local species pool [94]. Subsequent colonization often results in highly dynamic changes in species richness and composition.

An artificial watershed (Hühnerwasser/Chicken Creek) was constructed in the Welzow-Süd open cast mine and used as a terrestrial observatory for ecosystem development [95]. Its rapid colonization by plants has been annually monitored showing distinct phases of development [96]. On the other hand, active restoration and reclamation are important approaches to establish vegetation in former open cast mines, e.g., near-natural greening with local seed mixtures [97]. Afforestation in former Lusatian open cast mines, as planting of selected tree species, results in tree-dominated ecosystems with the respective microclimatic conditions within 25 to 30 years after initiation [98].

The colonization of Lusatian open cast mines by below-ground invertebrates via air, water, transported material or active locomotion [99] initially depends on the soil texture and the present pioneer or planted vegetation [100]. Bacterivorous Nematodes and Tardigrades dominate soil invertebrate communities in the first few years with subsequent shifts toward species that also utilize plant-based resources (dead organic matter and live biomass) [101]. Microarthropods (e.g., Collembola and Acari) immediately colonize mining sites as part of the aerial plankton community [102], but the establishment of populations of Trombidiformes mite or Tullberginae Collembola species, as the most successful microarthropod pioneer taxa, takes several months or up to 1 year [103]. The lack of competition with earthworms in initial stages may result in very high abundances of Collembola if post-mining sites provide sufficient plant litter [100]. However, even more than 40 years after afforestation, soil invertebrate communities do not reach abundance, biomass or richness levels that resemble communities in forest stands of similar age outside of the mining areas [100]. Generally, dynamics of soil invertebrates in afforested mining sites show a consistent trend from open pioneer to woodland communities in Lusatian open cast mines [99]. Lusatian post-mining habitats harbor approximately 30% of all insect and spider species described for the State of Brandenburg in total [104]. The species richness of aboveground arthropod communities of Lusatian post-mining landscapes is primarily related to the diversity of plant communities [105] and often includes otherwise rare pioneer species and steppe specialist (e.g., *Cylindera arenaria*) that can even act as important ecosystem engineers [106].

Economy and society

The valuation of ecosystem services depends on the relevant framework conditions. Regarding the situation in the two mining regions, they can relate, for example, to the need for jobs and the economic environment. When comparing the Rhenish mining area and the Lusatian

lignite mining area, succinct differences are apparent even at first glance [107]. While the absolute number of workplaces in both mining areas is roughly the same, with direct employment of 8278 employees in Lusatia and 8961 employees in the Rhineland, (direct plus indirect employment 13,245 in Lusatia and 14,338 in the Rhineland; all data for 2016 from RWI, 2018), there are distinct differences in the sector mix and the relative economic importance of lignite mining. At 4.3% of the gross value added and 3.3% of employees subject to social security contributions, the importance of mining-related workplaces in the Lusatian area is substantially higher than in the Rhenish region, where it accounts for 2.4% and 1.8%, respectively. The differences are even more pronounced in terms of commercial and income tax revenues, which account for 4.3% and 4.6%, respectively, for the Lusatian mining area and only for 2.4% and 2.0%, respectively, for the Rhenish mining area. Another major difference lies in the economic environment. Whereas the Rhenish mining region is mainly surrounded by economically strong cities that can absorb employees, the Lusatian mining region is mainly surrounded by structurally weak regions. This led to a massive migration and brain-drain from Lusatia during the last decades, which altered the demographic structure significantly. In addition, the Rhenish soils promise significantly higher agricultural productivity

than the soils in Lusatia. Without drawing any premature conclusions at this point, it can be noted that these factors play a role in evaluating and setting target levels for various ecosystem services in the two regions.

