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Soil fauna (Lumbricidae, Collembola, Diplopoda and Chilopoda) as indicators of soil eco-subsystem development in post-mining sites of eastern Germany – a review

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Abstract

The soil zoological department of the Senckenberg Museum of Natural History Görlitz has studied immigration, colonisation and biological activity of main groups of soil fauna on brown coal open-cast mine sites in eastern Germany for nearly half a century (1960 to 2006). The present paper provides a review and data on the long-term development of primary succession, mainly in a real-time series of soil macrofauna (especially Lumbricidae and Myriapoda) and soil microarthropods (especially Collembola).

The results were obtained for the most part from Upper Lusatian dumps (district Görlitz) with predominantly loamy, Pleistocene substrata, compared with Lower Lusatian dumps (district Cottbus) with predominantly acid, sandy, Tertiary substrata. Besides the substrata, the vegetation (promoted by rehabilitation) determines the process of colonisation and development of soil faunal assemblages. In particular, the difference between afforestation with deciduous, soft-leaved trees or with coniferous or hard-leaved trees was demonstrated in the different examples.

In the study sites, only 7 species of earthworms regularly take part in the colonisation of mine sites; 3 further species are found sporadically. They took normally 3 to 20 years to immigrate and establish populations under good conditions during10 to 30 years. In the last few years of this period an extremely high abundance of 100 gm^{-2} was observed with a subsequent reduction to the probable ‘predisturbance level’ (30–60 gm^{-2}) 40 to 54 years after reclamation. Very characteristic is the distribution of life forms during the succession, moving from a preponderance of epigeics in the pioneer period to the clear dominance of anecics in the progressed phase (organisation period). Comparision of the quantitative data from different mine sites and site ages allows the use of earthworms as indicators of mine-site soil quality.

Microarthropods invade, partly as aerial plankton, mine sites very quickly but have a different, species-dependent colonisation behaviour. Rapid production of deciduous litter after afforestation and the absence of competition from earthworms enable microarthropods to quickly develop a ‘pioneer-maximum’ with highest abundances and species diversity, followed by a minimum density after the incorporation of the ectohumus layer into topsoil by earthworms. Merely 30 to 50 years later microarthropods again reach an abundance as found in the control native woodlands. The study of colonisation behaviour typical of 113 species of Collembola indicated that there were eight different colonisation groups of springtails that were useful in characterising different stages of mine-site development. Compared with ‘native’ reference woodlands, the identity of collembolan species composition is highest in the 10th year after rehabilitation but declines later. There are ‘mine-site-phobic’ species – elsewhere very common – which behave in a stochastic ‘variable’ manner. As a result, the collembolan species composition of well-developed mined woodlands still show a lack of some species even after half a century following mining.

A further intensive study was made with millipedes and centipedes which need – like earthworms – a longer time for immigration. The presence of saprophagous millipede species showed a clear succession in parallel with mine-site development, but there is no species with true pioneer behaviour. Centipedes – with *Lamyctes emarginatus* as a true pioneer – as predators behave less predictably; Geophilomorphs, hunting in the subsoil, are the last to invade. After 50 years of development of mine-site woodlands, five species of millipedes and six species of centipedes, though common in adjacent reference woodlands, had not yet colonised the mine sites. Comparisons between myriapod assemblages at mine sites in Upper and Lower Lusatia that had different soil and age conditions revealed that myriapods are good indicators of biological soil quality and are reliable and easy to use.

The role of saprophagous fauna, esp. earthworms, in SOM decomposition was studied using metabolic parameters for the potential level of decomposition (DLZpot). For this, laboratory data of the metabolic equivalents (ME) of the studied saprophagous groups of the microfauna and macrofauna were combined with the present biomass of these groups (in gm^{-2}) and divided by the yearly SOM-production of litter and soil layer of vegetation (DLZpot). Minimal litter decomposition occurred during the pioneer optimum of microarthropods (3rd to 5th year) in deciduous-afforested sites. Later the total SOM decomposition becomes essentially higher up to 75 %. Here the contribution of earthworms was about 98 %, whereas the role of millipedes and dipteran larvae can be ignored. In pine afforestations, the decomposition efficiency of the (macro-)fauna was 4.5 to 7 times lower than calculated for deciduous mine sites.

Keywords: substratum types, recultivation, immigration, colonisation, succession, SOM decomposition, ecofaunistical groups, metabolic equivalences

1. Introduction

Lignite mining, which has had a long tradition in eastern Germany, increased after 1950. By 1989, 300 Mio t of brown coal were produced and about 700 km^2 were devastated by open-cast mining (Hüttl et al. 1996, Pflug 1998). Lignite open-cast mine sites not only offer a gigantic experimental field for soil ecological science (Majer 1989, Dunger 1991, 1992, Topp 2000, Wölleke et al. 2007) but also are of interest from an economical point of view. New biological criteria for assessing reclamation success at mine sites (Dunger & Voigtländer 2002, 2005) have been developed from evaluation of the biological soil quality (Römbke et al. 2000, Wanner et al. 2007) and soil ecological classification (Beck et al. 2005, Breure et al. 2005).

The aims of investigation of mine-site colonisation by soil animals over at least half a century were:

* to record which species are able to immigrate quickly and were pioneer colonisers,

* to observe the quantitative and qualitative development of the most important groups of soil animals on identical (or nearly identical) mine sites over a very long period,

* to determine which populations dominate the biotic processes in the development of the soil eco-subsystem and to understand the ecological significance of changes in species composition during different periods of the succession,

* to identify soil faunal groups or species with characteristic and predictable behaviour during mine-site colonisation that can serve as indicators for the different developmental steps of the eco-subsystems.

*In the final analysis an attempt should be made to discover whether the soil fauna reaches the 'pre-disturbance level' a half century after reclamation.

In the following, results and discussion are given for the main groups of soil animals.

2. Sites and methods

This paper deals with experiences made by the Soil Zoological Department of the Museum Görlitz with soil fauna on post-mining sites in different parts of Germany (Fig. 1). Field work was primarily done in the southern Upper Lusatian mining district (Berzdorf: 1960 to 2006), more sporadically in the Lower Lusatian district (19 sites between 1968 and 2003) and in the Central German district (Böhlen: 1960 to 1966); see Tab.1. In the Berzdorf region, long-term studies for nearly half a century were based on two adjacent sites (Fig. 1):

* series A with deciduous afforestation (*Alnus*, *Populus*, *Robinia*) was studied in a real-time series at the basic site A, 10 to 46 years after planting deciduous trees, combined with a false-time series of younger and similar neighbouring mine sites 1 to 12 years after rehabilitation (sites NA, T, H; see Tab. 1),

* series L 10 to 46 years after planting primarily pine trees. The site passed through a natural succession: about 20 years after rehabilitation the dense pine forest (without forest management) partly began to die off and a natural growth of deciduous trees (*Populus*, *Acer*, *Betula*) increasingly took place. After 30 years a typical mixed forest had developed.

Characteristics of the study sites are given in Tabs 1 and 2. In the Berzdorf district, the mining company used a simple 'mixed-by-chance' method for deposition. This caused a high soil-borne dynamic (Dunger 1968, Hauser & Kowarsch 1998 ined.) with extreme patchiness in the distribution of the soil fauna. Therefore, the variability was not only high as normal for natural soils (Römbke 1985, Scheu 1992), but was even higher compared with mine sites with a more or less uniform cover of cultivated soil or loess (Rhenanian district, Dworschak 1997) and with mine soils after agricultural rehabilitation (Rushton 1986, Wermbter 1999).

