Formation of soil lichen crusts at reclaimed post-mining sites, Lower Lusatia, North-east Germany

STELLA GYPSE, MAIK VESTE, THOMAS FISCHER and PHILIPP LANGE


Biological soil crusts were investigated at reclaimed post-mining sites near Welzow and Schlabendorf in Lower Lusatia (Brandenburg, Germany). Various development stages from initial biological soil crusts built up by green algae, to more developed soil crusts with mosses, as well as moss-soil lichen crusts, were classified. The spatial-temporal dynamics during the development resulted in a moss-lichens cover with discrete patches of pioneer organisms like green algae in between. At the study sites, 13 species of terricolous lichens were identified. The formation of the biological soil crust is important for the accumulation of soil organic matter in the first millimeters of the topsoil of these pioneer ecosystems. A correlation between cryptogamic biomass and soil carbon content were found.

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This paper is dedicated to Tassilo Feuerer (University of Hamburg) on the occasion of his 65th birthday for his international contribution to lichenology.

Introduction

Soil lichen communities can be found in many open landscapes in Europe, where the soil surface is free of higher vegetation or with a sparse cover as xerothermic steppes, heaths or coastal and inland dunes (Paus 1997, Fischer et al. 2010, Büdel et al. 2014). Such biological soil communities are built up by cyanobacteria, algae, bryophytes and lichens, which form complex structures with the soil mineral particles which are known as biological soil crusts (Büdel 2003). Various comprehensive phytosociological studies of these moss-lichen communities in natural and man-made ecosystems have already been undertaken (e.g. Büdel 2003). As pioneers, cryptogams play an important role in developmental processes, since they influence abiotic and biotic interactions in initial and disturbed ecosystems and may define successional pathways (Veste et al. 2001, Cutler et al. 2008). For the restoration of disturbed ecosystems, the development of soil lichen crust communities is an important successional step for the reclamation of soil and ecosystem
functioning in these highly stressed ecosystems (Veste 2005, Bowker 2007). On the other hand, these open landscapes are rare habitats in cultural landscapes of Central Europe. In Lusatia (Brandenburg, Germany) and other parts of Germany, Poland and the Czech Republic large areas have been degraded by large-scale open-cast mining activities; such landscapes in Central Europe this mining landscapes offer the opportunity to observe and analyze plant re-colonization starting from the point-zero (Wiegleb & Felinks 2001, Schaaf et al. 2011).

The aims of this study were to provide an inventory of soil lichen species and the development of biological soil crusts on reclaimed soils of former open-cast mining areas, and to link the crust formation with soil chemical parameters on two reclamation sites of different ages, but subjected to similar initial conditions, by repeated sampling in 2009 and 2014.

Methods

Study sites

Both study sites are located in the Lusatian open-cast mining district near Cottbus (Brandenburg, Germany), which is one of the driest areas in Germany. It is characterized by a transitional Atlantic to continental climate in Eastern Europe with a mean annual temperature of 9.3°C and mean annual precipitation of 581 mm measured at the nearest climate station in Cottbus (averages for the period 1981 to 2010; DWD 2014). The lignite open-cast mining Welzow Süd situated 20 km south of Cottbus includes the restored watershed “Neuer Lugteich” (51°35'53.00"N, 14°17'23.20"E) constructed in 2001 (Kendzia et al. 2008) and covers an area of c. 4.3 ha (Figs 1a–b). The overburden substrates are quaternary and tertiary sands, deposited on a clay layer without further amelioration measures (e.g. liming, fertilizing). The characteristic plant species of the sampling plots on the dune is Corynephorus canescens, with scattered pine trees (Fig. 1a). Here, soil samples were collected in April 2009 and March 2014. The post-mining landscape of Schlabendorf (40 km west of Cottbus) has been under reclamation since 1991 (LMBV 2012) and is now used for forestry. The entire area covers 3269 ha (LMBV 2003) and the layered dumped material consists of 80% tertiary and 20% quaternary substrate (Reichel & Uhlmann 1995). The sampling of the soil crusts in Schlabendorf took place at two locations: site I (51°46’11.88"N, 13°45’22.54"E) in June 2013 and site II (51°46’7.07"N, 13°44’27.70"E) in April 2009 and March 2014. Site I is characterized by a pine plantation, whereas at site II birch and pine were planted (Figs 1c–d).