Future challenges and perspectives

Challenges

In the previous sections, we have pointed out the impact of mining operation in both lignite mining districts on ecosystem compartments and with that on their ability for providing ecosystem services. Ecosystem services can be seen as connectors between vivid ecosystems and human well-being (see Fig. 1). The provision of different types of ecosystem services (supporting, providing, regulating, cultural) requires intact ecosystems. This view highlights that both humans and other living beings are dependent on well-functioning ecosystems with their various spheres. Only if the entire and complexly interacting ecosphere (atmosphere, hydrosphere, lithosphere, pedosphere, biosphere) is sufficiently understood, desired levels of biodiversity and the provision of ecosystem services can be successfully achieved. In this context, it is valuable to emphasize that a scientific analysis should precede the initiation of ecosystem design measures. Only then can reclamation and restoration measures be targeted and successfully implemented (Fig. 7).

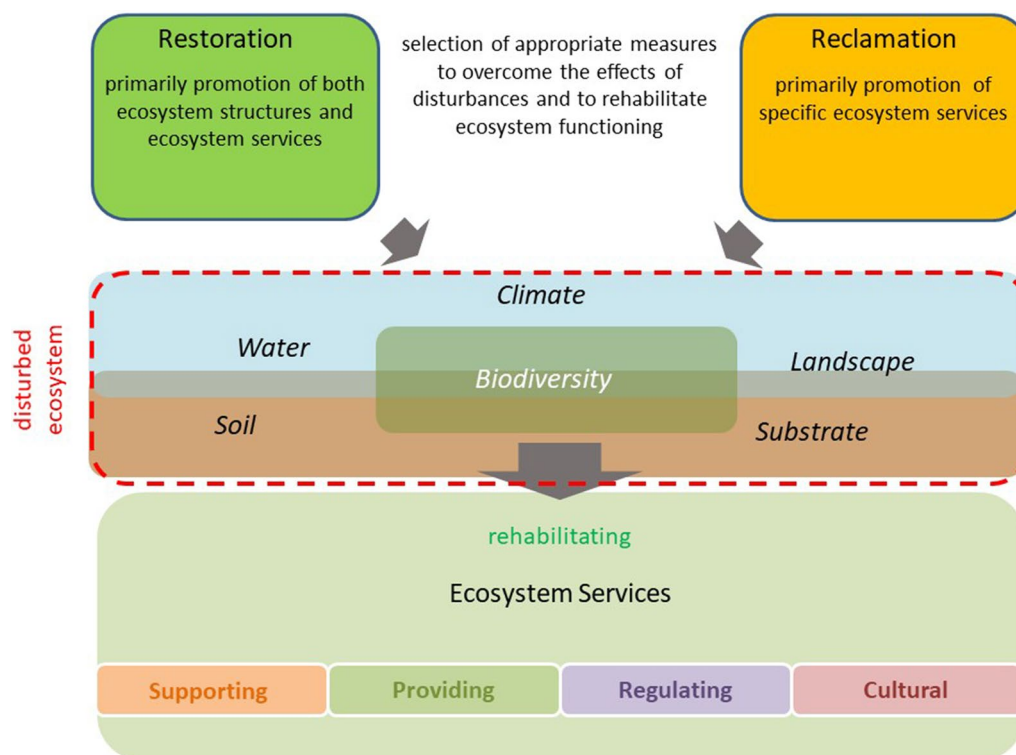


Fig. 7 Recovering ecosystem services by means of restoration and reclamation

Especially the transformation processes in the Rhenish mining area and in Lusatia offer the opportunity to reorient ecosystems, which were massively damaged in the past, in the sense of a stronger concentration on ecosystem services and not only on individual economic profits. However, a large number of challenges is coupled with this transformation process.