It was not possible (with the necessary constancy over a fifty-year period) to examine relationships between soil faunal characteristics and the physical, vegetation and rehabilitation parameters of the sites for using principal components analysis. Therefore, direct comparisons between soil faunal data and the observed environmental data are used in a more specified manner.

The zooecological methods used are described in general by Dunger & Fiedler (1997) and in particular by Dunger et al. (2001), here with information on the 26 animal groups studied between 1960 and 2001. Predominantly quantitative samples were taken using soil cores and pitfall traps three to four times a year. For earthworms, a combination of hand sorting and expelling animals with chemicals (standard approach; Römbke et al. 2005) was used.

At the species level, Lumbricidae were studied by W. Dunger, K. Voigtländer and H. Stöhr, Collembola by W. Dunger and H.-J. Schulz, Gamasida by A. Christian, Oribatida by T. Schwalbe (†), Myriapoda by K. Voigtländer. Determinations made in earlier years were updated to the present taxonomical knowledge. For additional work on microfauna see Wanner et. al. (1998) (testate amoebae) and Hohberg (2003, 2006) (nematodes, tardigrades), for studies on meso- and macrofauna, not presented in this paper, see Dunger et al. (2001).

Tab.1 Mine sites investigated in the Berzdorf, Böhlen and Lower Lusatian mining district. Site name, years of study, site age (years after rehabilitation) and site characterisation.

Site code name	Observation period	Site age (years)	Site characterisation
Upper Lusatian mining district (Berzdorf)			
A	1960–98	8–46	loamy, mainly Pleistocene substrata, low to medium content of lignite and pyrite, no soil cover, melioration by fertilisation and liming, afforestation with *Alnus, Populus, Robinia*
L	1960–98	8–46	as A, primarily afforested with *Pinus*, later becoming mixed forest by natural growth of deciduous trees (*Populus, Acer, Betula*)
NB	1985	24	as A, afforested with *Alnus, Populus, Betula, Acer*, surrounded by dense *Pinus* and *Picea* plantations
H	1960–65	5–10	as A, with a higher proportion of sand
T	1960–65	2–5	as A, with *Lupinus*
NA	1962–66	1–4	as A, afforested with *Alnus, Populus, Betula, Acer*
IK	1996	1	freshly dumped Pleistocene substratum, practically without vegetation
W	1961–65	–	native reference site near the spoil dump, bottom-land forest (*Fraxino-Ulmetum)* in a flat slope position
NVd	1962–88	–	native reference site, loess-loamy soil with mull-humus (*Arunco-Aceretum* in the 'Neisse Valley')
NVs	1962–88	–	as NVd; but spruce forest
Böhlen/Leipzig mining district			
BöI	1959–65	–	virgin Tertiary substratum, high lignite and pyrite content, practically no vegetation
BöTf	1962–67	4–9	Tertiary substratum meliorated 1958 up to 65 cm, 2 years agriculturally recultivated, 1961 planted with *Populus*
DH	1977–78	–	native reference site, podsolic brown-soil with moder-like mor humus layer (*Pinus sylvestris* forest)

Tab.1 cont.

Site code name	Observation period	Site age (years)	Site characterisation
Lower Lusatian mining district (Cottbus)			
LuC	1968–70	35–37	Tertiary silt with glacial and fluvial sands and high pyrite content, afforested with *Pinus*, dry mor-humus soil (‘Lugteich’)
Frei	1968–70	35–37	as LuC, by adding *Populus*, dry mor-humus soil (‘Freienhufen’)
NaA	1968–70	40–42	Tertiary and fluvial sands with high pyrite content, afforested with *Quercus robur, Fagus, Betula, Carpinus*, humid to dry moder-humus soil (‘Nardt’)
NaB	1968–70	40–42	as NaA, afforested with *Pinus* and *Prunus serotina*
NaC	1968–70	40–42	as NaB
DoKie	1997–98	35	ash ameliorated Tertiary substratum, humid to dry moder humus soil with pine afforestation (‘Domsdorf-Tröbitz’)
DoEi	1997–98	35	as DoKie, afforested with *Quercus rubra* and *Tilia cordata*
GrII	1968–70	35–37	as LuC, dry mor-humus soil, afforested with *Quercus robur* (‘Großräschen’)
Gr0	1968–70	50–52	as GrII
GrIII	1968–70	35–37	as GrII, dry-humid mor-humus soil, afforested with *Pinus*
GrI	1968–70	40–42	as GrII, dry-humid moder-humus soil, afforested with *Quercus robur*
GrIV	1968–70	40–42	as GrI, humid mull-humus soil, afforested with *Quercus robur* and *Fagus*
süd-rot	2001–03	2	unchanged sandy-loamy Pleistocene substratum, afforested with *Quercus rubra* + *Festuca, Poa angustifolia* (‘Schlabendorf-Süd’)
koy-rot	2001–03	20, 29	sandy-loamy Tertiary substratum, ash-meliorated, afforested with *Quercus rubra* (‘Koyne’)
koy-cal	2001–03	50	as koy-rot; *Calamagrostis epigejos*-association
ple-rot	2001–03	40	silty-sandy-loamy Tertiary substratum, root-humus-layer, afforested with *Quercus rubra* (‘Plessa’)
alt-rot	2001–03	40	native sandy brown soil, mor-like moder humus, afforested with *Quercus rubra* (‘Altsorgefeld’)
alt-tra-gew	2001–03	>50	soil like alt-rot, *Quercus petraea*-dominated mixed forest
altr-tra	2001–03	25	soil like alt-rot, humus layer 8 cm, afforested with *Quercus petraea*