Species inventory and chemical analysis

Undisturbed soil crusts were collected by gently coring with 55 mm diameter Petri dishes to avoid rupture of the crusts, and to obtain a well defined and comparable surface area between samples. The sampling points were selected by using the classification of biological soil crusts according to Fischer et al. (2014). This classification represents sites dominated by mosses, lichens and observable surface properties of the soil crusts (colour and crust thickness). Soil crust organisms were identified in the laboratory, and pH measurements of the substrate below the crust was determined by separating biological crust and subjacent soil. Soil samples were extracted with distilled water at a ratio of 1 : 2.5, and the pH measurements were performed in a clear supernatant. Total carbon content was determined with an elemental analyzer (Elementar VARIO EL Micro Cube, Hanau Germany) and chlorophyll a content was extracted from air-dried samples with 80% acetone and determined with a UV/VIS-spectrometer (Perkin Elmer Lambda 2, Norwalk
USA). The organic carbon content ($C_{\text{org}}$) of the samples taken in 2009 was determined by Spröte (2013) by ashing the samples at 430°C and analysis with an elemental analyzer (Elementar VARIO EL Micro Cube, Hanau Germany).

Figures 1a–d. Study sites.  
1a. Overview of the artificial dune Welzow “Neuer Lugteich” (photo March 2014),  
1b. Moss-soil lichens crust at Welzow “Neuer Lugteich” (photo March 2014),  
1c. Overview of study site II at the reclaimed post-mining site at Schlabendorf (photo September 2014),  
1d. Overview of study site I Schlabendorf (photo June 2013).

Results and discussion

Floristic inventory and crust succession
At both study sites biological soil crusts were build up by the green algae Zygogonium sp. Kützing and Ulothrix sp. Kützing, representing the initial stage of development (Spröte et al. 2010, Fischer et al. 2014) (Figs 2a–b). Later, bryophytes such as Ceratodon purpureus (Hedw.) Brid. and Polytrichum piliferum Schreb. ex. Hedw. (Figs 2c–d) appeared. These green algae and moss dominated crusts initially stabilize the soil surface and create soil conditions which favour further development towards a characteristic moss-soil lichen crust (Büdel & Veste 2008, Langhans et al. 2009) (Fig. 3). On the artificial sand dune of “Neuer Lugteich”, the soil lichens Cladonia glauca and Cladonia coniocraea are found on the upper slope, where, together with Ceratodon purpureus, they form a moss-lichen community. In contrast to the younger site in Welzow-Süd,
the reclaimed area in Schlabendorf had a richer soil lichen diversity, 13 species being identified at
the two study sites (Tab. 1). This change from initial soil crusts to developed moss-lichen crusts
follows the classical model of surface development, with initially discrete patches of primary and
later secondary colonists spreading over time to create a homogeneous cover (Cutler et al. 2008).
Likewise, small patches of soil lichens in less developed bio-crusts developed into a more
heterogeneous moss-lichen cover in our study (Fig. 4). At an advanced stage of succession, these
soil lichen-moss communities included lichens growing on both mineral soils and thin humus
layers.

Table 1. Checklist of soil lichens in the reclaimed post-mining sites in Welzow-Süd (Neuer Lugteich) and
Schlabendorf.

<table>
<thead>
<tr>
<th>Species</th>
<th>Welzow-Süd</th>
<th>Schlabendorf</th>
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<tbody>
<tr>
<td><strong>Cladonia glauca Flörke</strong></td>
<td>+</td>
<td>+</td>
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<tr>
<td><strong>Cladonia rei Schaer.</strong></td>
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<td>+</td>
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<tr>
<td><strong>Cladonia coniocraea (Flörke) Spreng.</strong></td>
<td>+</td>
<td>+</td>
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<tr>
<td><strong>Cladonia fimbriata (L.) Fr.</strong></td>
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<td>+</td>
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<tr>
<td><strong>Cladonia floerkeana (Fr.) Flörke</strong></td>
<td></td>
<td>+</td>
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<tr>
<td><strong>Cladonia portentosa (Dufour) Coem.</strong></td>
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<td>+</td>
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<tr>
<td><strong>Cladonia ramulosa (With.) J. R. Laundon</strong></td>
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<td>+</td>
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<tr>
<td><strong>Cladonia subulata (L.) Weber ex F. H. Wigg.</strong></td>
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<td>+</td>
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<tr>
<td><strong>Micarea prasina Fr.</strong></td>
<td></td>
<td>+</td>
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<tr>
<td><strong>Peltigera didactyla (With.) J. R. Laundon</strong></td>
<td></td>
<td>+</td>
</tr>
<tr>
<td><strong>Placynthiella icmalea (Ach.) Coppins &amp; P. James</strong></td>
<td></td>
<td>+</td>
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<tr>
<td><strong>Placynthiella oligotropha (J. R. Laundon) Coppins &amp; P. James</strong></td>
<td></td>
<td>+</td>
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<tr>
<td><strong>Steinia geophana (Nyl.) Stein</strong></td>
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</table>