Supporting ecosystem services—soil health and biodiversity

Supporting ecosystem services are the basis for ecosystem functioning but also for agricultural and silvicultural production. Soil health plays a central role here. Post-mining landscapes, both in the Rhineland and in Lusatia, represent sites after severe disturbance. As a result, former soils are more or less completely destroyed and soil health minimized. In the past, massive soil physical problems occurred (compaction and wetting) at post-mining sites of the Rhenish district [108]. Adequate management options had to be developed for carefully handling loess as a highly sensitive material, so that a stabile soil structure can develop again with time [109]. Even if soil compaction is also a challenge for reclamation processes in the Lusatian lignite mining district [110], the main issues in Lusatia are related to the chemical properties of mine soils. In part of the post-mining landscapes of Lusatia, pyrite containing sediments of Tertiary origin have been dumped to the surface of spoil heaps, with significant negative effects on soil acidity and related soil chemical properties due to oxidation processes (AMD processes, see above). Such acidic mine soils have to be ameliorated with huge efforts [111] and can be frequently found in open cast mines of Lusatia that had been reclaimed already during former GDR times. But still today, Tertiary substrates with higher amounts of pyrite are partially in use for reclamation. Legally, mining companies are obliged to preferentially use pyrite-free, Quaternary substrates at the surface of the dumpsites, particularly, for later agricultural sites [112]. However, suitable substrate is partly not available, at least in the needed quantities. Furthermore, quantity and quality of soil organic matter (SOM) are of crucial importance for soil health. Mine soils are usually characterized by very low recent SOM or humus content due to the mixing of substrates from different depths during overburden removal. In contrast, geogenic organic matter (lignite particles) can be frequently found in mine soils of Lusatia, so that the total carbon content might be high despite very low humus contents [113]. SOM is gradually accumulating with soil development [114, 115], but for a fast and proper provision of soil functions and related ecosystem services, this process needs to be accelerated—if possible. Positive effects of compost or sewage sludge application have been observed [116–118].

Due to the excavation of the Hambach forest, large parts of a 5,500-ha large area of the valley forest with very old oak, hornbeam, and lily have been lost, except for 500 ha. Reintegrating the lost forest areas into the future landscape with a quality of a near-natural managed forest with native species will be a challenge for the future. The re-establishment of near-natural meadows, field margins, and hedges as landscape elements typical of the natural area must be included in the development of the area. To achieve this goal, overall concepts (Leitbilder) and thresholds for biodiversity are needed to define the best case given for agricultural usage within a certain class of cultivated landscape and give information about the regional ecological potential of biodiversity.

Providing ecosystem services—fresh water and biomass

Hydrological issues will occur during the following decades in the Rhenish district. Dump-seepage water has higher mineralization and is dominated by sulfates compared to groundwater [119]. Only over long periods of time, regional groundwater flow will restore chemical equilibria in the dumps. Initially, only the uppermost groundwater horizon, which is controlled by groundwater recharge, is amenable to groundwater extraction in these areas. For several decades, deeper dump water is feasible for irrigation and industrial water only when linked to adapted sulfate-tolerant cultivation methods and sulfate-compatible industrial processes. Such planned measures would increase the exploitable groundwater reserve. Quantity and quality of both groundwater and inland waters of Lusatia have been heavily affected as well by mining operation during the last decades [14]. Due to groundwater lowering, the regional water balance is severely disturbed. In 2020, 256.1 Mill m³ pumped groundwater was discharged into the river Spree [120] guaranteeing a sufficient flow volume for securing important ecosystem services (e.g., conservation of the semiterrestrial landscape of the biosphere reserve Spreewald or the provision of drinking water for the metropole region of Berlin). With progressive mine closures, the amount of pumped water is constantly decreasing during the last 30 years and it is under debate if the remaining water will be sufficient for maintaining a minimum flow volume in the river. The situation is getting worse with the already noticeable consequences of regional climate change (see below) and new concepts for water storage are discussed [120] including the emerging mining lakes as reservoirs. However, not only the quantity of water must be considered as critical. Due to AMD processes, huge amounts of iron hydroxides and of sulfates are discharged.

The agricultural yield potential of post-mining sites in Lusatia is often low. This classification is generally confirmed by the official German land appraisal