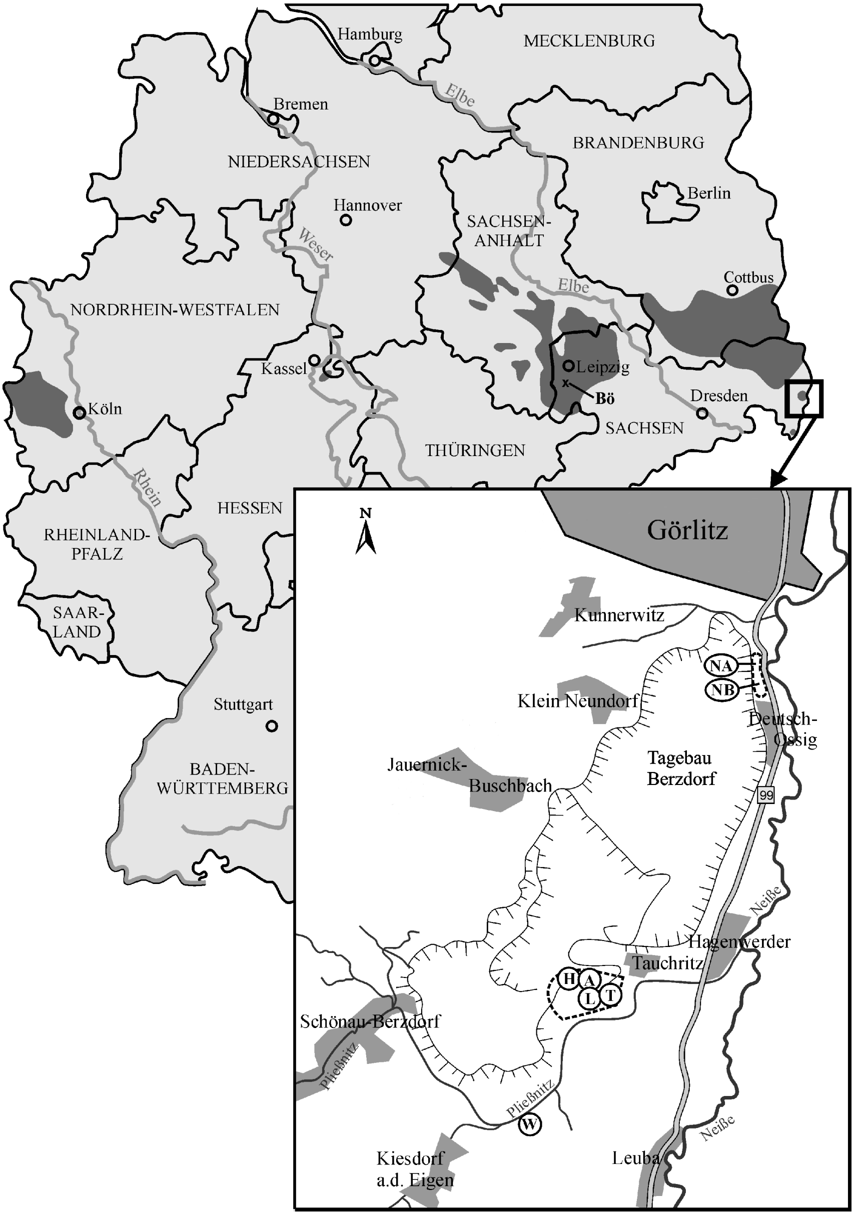


Fig. 1 Lignite mining districts in Germany (hatched areas), box: Berzdorf mining district (Upper Lusatia) with positions of the study sites. For code names of studied sites see Tab. 1.

Tab. 2 Soil properties of Berzdorf mine sites A (deciduous forest) and L (mixed forest). For description of the mine sites see Tab. 1. (After Dunger 1968, Hauser & Kowarsch 1998, Wanner & Dunger 2001).

Site	Year	$pH_{(KCl)}$		SOM %	N	S	C/N	Pore volume %
		0–3 cm	5–8 cm					
A	1963	5.8–5.5	5.9–4.9	8.1	indet.	indet.	indet.	46.0
	1998	5.1–4.3	5.1–4.2	9.9	0.2	0.001	20.0	48.4
L	1998	5.1–4.4	4.1–4.0	4.5	0.1	0.007	22.0	49.8

A selection of the material determined is stored at the soil-zoological collections of the Senckenberg Museum of Natural History Görlitz, Germany. Specimens of other groups of the mesofauna and macrofauna were counted and may be worked up in the future.

For pedological studies, realised between 1960 and 1990, see Dunger (1968, 1989); studies of the topsoil as life zone of the litter- and soil fauna, carried out between 1996 and 1999, see Kobel-Lamparski & Lamparski in Dunger & Wanner (1999). A pedological characterisation of the studied sites in the region Berzdorf was worked out by Hauser & Kowarsch (1998 ined.). For results of botanical studies of dumps (region Berzdorf) (S. Bräutigam, P. Gebauer, M. Reimann) see Dunger & Wanner (1999).

3. Earthworms

3.1. Immigration and colonisation

Immigration

In the Berzdorf region, freshly dumped substrate is found to be free of earthworms for at least four years, i.e., immigration starts later as is known from the ‘Rhenanian brown coal district’ (Dworschak 1997, Topp 2000) or after agricultural recultivation (Rushton 1986). An introduction is facilitated by ‘contaminated’ plant root material (Topp et al. 1992, 2001) or in soil and mud attached to car wheels or to animals, especially birds (Schwert 1980). The part played by the natural locomotory activity of earthworms was noted by us (Dunger 1969) at a Tertiary dump (Böhlen district) as very low (1 to 10 m per year on average), which was corroborated by Barley (1961), Graff (1961), Marinissen & Bosh (1992) and Ma & Ejisackers (1989). Very high surface locomotory activity, especially of juvenile specimens of *Lumbricus rubellus*, as observed by Kobel-Lamparski (1987) under humid temperate conditions on smooth areas, could only be found to a limited extent under the conditions at the Berzdorf mine sites (Dunger et al. 2001). In general, the migration capability of different ecological groups of earthworms is discussed by Mazaud & Bouché (1980), Satchell (1983) and Elmer et al. (2007). Under mine-site conditions, the existence of ecological barriers to immigration must be taken into consideration. Such a situation is described by Dunger (1987) from the site NB of the Berzdorf mining district. Here, a wide strip of pine plantation acted as an immigration barrier, preventing the immigration of earthworms of the genus *Lumbricus* into a small deciduous wood strip populated predominantly by *Populus* sp.

Colonisation depends not only from the immigration of a species into any particular habitat. Four main ecological factors were found to influence the conditions for persistence of a species in dump soils:

Firstly, the activation of sulphuric acids by oxidation causes damage especially to the integument of earthworms, even if pH values are increased by liming (Dunger 1969). Therefore endogeic life forms with higher acid tolerance can colonise first (see paragraph 3.4.).

Secondly, Tertiary dump substrate is often water repellent, acting detrimentally on the mucous cover of the epidermis.

Thirdly, sandy dump soils are (virtually) without a vegetation cover, dry up very quickly. The slow rehabilitation of soils from top to bottom makes the soils ‘flat-bottomed’. Earthworms cannot escape desiccation by retreating into deeper soil layers.

Fourthly, during initial stages there is a nearly complete lack of food, especially from litter-fall. At first, an increase in microorganism biomass promotes the development of pioneer mineral soil forms (e.g. *Aporrectodea caliginosa*).

The effect of these factors was tested by Dunger (1968, 1969) studying the survival of eight earthworm species introduced to the Tertiary mine site BöTf in the Böhlen district, which fulfilled all the detrimental conditions mentioned above (5-year-old meliorated *Populus* afforestation with pH 5.0 without earthworms). After one year, none of the 125 specimens of eight species, introduced in each plot, survived under original or even under limed soil conditions. Only with the help of a 20 cm mulching layer of poplar litter, one species, *Aporrectodea caliginosa*, survived and propagated. It is remarkable that mulching did not support the litter-inhabiting species (*D. octaedra*, *L. rubellus*) but the mineral soil species *A. caliginosa*, which has the highest resistance against soil acidity and probably profited from the increasing microbial activity or/and water capacity. Obviously the site factors have a complex impact on the colonisation process.

3.2. Development of earthworm populations depending on site factors

3.2.1. Species

The spectrum of earthworm species continuously inhabiting the Berzdorf mine sites can be listed as follows (the first record, dependent on rehabilitation age, indicated in brackets; species names follow Sims & Gerard (1999):

Lumbricus rubellus rubellus Hoffmeister, 1843 (from the 7th year on),

Lumbricus terrestris Linnaeus, 1758 (from the 14th year on),

Dendrobaena octaedra (Savigny, 1826) (from the 6th year on),

Dendrodrilus rubidus rubidus (Savigny, 1826) (from the 33rd year on),

Aporrectodea caliginosa caliginosa (Savigny, 1826) (from the 3rd year on),

Aporrectodea rosea rosea (Savigny, 1826) (from the 10th year on),

Octolasion tyrtaeum (Savigny, 1826) (from the 10th year on).