The observed Cladonia rei, Cladonia fimbriata, Cladonia portentosa, Cladonia ramulosa,
Cladonia subulata, Cladonia glauca, Peltigera didactyla, Placynthiella icmalea, Placynthiella
oligotropha and Steinia geophana (Figs 5a–g) are characteristic of acidic, sandy and nutrient-poor
soils (Wirth et al. 2013, Wirth & Kirschbaum 2014). As with Cladonia rei, Peltigera didactyla is
an ephemeral pioneer on disturbed soil, which often occurs in association with mosses (Wirth et al.
2013). Steinia geophana was found in shady places on small organic residuals in the soil lichen
crusts. Micarea prasina, which normally grows on tree barks, especially at the stem base of
deciduous and coniferous trees or on rotten wood (Wirth et al. 2013), was observed in
Schlabendorf on detritus and directly on the surface of the biological soil crusts composed of green
algae and mosses.

Cladonia coniocraea, which occurred at both sites, is widely distributed throughout the world
and has a wide ecological amplitude, being found on acidic and humic, well-drained soils, often on
desiccating raw humus layers or mosses, but rarely on bare humus-poor mineral soils (Wirth et al. 2013). However, it was not found on the dune covered with initial green-algal crusts, but at the dune base, where already a thin humus layer was formed by surrounding vegetation or by biological soil crusts themselves. In Schlabendorf, this species is mainly found near birch plantations (site II), where humus has been accumulated due to longer ecosystem development. *Cladonia ramulosa* occurs on acidic, nutrient-poor substrates, especially on mossy, mineral-poor silicate rocks and sandy mineral soil and on fresh raw humus layers (Wirth et al. 2013). *Cladonia floerkeana*, developed mainly in pioneer communities of Ceratodonto-Polytrichetalia associations. *Cladonia portentosa*, found in the mining area of the Schlabendorf site, can also be found in Corynephorus-dominated acid dry grasslands (Wirth et al. 2013), on humus-rich soils (Moberg & Holmåsen 1985) and on raw humus layers (Wirth et al. 2013).


At the Schlabendorf site, the diversity of soil lichens was higher than in a nearby post-mining site. The mining landscape of the former open-cast mining Koyne and Kleinleipisch, later also Klettwitz near Lauchhammer (Brandenburg, Germany) was reclaimed in the early 1990s (FiB 2009) and has a similar reclamation period as the Schlabendorf study site. The later established nature protection area “Naturparadies Grünnhaus” provided ecological priority areas and protection of natural processes (FiB 2009). In the nature protection area “Naturparadies Grünnhaus” eight soil
lichen species were reported (FiB 2009): the seven species of *Cladonia*, with *Cladonia rei* and *Cladonia fimbriata* were dominant, while *Peltigera didactyla* was characteristic of grasslands. On recultivated areas of post-mining sites in the Czech Republic, the lichen *Porpidia crustulata*, which grows on stones, first occurred after 15 years, while the coverages (average 4%) and species diversity (15) of soil lichens peaked in 25 year-old areas with *Cladonia coniocraea* and *Cladonia fimbriata* as the dominating species (Lukešová et al. 2013).

![Soil lichens, mainly Cladonia spp., and mosses at the reclaimed post-mining site in Schlabendorf site II.](image)

**Figure 3.** Soil lichens, mainly *Cladonia* spp., and mosses at the reclaimed post-mining site in Schlabendorf site II.