(*Bodenschätzung*). Soil scores are between 25 and 30, with the only exception of loamier sites with scores up to 38, whereby 100 is the maximum for soils in Germany [112]. In contrast, reclaimed post-mining sites in the Rhenish district with loess as a substrate reach a high soil quality after 20–30 years of soil development. For instance, in the reclamation area of the Inden open cast mine, soil scores of up to 80 can be frequently found [121]. The frequently infertile post-mining soil conditions in Lusatia, however, are the reasons for experimental cultivation of alternative crops [122]. Particularly, renewable resources such as fast growing tree species seemed to be a promising alternative to conventional agricultural crops [123]. However, a comparison of growing conditions of black locust on fertile agricultural sites and post-mining sites in Lusatia made clear, that post-mining sites are more seriously affected by drought periods with negative impact on the growth rate [124] and, therefore, also on the practicable implementation of such land-use concepts seems to be questionable. Potential deficits of water supply for trees have also been reported for forest stands in post-mining lands of Lusatia with sandy substrate due to chemically limited rooting depths as result of pyrite weathering and extreme acidification in the subsoil [125]. Generally, the tree species composition of a large number of forest sites in the post-mining areas of Lusatia is still dominated by pure Scots pine (*Pinus sylvestris*) stands. Such monocultural stands will most probably be a rapidly growing challenge in future with regard to their susceptibility to diseases, to their negative impact on groundwater recharge and soil conditions as well as to their high predisposition for wild fires.

Regulating ecosystem services—climate regulation and groundwater recharge

New challenges are also coupled with the ongoing climate change. According to the RCP8.5 scenario [18], both areas will exhibit an average increase in annual precipitation by 11.1% (Lusatian) and 5.3% (Rhenish), mainly driven by a strong increase of winter precipitation. While in the Lusatian area, summer precipitation is expected to increase slightly (4.1%), the Rhenish area will face a reduction of almost 9% during the summer months. A clear difference in the development of precipitation in both areas can also be seen in the number of dry days, which are projected to increase by more than a week in the Rhenish area, while staying unchanged in the Lusatian area. Heavy precipitation events will increase in both areas quite similarly. Concerning the air temperature, a warming trend can be observed for both areas. The projections for air temperature until the end of the century see an increase of 3.5 °C for the Lusatian area, driven mostly by a stronger increase in the winter time

with 4.0 °C, and 3.2 °C for the Rhenish area. The number of hot days is expected to increase with this scenario by 12.5 (Lusatian) and 10.9 (Rhenish) days per year, respectively, so is the number of tropical nights around 8 days per year and the maximal duration of heat periods by around 3 days per year for both areas. The number of days per year above 5 °C increases by 60.2 (Lusatian) and 56.8 (Rhenish), the number of frost nights decreases in both areas by 57.5 (Lusatian) and 40.6 (Rhenish), respectively. Other scenarios yield different values; however, the general trends are consistent. The increase in temperature will lead to higher evaporation rates leading to lower surface and soil water availability, especially in the summer season in the Rhenish area. In total, these climate changes will result in negative effects on ecosystems (e.g., by enhanced erosion) and human well-being and health.

Groundwater recharge is not only influenced by temperature or evapotranspiration, quite crucial is the amount and timing of winter precipitation in particular. Hermann et al. [126] have examined 37 climate projections. In the vast majority of projections, groundwater recharge will remain the same or increase slightly over the reference period through the end of the century in the LRE. Drier and warmer summers will result not only in increased groundwater pumping for public water supplies, but also in increased demand for irrigation water in agriculture. There is a need for optimized irrigation methods and comprehensive water demand assessments including rigorous monitoring. Although groundwater recharge will remain largely unchanged according to current projections, the sustainably available groundwater reserve will nevertheless come under pressure due to the effects of climate change.

Cultural ecosystem services—socioeconomic development

Both regions face the same challenge that the employment in mining and the related industries and services has to be replaced by employment in other sectors and/or nearby regions (for an overview of the general socioeconomic challenges of fossil fuel phase-out [127]). This is likely to be more difficult in Lusatia than in the Rhineland due to the higher relative economic importance of the mining sector and related industries (see for a comparison of the two regions: [127]). For Lusatia, several specific challenges arise. The surrounding areas are economically weak and the next economically strong regions, namely Dresden and Berlin and their surrounding areas, are not well connected to Lusatia in terms of transport infrastructure. There is no substantial industrial or service sector with a high growth potential in Lusatia. Land-use-based economic activities have partly contradicting requirements. In particular, nature-based tourism such as cycling and boating is expected to have