Additionally, three inhabitants of open landscapes occurred sporadically: *Allolobophora chlorotica chlorotica* (Savigny, 1826) on site A33, *Aporrectodea longa longa* (Ude, 1885) on site H10 and *Octolasion cyaneum* (Savigny, 1826) on site A33. They disappeared as soon as the canopy of the mine sites closed. These, and possibly some other non-detected species, take advantage of the heterogeneous and variable life conditions of young stages of the dump ecogenesis (Den Boer 1981).

3.2.2. Population development

The development of earthworm populations was studied extensively under rather favourable substratum conditions on predominantly Pleistocene dumps in the Berzdorf region as well as to a lesser degree under less favourable Tertiary substratum conditions in the Lower Lusatian region.

Population development type I

Under the 'good' conditions of Berzdorf mine sites with deciduous afforestation on suitable soil substratum (Tab.1), earthworm population development began with an **initial phase** from the 3rd to the 6th year, reaching a biomass of between 0.2 and 10 gm^{-2} comprising only two species (*A. caliginosa, D. octaedra*) (Tab. 3, Fig. 2). After six and up to about 25 years a **pioneer phase** follows with stepwise increases until nearly the whole set of species is present and a biomass up to 40–50 gm^{-2} is reached. After about 30 to 40 years, an early **organisation phase** (Dunger & Wanner 1999) can be observed but not yet a transition to a site-typical 'stable' dynamic. The biomass, rising to a maximum of more than 100 gm^{-2} after about 30 years (Dunger 1987), levels out later (after 46 years) to about 83.1 ± 38.9 gm^{-2} (Dunger et al. 2001), but is probably still higher than the typical values for a persistent site (between 30 and 50 gm^{-2}). Such 'overshooting' in an early organisation phase of development was also found by Kobel-Lamparski (1987) in recultivated vineyards.

Population development under different types of unfavourable conditions (type II)

Type IIa: Very close to the Berzdorf site A, the somewhat younger site H exhibited more unfavourable conditions with a complex of more sandy and dry dump substratum. Observations took place in the 6th (H6), 7th (H7) and 10th (H10) year after rehabilitation. *D. octaedra* initially dominated with 98 % (H6), 60 % (H7) and 26 % (H10), whereas *A. caliginosa* reached 2 % (H6), 25 % (H7) and 67 % (H10); additionally *A. longa* was present in H10. As shown in Fig. 2, the developmental character of site H was poorer than in the site-series NA, T, A. It can therefore be termed as a separate type IIa with poorer substratum quality but without further unfavourable conditions.

A possible type IIb (Fig. 2), the Berzdorf mine site NB24, was studied only once. This site was a small isolated deciduous (poplar) strip between extensive large pine plantations (see paragraph 3.1.). The site conditions may be near to those of site A, but an immigration barrier caused by the pine plantations prevented colonisation by *Lumbricus terrestris* and *L. rubellus*. As can be seen from Tab. 3, *Octolasion tyrtaeum* dominated with 53 %, whereas *A. rosea* reached 24 % and *A. caliginosa* only 17 %. Epigeic species (*D. octaedra*) were – in relation to site age – already reduced (7 %). Further investigation was not possible because the site was destroyed by the mining company two years later. The development type IIb is interpreted as a development under deciduous afforestation and more or less adequate substratum conditions but with an immigration barrier.

Tab. 3 Average biomass of life forms of Lumbricidae from Berzdorf mine sites between 1960 and 1998 (gm^{-2}). Species recorded only once or twice with minor biomass not listed. Total biomass from whole-year investigations are in bold type; percentages in italics. For description and code names of mine sites see Tab. 1.

Site/age	NA	T	NA	T	H	H	H	A	L	A	NB	A	L	A	L
deciduous	1	3	4	6	6	7	10	10		14	24	33		46	
prim. pine									10				33		46
Epigeic species															
D. octaedra	–	–	–	4.8	4.1	4.0	2.3	4.3	3.8	1.1	2.1	1.1	0.6	1.0	1.6
	–	–	–	*46.2*	*97.7*	*59.7*	*26.4*	*10.5*	*84.4*	*2.2*	*7.2*	*1.1*	*1.6*	*1.2*	*3.0*
D. rubida	–	–	–	–	–	–	–	–	–	–	–	1.1	1.1	0.7	1.6
	–	–	–	–	–	–	–	–	–	–	–	*1.1*	*2.9*	*0.8*	*3.0*
L. rubellus	–	–	–	–	–	+	–	9.6	–	16.1	–	24.8	13.0	18.8	14.9
	–	–	–	–	–	+	–	*23.0*	–	*32.5*	–	*23.8*	*34.0*	*22.6*	*28.3*
Totals for epigeics	–	–	–	4.8	4.1	4.0	2.3	13.9	3.8	17.2	2.1	27.0	14.7	20.5	18.1
	–	–	–	*46.2*	*97.7*	*59.7*	*26.4*	*34.1*	*84.4*	*34.7*	*7.2*	*26.0*	*38.5*	*24.6*	*34.3*
Anecic species															
L. terrestris	–	–	–	–	–	–	–	–	–	15.1	–	24.8	15.3	29.9	23.6
	–	–	–	–	–	–	–	–	–	*30.5*	–	*23.8*	*40.0*	*35.9*	*44.8*
Totals for anecics	–	–	–	–	–	–	–	–	–	15.1	–	24.8	15.3	29.9	23.6
	–	–	–	–	–	–	–	–	–	*30.5*	–	*23.8*	*40.0*	*35.9*	*44.8*
Endogeic species															
A. caliginosa	–	0.2	2.2	5.6	0.1	1.7	5.8	24.6	0.7	11.8	4.8	25.3	7.5	14.1	6.6
	–	*100*	*100*	*53.8*	*2.3*	*25.3*	*66.7*	*60.4*	*15.5*	*23.8*	*16.5*	*24.3*	*19.6*	*16.9*	*12.5*
A. rosea	–	–	–	–	–	0.7	0.4	1.1	–	1.1	6.9	25.9	0.4	9.5	3.5
	–	–	–	–	–	*10.4*	*4.6*	*2.7*	–	*2.2*	*23.7*	*24.9*	*1.0*	*11.4*	*6.6*
O. tyrtaeum	–	–	–	–	–	0.3	0.2	1.1	–	3.2	15.3	0.6	0.4	8.9	0.9
	–	–	–	–	–	*4.5*	*2.2*	*2.7*	–	*6.5*	*52.6*	*0.5*	*1.0*	*10.7*	*1.7*
Totals for endogeics	–	0.2	2.2	5.6	0.1	2.7	6.4	26.7	0.7	17.2	26.9	52.4	8.3	32.5	11.0
	–	*100*	*100*	*53.8*	*2.3*	*40.3*	*73.6*	*65.9*	*15.5*	*34.7*	*92.8*	*50.2*	*21.5*	*39.0*	*20.8*
Total biomass gm^{-2}	**0**	**0.2**	2.2	10.4	4.2	6.7	8.7	**40.6**	**4.5**	49.5	**21.9**	**104.2**	**38.2**	**83.1**	**52.7**

Type IIc: Coniferous afforestations on mine sites with the normal substratum conditions of the Berzdorf region (site L) were studied during their initial *Pinus*-phase (L10) as well as during their succession into a mixed woodland (see paragraph 2). This type of earthworm population development is described as type IIc. The first investigation of the site L10 under a dense stand of 2–4 m tall pine trees found a biomass of 4.5 gm-2 with *D. octaedra* (85 %) and *A. caliginosa* (15 %). The next ten years as changes in tree combination took place were not studied. Earthworms were favoured by an improved food supply and rising pH values. After 33 years, earthworm biomass was at 38.2 gm-2 well developed, comprising *L. terrestris* (40 %), *A. caliginosa* (20 %), *L. rubellus* (34 %) species and fewer specimens (1–3 % each) of *D. rubida, D. octaedra, A. rosea* and *O. tyrtaeum.* At an age of 46 years, the Berzdorf mine site L had an earthworm population with a biomass of 52.7 ± 15.0 gm-2 with high proportions of *L. terrestris* (45 %) and *A. rosea* (7 %).