**Soil chemical parameters**
The pH of the substrate below the biological soil crusts ranged from 5.1 to 5.6 on the artificial sand dune at Lugteich, and from 4.9 to 5.7 for all sampling plots in Schlabendorf. These pH values are characteristic of dry acidic grasslands (Olsson et al. 2009). Especially in Schlabendorf, the pH values showed high small scale heterogeneity and decreased with the appearance of soil lichens and mosses.
At both sites the sampling strategy was designed to represent all units of surface patterns observed in the field (Fischer et al. 2014), resulting in the collection of the following sequence of soil crusts: non-crusted soil, initial and developing soil crusts, mosses as well as pronounced moss-lichen crusts. Along the catena of this crust development, due to the progressive build-up of biomass, the chlorophyll a content and the organic carbon content of the bio-crusts increased with a spatial variance (Tab. 2). Therefore, a spatial development of crusts on the individual study areas, also a temporal growth from 2009 to 2014 was observed. A correlation between chlorophyll a and organic carbon content is only linear in the initial stages of biological soil crusts (Dümig et al. 2014), whereas with further increase in carbon content (in developed moss-lichen crusts), the chlorophyll a content reached a nearly constant level (Fig. 6). An explanation could be the structure of the lichens itself, since the photosynthetic phycobiont accounts for only 5 to 10% of the lichen’s volume (Masuch 1993). Thus it is possible in spite of a rising ratio of lichens the chlorophyll a content in the crusts is only slightly increased. Therefore, the distinctive moss-lichen crusts with a higher portion of lichens have more chlorophyll a but less biomass. Also the heterotrophic community of lichen mycobionts and heterotrophic soil bacteria increased with bio-crust development.

Conclusions

This study showed that soil lichen crusts are able to colonize soil surfaces in post-mining sites. In terms of species composition, differences could be found between the two sites investigated due to the longer time of restoration and variation in substrate properties. In the reclaimed sites the primary succession started with green-algae dominated biological soil crusts, which developed into distinctive moss-lichens crusts at the final stage, which created a small-scale heterogeneous cover over time. The growth of cryptogams increased the organic carbon content of the topsoil. The occurrence of biological soil crusts represents an important successional stage in the reclamation of an ecosystem and its development on post-mining sites (Bowker 2007).

Table 2. Mean and standard deviation (± SD = standard deviation) of organic carbon content (C_{org}) and chlorophyll a content (Chl a) at the artificial dune Welzow “Neuer Lugteich” and the reclaimed post-mining site II in Schlabendorf in 2009 and 2014. Data for 2009 according to Spröte (2013).

<table>
<thead>
<tr>
<th>stages of soil crust development:</th>
<th>substrate</th>
<th>initial soil crust</th>
<th>developing soil crust with moss</th>
<th>moss-lichen crust</th>
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<tbody>
<tr>
<td>Welzow</td>
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<tr>
<td>2009</td>
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<td></td>
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<tr>
<td>C_{org} [%]</td>
<td>-</td>
<td>0.24 ± 0.05</td>
<td>0.40 ± 0.06</td>
<td>-</td>
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<tr>
<td>Chl a [mg m^{-2}]</td>
<td>-</td>
<td>9.46 ± 2.43</td>
<td>19.77 ± 9.91</td>
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<tr>
<td>2014</td>
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<tr>
<td>C_{org} [%]</td>
<td>0.05 ± 0.01</td>
<td>0.25 ± 0.00</td>
<td>2.60 ± 2.45</td>
<td>37.54 ± 0.00</td>
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<tr>
<td>Chl a [mg m^{-2}]</td>
<td>0.61 ± 0.37</td>
<td>2.50 ± 0.68</td>
<td>29.04 ± 10.91</td>
<td>49.30 ± 0.00</td>
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<tr>
<td>Schlabendorf</td>
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<tr>
<td>2009</td>
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<tr>
<td>C_{org} [%]</td>
<td>0.58 ± 0.13</td>
<td>1.16 ± 0.22</td>
<td>1.44 ± 0.32</td>
<td>-</td>
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<tr>
<td>Chl a [mg m^{-2}]</td>
<td>2.11 ± 0.72</td>
<td>15.53 ± 7.19</td>
<td>15.51 ± 7.00</td>
<td>-</td>
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<td>2014</td>
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<tr>
<td>C_{org} [%]</td>
<td>0.10 ± 0.00</td>
<td>0.51 ± 0.10</td>
<td>1.27 ± 0.52</td>
<td>41.38 ± 0.00</td>
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<tr>
<td>Chl a [mg m^{-2}]</td>
<td>0.71 ± 0.08</td>
<td>5.32 ± 2.13</td>
<td>9.25 ± 4.26</td>
<td>91.11 ± 0.00</td>
</tr>
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</table>
Figure 6. Correlations between soil carbon content and chlorophyll a content of the investigated biological soil crusts at the artificial dune Welzow “Neuer Lugteich” (A) and Schlabendorf (B) in 2009, 2013, 2014. (Data for 2009 according to Spröte (2013)).
Acknowledgements

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References


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