some potential for the further economic development of Lusatia, but other economic development options like “energy landscapes” with a large-scale installation of photovoltaic parks may have a negative impact on tourism. Further negative impact on tourism in the Lusatian post-mining areas results from access restrictions due to still existing severe risks from former mine sites. Particularly, extreme acidity and mechanical stability of spoil heaps make access to many watersides and their use for aquatic sports impossible [128, 129]. Stabilization measures will take many years to be completed [130]. In the mid-to-long term, climate change may lead to water scarcity in summer with negative impacts on the economically relevant areas of agriculture and tourism, e.g., due to reduced boating opportunities in the biosphere reserve Spreewald. The Rhenish mining area offers better conditions—both climatically and in terms of the surrounding economic landscapes. Several major cities (Düsseldorf, Mönchengladbach, Aachen, Cologne) can absorb employees and provide skills for the Rhineland region through their strong educational institutions. These become important when enterprises drawing on sophisticated technologies become active and invest in the former Rhenish mining area. In addition, the aforementioned metropolitan areas have a need for expansion in terms of living and working space due to the very high real-estate price levels and high land prices. However, expansion of metropolitan areas needs careful planning to avoid further losses of ecosystem services due to sealing surfaces with settlements and traffic infrastructure.

Perspectives

Adapted land use and land-use change

As outlined above, both lignite mining districts are still characterized to a large extent by agricultural landscapes. In the case of Lusatia, however, poor soil quality impedes successful reclamation and the resulting post-mining sites must be frequently considered as marginal lands. The utilization of marginal lands is a scientific research area that rapidly developed over the last two decades worldwide. The use of marginal land that is not productive for traditional agriculture, might be a solution for mitigating land-use conflicts and for promoting a future bioeconomy. Studies on potentials for cultivating, e.g., fast growing trees for bioenergy production in Germany, showed that particularly the State of Brandenburg offers opportunities in this regard [131]. A large number of scientific publications is dealing with definitions of marginal lands (for an overview, see [132]) and often poor soil quality is seen as the main factor for marginality. Poor soil quality of post-mining lands in Lusatia is a clear constraint for traditional land use, so that alternative land-use options might be of interest. They might include short rotation

coppices and agroforestry systems for producing biomass for heating and electricity production [133], even if the expected yields are not very high. However, cultivating perennial crops like fast growing tree species probably promotes the development of soils and of their functions by SOM accumulation [134] and formation of a stable soil structure [109]. Careful planning of such alternative land-use concepts and integration into existing land-use strategies is necessary to avoid new conflicts with biodiversity conservation [135]. In addition, post-mining lands offer further potentials for special crops, e.g., winegrowing can be an option if site conditions (relief, substrate) are formed adequately [136]. Viticulture is already successfully practiced in the reclamation areas of two former lignite mines in Lusatia and might attract also tourists in the future. Research on further ideas for future land use and concepts for the bioeconomic use of the Lusatian lignite mining district is funded by the Federal Ministry for Education and Research (BMBF) within the initiative “Land-Innovation Lausitz (LIL)” as part of the recent national support activities for structural change in the lignite mining districts [137]. New technologies are tested for mitigating low soil quality, e.g., by means of soil additives. Positive effects of their application on soil properties in post-mining substrates of Lusatia had been reported already earlier [138]. Regarding ideas of increasing renewable energies in form of wind parks and especially large-scale photovoltaic (PV) fields, marginal lands might offer sufficient space and thus could also be an interesting option for alternative land use. However, competing aspects on land demand and negative environmental impacts such as biodiversity loss, change of soil properties, groundwater recharge or local climatic conditions in huge monocultural PV parks must be considered and should be subject of further research.