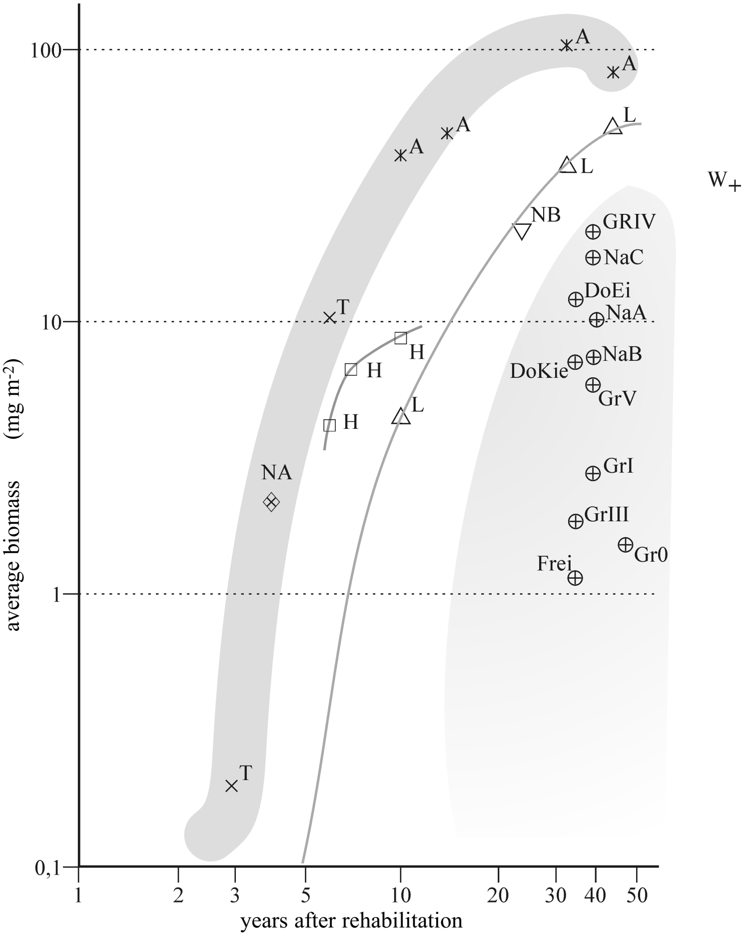


Fig. 2 Earthworm population development (biomass) from Berzdorf (Upper Lusatia) and Lower Lusatian mine sites. The shaded area on the left side combines mine sites fitting the type I-conditions; sites coupled with lines represent the types IIa (H) and IIc (L); sites at shaded area on right side are type III. For description and code names of mine sites see Tab. 1.

Further population development of managed sites of types I and II

The planned further investigation of the Berzdorf mine sites A and L was restricted by the planting of beech seedlings by the forestry office in 2000 in order to obtain economically desirable tree species. Under these new conditions the earthworm populations of the sites A and L were first checked in June 2006 after rain in a generally dry early summer period. At that time, the *Fagus* litter began to influence the litter composition of both sites.

The earthworm population of site A had an average (summer-) biomass of 46.1 gm^{-2}, which possibly corresponds to a yearly-average of about 50–60 gm^{-2}. The species composition changed on the site from 46 to 54 (additional late control) years of age for *Lumbricus terrestris* from 36 to 51 %, for the endogeics from 39 to 10 % and for the epigeics from 25 to 34 % (see Tab. 3); i.e., the proportion of anecics increased (missing per cent shares are caused by non-assignable juveniles).

The population at site L showed in June 2006 a biomass average of 27.7 gm^{-2}, which possibly equates to a yearly average of about 35–45 gm^{-2}, thus still showing a somewhat lower level as compared with mine site A. The proportional species composition changed in L from 45 to 54 years for *Lumbricus terrestris* from 45 to 29 %, for the endogeics from 21 to 22 % and for the epigeics from 34 to 36 %; i.e., the proportion of anecics decreased.

Conclusions on the future population development can be drawn only with caution from this information, especially as the likely increasing dominance of beech can also diminish the earthworm population to a greater extent (‘vegetation-typical biomass’). Nevertheless, the population studied on mine site A seems to arrive at a ‘site-typical biomass’ after half a century of development, but the population of the site L will need more time to reach a nearly ‘pre-disturbance level’. As Fig. 2 shows, all type II sites studied can transform during the later stages, approximating to the type I development with a delay of some decades.

Population development at mine sites under unfavourable substratum conditions (type III)

Pine- and even deciduous-planted mine sites under poor Tertiary substratum conditions were studied for comparison with the Berzdorf sites in the mining district of Lower Lusatia (Dunger 1979, Dunger et al. 1997, 2004a, Dunger & Voigtländer 2005). All these sites possessed a more or less lignite-rich and sandy, poor substratum with a topsoil pH between 4 and 5 after melioration. There, the type of earthworm population development is characterised as type III (Fig. 2).

These mine sites never experienced colonisation by earthworms at stages younger than 8 years after rehabilitation. Repeated investigations were made at five mine sites 35 (to 40) years after pine and 35 to 50 years after deciduous afforestation (Tab. 1). All these sites were inhabited by a poor or very low earthworm population with *D. octaedra* predominating, but also with *D. rubida.* The site Lugteich C had an earthworm biomass of only 0.2 gm^{-2}, the site Freienhufen was somewhat higher with 1.2 gm^{-2}. Improved nutrition was present on sites Nardt B and C (with *Prunus serotina* trees) with biomasses of 7.4 and 16.9 gm^{-2}, resp., both where some specimens of *A. caliginosa* were present. The same is true for the Domsdorf sites with biomass of 7.1 gm^{-2} under pine (DoKie) and 12.1 gm^{-2} under red oak and linden (DoEi). The biggest difference was found at the mine sites of Großräschen where only 0.17 to 1.89 gm^{-2} biomass of earthworm under dry and mor-humus conditions (GrII, Gr0, GrIII), 2.79–5.89 gm^{-2} under more humid moder-humus conditions and a mix of hard- and soft-litter trees (GrI, GrV) and even biomass of 21.55 gm^{-2} under humid and mull-humus conditions with the same tree canopy (GrIV) (see Fig. 2). A further increase in the development of the earthworm populations can not be expected in these mine sites. Therefore this development is regarded as a separate type III.

3.3. Behaviour of life-form types during colonisation

The part taken by an earthworm species during ecosystem development is very different depending upon its ecological behaviour, especially its life-form type.

Epigeic earthworms inhabiting the litter or humus layer are usually small, parthenogenetic species with a life span shorter than one year that overwinter in an egg stage. They have a high capacity to disperse. In the mine sites under study, typical epigeic species are *Dendrobaena octaedra* and *Dendrodrilus rubidus*. The first species immigrate as early as (5–) 6 years after recultivation. As they depend on a humus layer, it is not possible that they could have survived in primarily dumped material. On the mine sites under study, the highest biomass of this group (4.8 gm^{-2}) was observed on T 6 with nearly 450 individuals m^{-2} in spring. On sites older than 10 years a biomass of more than 2.0 gm^{-2} is reached only exceptionally. The highest proportion of biomass of *Dendrobaena* (84.4 %) was found in the young, poor pine plantation (L10). *Dendrodrilus rubidus* was recorded the first time as late as 33 years after rehabilitation. During the years following, this species can even exceed the biomass of *D. octaedra*.