Nature conservation

In previous sections, demands for integrating nature conservation into concepts for post-mining landscapes have been formulated. Future post-mining management should consider cultural ecosystem services aiming for synergies between recreational benefits, environmental education, ecological functions, and nature conservation. Closing areas to the public and facilitating succession of plant communities will enhance biodiversity and could still provide economic benefits for local communities through nature information centers, guided walks, and educational activities. Some examples for such priority areas for nature conservation have been already established in former mine sites of Lusatia, particularly at sites with extremely low potential for agricultural or silvicultural land use. Nature conservation organizations such as the Nature and Biodiversity Conservation Union (NABU)

(Grünhaus area [139] or the Heinz Sielmann Foundation (Wannichen) [140]) were able to acquire larger areas of post-mining landscapes in Lusatia. Both areas are protected as absolute reserves and access is strictly forbidden for the public also for safety reasons (mechanical stability of spoil heaps), so that an undisturbed and widely unregulated self-organization of these landscapes takes place. A large number of endangered and often highly specialized species, both from flora and fauna, found habitats in these refuges. In a multifunctional landscape, these nature reserves represent a vital part, whose role for the socioeconomic development must be seen much more positive.

Tourism

Post-mining landscapes are able to attract tourists as can be seen in the Central German lignite mining district around the cities of Leipzig and Halle, where a large number of former open cast mines has been closed and already finally reclaimed. Particularly, the developing mining lakes offer manifold potentials for touristic attractions. In the Rhineland, there are several viewpoints, e.g., the Indemann or the “skywalk” at the Inden and Garzweiler open cast mines, respectively. In Lusatia, lake Senftenberg is already in use for aquatic tourism since the 1960s and a related touristic infrastructure developed during the last decades. A number of additional mining lakes will be opened for recreation during the few years, with the future Cottbus Ostsee as the temporarily largest artificial lake in Germany. Several of these lakes will be connected by navigable channels so that an attractive aquatic landscape will offer new potentials for expanding touristic activities within the region. New impulses for future utilization of former mine sites were provided by the international construction exhibition (*IBA Fürst-Pückler-Land*) that took place in Lusatia between 2000 and 2010. A number of workshops for new landscapes and in total 30 individual projects were carried out [141]. Some of the projects developed into touristic hotspots in Lusatia, such as the visitors mine F60—a former overburden conveyor belt bridge which is also known as the “horizontal Eiffel tower” [142].

Economic development and political initiatives

The German federal government passed the law for strengthening the lignite mining districts in the ongoing structural transformation process (*Strukturstärkungsgesetz Kohleregionen*) in 2020. With this political decision, financial support of up to 40 billion Euros has been made available for the coming years until 2038 to be invested into the lignite mining districts of Germany. It includes among others massive investments into traffic infrastructure and innovative new scientific institutions in both

regions. To be able to moderate this process in a meaningful way, a transformation compass should be discussed that takes up various target dimensions in a suitable way and balance them as far as possible.

Both regions can benefit from their proximity to technical universities (RWTH Aachen and BTU Cottbus-Senftenberg) when analyzing the overall situation and when initiating and implementing entrepreneurial ideas at a high technological level. Especially at RWTH Aachen, there are comprehensive activities like the transformation platform REVIERa, which brings together internal and external partners, discusses ideas for the future design of the Rhenish mining area and which proposes project ideas that can generate positive economic and ecological effects in the Rhenish mining area (www.rerviera.rwth-aachen.de). In the next step, decision processes need to derive concrete measures to achieve desired target levels of ecosystem services in the long term and cost-effectively.

In Lusatia, BTU aims to bundle different emerging research activities on innovative and sustainable transformation of the economy in the so-called Lausitz Science Park (LSP). Large project groups and institutions funded in the framework of the structural transformation supported by the federal government will deal with decarbonization processes for industry and traffic. It is expected that the settlement of numerous top-level research institutes will significantly promote the socioeconomic situation of this region. Further investments are planned into a better public health system for marginal regions by establishing a new medical university in Cottbus. In addition, existing and new cultural institutions receive financial support to make the region attractive again for the expected new employees.

Conclusion and outlook

In conclusion, both lignite mining districts are characterized by distinct differences even if several overall issues related to direct and indirect impacts of mining activities are similar. Particularly, the natural environment with regard to soil quality, climatic conditions but also the socioeconomic framework lead to very different perspectives for the development of these two regions during and after the ongoing transformation process. A great challenge in both mining districts is preparing the landscape for providing manifold ecosystem services again. Figure 8 shows model-like change of ecosystem services provision before, during, and after mining. For the situation after mining, scenarios with different land-use options (residential, industrial, infrastructure, natural ecosystems) can be imagined with different focus on ecosystem services. The transformation process itself needs to be moderated with an early and proper integration

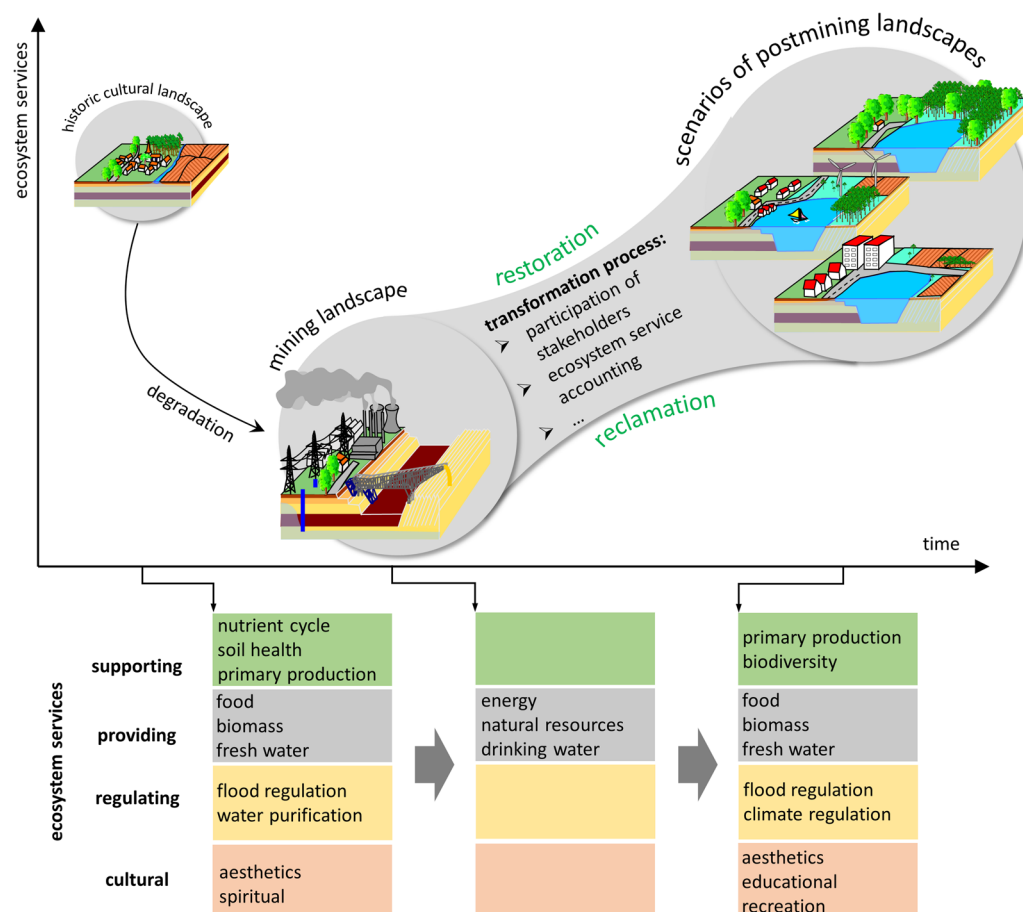


Fig. 8 Model of different stadiums of a cultural landscape disturbed by lignite mining activities and subsequent restoration or reclamation with potential land-use scenarios for the post-mining landscape; examples of ecosystem services in the foreground of the respective stadium of development are shown in the tables below (examples of ecosystem services and color codes from Figs. 1 and 7)

and participation of potential stakeholders to reach wide acceptance for the resulting landscape and ecosystem services. The utilization of economic instruments like ecosystem services accounting may provide decision support for these processes.

The Eastern German post-mining landscapes offer potentials for future bioeconomy not despite, but precisely because of their marginality. Instead of the useless attempt to perform less successful agriculture at such sites, they could provide important production sites for diverse renewable resources without provoking conflicts with agricultural food and feed production at more fertile sites. Integration of biodiversity protection is an urgent demand for fertile reclamation sites in the Rhineland with high potentials for intensive agriculture. Extensification and creation of integrated refuges for plants and animals are needed to avoid failures already made in previous decades. Thus, landscape planning of post-mining landscapes must include even stronger than before the integration (not segregation) of ecologically important

structures like hedgerows or natural courses of streams. Furthermore, extensification of agriculture on fertile sites is of importance with regard to a sustainable maintenance of soil health.