Though adult *Lumbricus rubellus* undergo a transition to an anecic life form, this species is normally part of the epigeic earthworm fauna. The total density of this species is obscured by the difficulty in distinguishing juveniles of this genus, therefore young and small specimens are assigned to *L. rubellus* and *L. terrestris* according to the proportion of the adults present. *Lumbricus rubellus* appeared for the first time 10 years after deciduous recultivation (A10) with such a high density that it is likely to have been present from the 8th or 9th year on (Tab. 3). From this site age, *L. rubellus* dominates by far the epigeic earthworms in mine sites of the optimal development type I. Nevertheless, the proportion of its biomass becomes less than that of *L. terrestris* at older mine sites. According to Brauckmann & Broll (2005) this phenomenon can be caused by competition between these two species.

The overall biomass proportion of epigeic earthworms is highest (up to nearly total) at the younger sites (H6) and lowest (at a range of 25 %) at the oldest observed sites (A33, A46; see Tab. 3).

Anecic earthworms usually burrow deeper than 1 m and are expected (but it has not been tested) to do so in mine soils. They take their food from the litter layer on the soil surface (as do the epigeic life forms). From all the mine sites investigated, true anecic forms are nearly limited to *Lumbricus terrestris* (Berzdorf mine sites A, L). *Aporrectodea longa* was present on Berzdorf mine site H7 for a short period but this seemed to be an unsuccessful attempt to establish.

Lumbricus terrestris was found for the first time on the deciduous Berzdorf site A 14 years after restoration, but at such a high density that it was suspected that they had become established 1 to 2 years earlier. From this time the species increased in biomass continuously: to 15.1 gm^{-2} after 14 years, 24.8 gm^{-2} after 33 years and 29.9 gm^{-2} after 46 years (Tab. 3).

In the primarily coniferous afforestation L, *L. terrestris* was recorded the first time 33 years after restoration, i.e. in the stage of a mixed forest. The already high density (15.3 gm^{-2}) indicates here also an earlier beginning of establishment. After 48 years, its biomass reached 23.6 gm^{-2} to nearly one-half of all earthworms. Together with *L. rubellus,* the genus *Lumbricus* dominated the earthworm fauna on the mine sites from the 15th year onwards with regard to biomass as well as in bioturbation activity.

Endogeic life forms (mineral soil inhabitants) depend on a different food supply as they ingest soil particles, including any organic matter and microorganisms present. Therefore, these forms can find food before a litter layer has been built up. This is an important reason for the first occurrence of *Aporrectodea caliginosa* from the 3rd year on T3. None of the Berzdorf mine sites investigated (older than 3 years) was free of this species. As mentioned in paragraph 3.1 (Colonisation), the tolerance of this species to acids and desiccation further explains the success of *A. caliginosa* as an initial coloniser on mine sites. Nevertheless, the biomass remains, on non-optimal sites (Berzdorf sites H, L, NB), lower than 5–7.5 gm^{-2}, but rises on mine site A to about 25 gm^{-2} after 10 to 33 years, decreasing later (A46), however, to about 14 gm^{-2} (Tab. 3).

The first colonisation by *A. rosea* occurred not earlier than seven years after rehabilitation (H7). Here, as in A (10 and 14) and even in L33, the density was still low (hardly more than 1 gm^{-2}). An exceedingly high biomass of *A. rosea* was found only in A33 with 25.9 gm^{-2}. *Octolasion tyrtaeum* inhabits mine sites of the same age as *A. rosea*, but with clearly other preferences and at different densities. There are only two exceptions to their normal biomass of between 0.3 and 3.2 gm^{-2}. On A48, with a reduced density of *Allolobophora* species, the biomass of *O. tyrtaeum* increased to 8.9 gm^{-2}, and on NB24 with the same reduction and additionally the genus *Lumbricus* entirely absent*,* this species reached a maximum of 15.3 gm^{-2}. As mentioned above, other *Allolobophora* and *Octolasion* species occurred only once for a short time and therefore seem not to be able to establish themselves.

The differing proportions of epigeic, endogeic and anecic life forms of earthworms found during the development of mine sites of the Berzdorf region (Tab. 3) can be used as an indicator of biological mine site quality. Sites with a high ecological capacity (T, A) begin with endogeic forms and later are invaded by epigeic forms with high, but not dominant density from the 6th year on. After joining with anecic forms (from the 14th year on), the proportion of endogeic forms varies from between 1/3 and 1/2 of the total biomass, whereas epigeic forms tend to have the same or a distinctly lower biomass than the anecic ones. Sites with poorer soil quality (Berzdorf H, L) are dominated by epigeic forms in the first ten years and showed higher, but with subsequent ecological development decreasing percentages of this group of life form. Nevertheless, at these sites the share of anecic earthworms is lower than on more favourable sites. After Lavelle (1983), it can be accepted that for temperate deciduous forests, the share of the anecic forms is about 50 %, that of (polyhumic) endogeic forms about 35%, and of the epigeic forms about 15 % of total earthworm biomass. During development of earthworm populations in afforested Berzdorf mine sites with a higher ecological capacity, the biomass of anecic earthworms increased (in A54 [2006] to 51 %) and that of both epigeic and endogeic forms decreased. This suggests that Berzdorf mine sites become more typical of temperate deciduous forests after 40 years of succession (e.g. during the organisation phase).

3.4. Reactions of earthworms to ecological factors

Substratum. As discussed above, colonisation by earthworm species depends primarily on the soil texture, the content of organic matter and, as a consequence of these factors, on its moisture-holding capacity (Edwards & Lofty 1977, Satchell 1983, Lee 1985, Heuser & Topp 1989, Elmer et al. 2007). The lignite content of the mine soils studied has two effects. At high concentrations it can cause a very acid reaction because of their high sulphur content (Katzur 1977) and it is therefore responsible for virtually sterile soils (Beylich 1995). That is also true for coal ash as a substratum for earthworms (Wermbter 1999). On the other hand, tertiary soils containing lignite in fine granular distribution are known to have a better capacity for water sorption and supply of nutrients (Thum et al. 1992, Hauboldt-Rosar et al. 1993) as well as a higher microbial activity (Emmerling et al. 2000). All these effects were supported by our investigations on earthworm development in mine sites.

Food. The importance of the quality of food for earthworm populations is well known. On mine sites, the influence of plantations with conifers, hard-leaved (*Quercus*, *Fagus*) or soft-leaved deciduous trees with more easily decomposed litter (*Acer*, *Tilia*, *Alnus*) is confirmed by investigations. On the surface, the herbaceous and soil layers have to be taken in consideration as they can facilitate the food supply for earthworms in open pine forests. That is not the case in pine-planted mine sites with soil vegetation of poor palatability, for example, with a grass layer of *Calamagrostis* species (DoKie35) in the Lower Lusatian district (Keplin & Düker 1996, Dunger et al. 1997). Even on mine sites restored for agriculture, the type of the plants cultivated determines earthworm development (Wermbter 1999).

Soil surface: crests and troughs. In addition to the habitat diversity mentioned above, characteristics of the surface relief of some mine sites, expressed by troughs and crests, provide a regular alteration in ecological mesohabitats. The troughs and crests are caused by the different ways of dumping either by using primitive or high-tech devices (Simon & Topp 1999, Topp et al. 2001).