In the short to medium term, great potentials are expected especially in the Lusatian district with regard to tourism. An attractive post-mining landscape may provide the necessary cultural ecosystem services. The emerging new lakes play a pivotal role here. Of growing relevance will be the intensifying influence of regional climate change which representing a main future constraint for a fast realization of mining lakes in Lusatia. Furthermore, the behavior of large mining lakes like the Cottbus Ostsee and its contribution to additional water losses due to intensified evaporation as well as the potential release of sulfate into the rivers are still unclear. The expectation in this region that the closure of mine sites might be compensated by the settlement of new industrial companies could be disappointed due to missing water resources. The broad ongoing public

debate on the establishment of the Tesla Gigafactory in the vicinity of Berlin can be seen as an example. In a long-term perspective, the huge open cast mines of the Rhineland will provide the basis for the largest man-made lakes in Central Europe. Challenges and potentials related to the flooding and later utilization of these future waterbodies are not completely clear today.

Former mining regions have to be made attractive not only for tourists but also for new employers. Infrastructure like efficient transportation services and fast internet is of crucial importance. In this regard, the recent national and also European funding programs offer support for several projects on mitigating the effects of upcoming mine closures. Differences of necessary requirements for both mining regions have to be tackled: For example, a large part of the regional transportation system in Lusatia still suffers from missing investments during the last 30 years, whereas the Rhineland is a highly developed business location in the center of Europe with a modern infrastructure and diverse economy. Modernization of Lusatian infrastructure seems to be the crucial prerequisite for future economic development without mining companies as main employer. Again, careful planning and consideration of the available scientific insights into the impact of still ongoing disturbances but also into changing prerequisites for successful restoration of these disturbed landscapes is demanding.

Abbreviations

AMD	Acid mine drainage
LMBV	Lausitzer und Mitteldeutsche Bergbauverwaltungs-gesellschaft mbH
LRE	Lower Rhine Embayment
SOM	Soil organic matter

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Author details

¹Research Center Landscape Development and Mining Landscapes (FZLB), Brandenburg University of Technology Cottbus-Senftenberg, Konrad-Wachsmann-Allee 6, 03046 Cottbus, Germany. ²Chair of Geopedology and Landscape Development, Brandenburg University of Technology Cottbus-Senftenberg, Siemens-Halske-Ring 8, 030426 Cottbus, Germany. ³Department of Ecology, Brandenburg University of Technology Cottbus-Senftenberg, Konrad-Wachsmann-Allee 6, 03046 Cottbus, Germany. ⁴Chair of Hydrology, Brandenburg University of Technology Cottbus-Senftenberg, Siemens-Halske-Ring 8, 030426 Cottbus, Germany. ⁵Faculty of Business and Economics, Chair of Management Accounting, RWTH Aachen University, 52062 Aachen, Germany. ⁶Physical Geography and Climatology, Department of Geography, RWTH Aachen University, Wüllnerstr. 5b, 52056 Aachen, Germany. ⁷Institute for Environmental Research, RWTH Aachen University, Worringerweg 1, 52074 Aachen, Germany. ⁸Institute of Hydrogeology, RWTH Aachen University, Lochnerstr. 4-20, 52064 Aachen, Germany. ⁹Chair of Atmospheric Processes, Brandenburg University of Technology Cottbus-Senftenberg, Burger Chaussee 2, 030426 Cottbus, Germany. ¹⁰Chair of Economics, in Particular Environmental Economics, Brandenburg University of Technology Cottbus-Senftenberg, Erich-Weinert-Str. 1, 03046 Cottbus, Germany. ¹¹Chair of Physical Geography and Geoecology, Department of Geography, RWTH Aachen University, Wüllnerstr. 5b, 52056 Aachen, Germany.

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