General ecological characteristics of troughs and crests are (Dunger 1968, 1989):

* The soil texture is finer in troughs since fine material is moved by wind and rain down from the crests.

* Together with fine-grained material, organic debris is accumulated in troughs.

* The higher content of clay and loam as well as of organic material in troughs results in a higher water-holding capacity so that the water running down to the bottom of the troughs is absorbed.

* Vegetation begins to grow in the troughs because of a more stable humidity.

* Crests are susceptible to drying out more quickly and to suffering higher fluctuations in temperature.

From this, it becomes easily clear that initial colonisation by soil animals, especially earthworms, occurs in troughs. This is demonstrated by the first record of *Aporrectodea caliginosa* only in troughs of the mine sites NA (3, 4 years) and T (3 years) in the Berzdorf district. With further development of the ecosystem, soil cores from deciduous sites (H, A), 6 to 46 years after afforestation, show an increasing but still not regular colonisation of the crests (compared with troughs; Tab. 4). It is evident that the beginning of canopy closure and the development of a more homogeneous habitat climate after about 10 years enable earthworms also to invade crests. At a site age of about 40 to 50 years, the endogeic life forms are nearly evenly distributed over troughs and crests, the juveniles of the anecic forms inhabit the crests in smaller numbers, but only the epigeic life forms continue to colonise the crests in lower numbers than the troughs. This may be caused by the distribution of the litter layer (Wanner & Dunger 2002).

Tab. 4 Percentages of lumbricid density on crests in relation to that on troughs (trough values = 100 %) of the deciduous afforested mine sites A and H of the Berzdorf region between 1961 and 1998. ind. = average of individuals per m^2; mass = average wet weight gm^{-2}. For description and code names of the mine sites see Tab. 1.

Site/age	ind.	mass	ind.	mass	ind.	mass	ind.	mass
life types	epigeic		endogeic		anecic		total	
H (6–7)	39.2	45.2	4.9	60.9	–	–	39.4	45.3
A (10–13)	78.6	62.9	86.3	70.5	–	–	83.8	68.7
A (46)	85.3	88.5	119.6	102.3	87.1	105.7	77.1	98.8

Vertical distribution. The vertical distribution of earthworms was studied in the first ten years on sites A and H only. There was no barrier in respect to pore volume, mineral grain size or soil compaction up to 60 cm depth. On the sites tested, pH values decreased from about 5.5 at the surface to about 4.5 from 20 cm downwards. An exception was found in crests of site A, where pH maintained values between 5.5 and 6.0 up to 60 cm depth. Nevertheless, the acidity in Berzdorf mine sites can be considered as a colonisation barrier at depths more than 30 cm. In accordance with this, soil profiles showed earthworm burrows up to 50 cm below crests and only up to 30 cm below troughs. On excavation tests, at site H (6 to 7 years), *Aporrectodea caliginosa* and *Dendrobaena octaedra* were found up to a depth of 30 cm and *A. caliginosa* only up to 50 cm. On mine site A10, more than 20 cm deep (up to 40 cm) only *A. caliginosa* could be found. Unfortunately, soil profile investigations made in 1998 failed to determine the vertical distribution of *Lumbricus terrestris*. At this time, earthworm burrows that are thought to be produced by this species were found on mine site A up to 80 cm depth.

3.5. The role of earthworms in SOM decomposition on mine sites

A further aspect of soil biological development at mine sites is the decomposition of Soil Organic Matter (SOM). Numbers of individuals or even biomass are not adequate to calculate the role played by saprophagous soil faunal groups in decomposition of SOM. Any estimation must be based on metabolic parameters. For this, the respiration contributed by each individual is used, measured as the inactive respiration under standard conditions (laboratory: metabolic equivalent; ME) (Persson & Lohm 1977, Petersen & Luxton 1982). Basic data are listed in the literature on methods (Dunger & Fiedler 1997). From this, the potential level of zoogenic decomposition (DLZpot) (of earthworms and other members of saprophagous macrofauna) is derived as the metabolic equivalent (ME) of this group in relation to the energy yield of the yearly production of litter and soil layer (Dunger 2004) as follows:

$$DLZpot = \frac{sum\ of\ ME\ (saprophagous\ soil\ macrofauna)}{energy\ yield\ (yearly\ production\ of\ litter\ and\ soil\ layer\ of\ vegetation)}$$

At the Berzdorf mine sites, litter and soil layer organic matter production has been measured for a chronosequence of mine sites covered by a deciduous tree plantation from the first to the 46th year and the pine to mixed forest site (L) at the 10th and the 46th year (Tab. 5). The nutrients available initially at the deciduous tree sites are rapidly used by the vegetation giving rise to a rapid increase in the litter layer. This offers an optimal habitat immediately for the immigration of microarthropods, which shows a ‘pioneer optimum’ as early as in the 3rd year (T3; see Fig. 3). An essential zoogenic decomposition of SOM is provided later by the immigrating earthworms, beginning with the 7th year (H7) and acting at full strength as early as in the 10th year (A10). From this stage on, the contribution of earthworms to the total SOM decomposition is higher than 98 % (as quoted by DLZpot) and the role of millipedes and dipteran larvae can be ignored. There are complete data sets (simultaneously checking the whole-year earthworm density and production of litter and soil layer of vegetation) from the first to the tenth and from the 46th year (Tab. 5). At the stages A10 and A46, the DLZpot shows very similar values (7.7 and 7.5, resp.). In between, only short controls were carried out each year. The nearly stable DLZpot over such a long period indicates that the ME-sum of the saprophagous fauna increases and decreases in parallel with changes in litter production. Nevertheless, this conclusion is has still to be verified.

DLZpot results from the originally pine-afforested site L are very low at the pine stage (L10) and near to the level of the deciduous site A in the mixed-forest stage (L46; Tab. 5). Other comparisons were only possible with mine sites at Domsdorf, Lower Lusatia, which show the high impact of the substratum. Both Domsdorf mine sites were 37 years old and, based on ash-meliorated Tertiary substratum, afforested with pine (DoKie37) or red oak and linden (DoEi37), respectively. The DLZpot of these sites could be calculated on the basis of the litter production recorded by Keplin & Hüttl (1999) and Embacher (2000) and earthworm populations recorded by Dunger et al. (1997) as being only between 1.0 and 1.5 (Dunger & Voigtländer 2005). This means that the decomposition efficiency of the macrofauna on Domsdorf mine sites is 4.5 to 7 times lower than that calculated for Berzdorf mine sites.

Tab. 5 Litter production and potential zootic decomposition level (DLZpot) of Lumbricidae (Lu) and other saprophagous macrofauna (Ma) in Berzdorf mine sites. For description and code names of mine sites see Tab. 1.

Site/age	NA1	T3	E7	A10	L10	A33	L33	A46	L46
litter (gdw m^{-2} a^{-1})	35	442	327	282	175	indet.	indet.	570	468
litter (kJ m^{-2} a^{-1})	659	8328	6161	5313	3188	indet.	indet.	10739	8818
DLZpot (Lu+Ma)	0.78	0.40	1.65	7.72	0.95	indet.	indet.	7.49	5.96

In general, the earthworm populations are able to ingest approximately 75 % of the yearly litter production (and to deposit it as faeces into the upper soil) from the 10th year of deciduous mine-site development onwards, provided that the substratum quality does not prevent a rapid development of earthworm populations and the litter palatability is not reduced or even poor (as it is for conifer needles or hard-leaved deciduous litter in the Domsdorf sites).

4. Soil microarthropods, concentrating on springtails

4.1. Immigration and dispersal to mine sites

Arthropods of the soil mesofauna (Collembola, Oribatei, Gamasida) are known to be passively dispersed in different ways. It is possible that eggs or individuals of the mesofauna are imported together with the geological overburden mass to lignite opencast areas. However, checks on very freshly dumped substrates (in the Berzdorf mining district) never resulted in finding any animals. It is known that distribution by people (plants, cars, shoes etc.) or by animals (phoresy: Gamasida, Christian 1993) can occur, but the quantitative effect has never been tested.

Another possible route is the transportation in aerial plankton (Palmén 1944), which is the most probable way that newly emerged islands are colonised (Surtsey: Lindroth et al. 1973). Immigration by air was tested at the Berzdorf mine sites by isolated plots of sterile and humus-free Pleistocene substratum for 497 days (Dunger et al. 2002, Wanner & Dunger 2002). The percentage of animals caught was highest for Collembola (46), followed by Trombidiformes (26), Oribatei (16), Parasitiformes (4) and other groups of arthropoda (8). Seventeen species of Collembola were found, from which only three (*Mesaphorura florae*, *Parisotoma notabilis*, *Bourletiella pistillum*) were able to establish populations after ca. 200 days (supported by nutrative litter fragments that blew in naturally). These tests indicate that immigration by air currents may be effective especially for soil microarthropods.

In general it can be assumed that the absence of certain springtails at any mine site is not the result of prevention in immigrating but mainly by difficulty in colonising. Which relative contribution each immigration route makes to the total is unknown.

The horizontal dispersal of epedaphic-living, small animals along an open dump area by wind drift (as sometimes observed at open sandy beaches) was studied on an open kaolin-covered area at a Berzdorf dump (Dunger et al. 2002). For this, pitfall trapping was used combining normal open traps with drift-protected traps (Dunger & Engelmann 1978). From 14 captured epedaphic springtail species, nine species were trapped at an average of 3.8 times more often in open, normal traps (partly blown in by the wind). This result did not depend on the animals' size or shape (body round, long or small). The largest difference was found with the spherical *Bourletiella pistillum*, where 61 times more specimens were obtained from normal pitfall traps. On the other hand, to fall into drift-protected traps, the animals had to move actively into a more or less dark protected area. Interestingly enough, most of these species actively visiting the drift-protected traps were found to be typical pioneers in mine site colonisation (*Entomobrya lanuginosa, Lepidocyrtus lanuginosus*, *L. paradoxus, Parisotoma notabilis*). Only one of these species (*P. notabilis*) was imported by air during the experiments. Our knowledge of the behaviour of microarthropods in immigration and dispersion is still very incomplete.

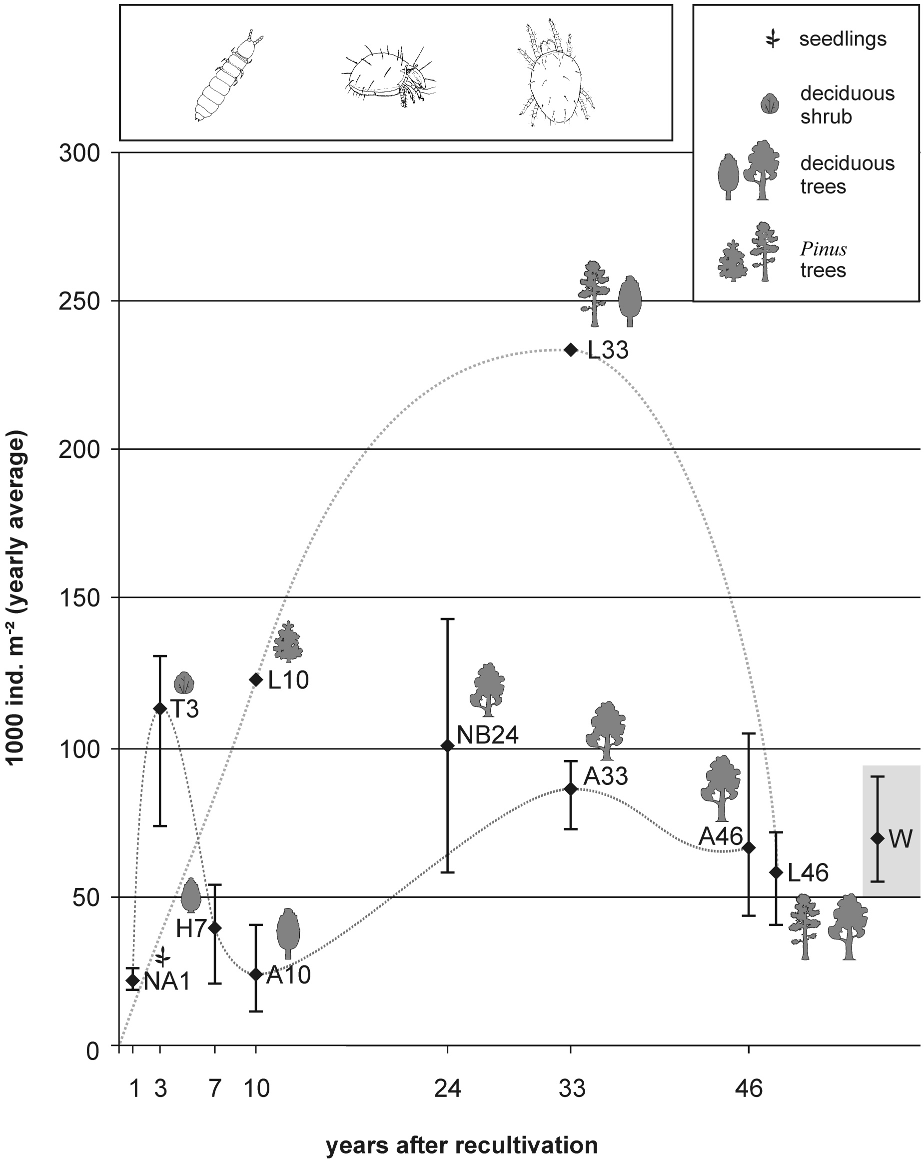


Fig. 3 Development (abundances) of microarthropod populations (mainly springtails and mites) at mine sites of the Berzdorf mining district during 46 years and at a 'native' woodland (W). Points document whole-year-investigations. Lines between the points combine developmental stages of identical (or similar) mine sites (results based on short checks with limited numbers of samplings). For description and code names of mine sites see Tab. 1. (After Dunger 2004).

4.2. Development of microarthropod populations

In mine sites with deciduous trees in the Berzdorf mining region, the overall population density of edaphic microarthropods increased very rapidly under the influence of a fast-growing deciduous shrub vegetation with high litter production during the first three years (site T3). As Fig. 3 shows, a very high pioneer maximum with 127 000 ind. m^{-2} is quickly reached. Such an early increase maximum of microarthropods, especially Collembolans, in the absence of earthworms was also described by Luff & Hutson (1977) and Hutson (1980) from young English mines. During the following years, this litter-layer development was reduced by increased competition from earthworms, which consumed the litter layer. Microarthropods reacted to that by a decreasing density, accompanied by changes in species composition. Lowest densities of about 24 000 ind. m^{-2} were found 8 to 15 years after rehabilitation (Tab. 6). The period between the 15th and 35th year after rehabilitation is characterised by a continuous increase in total of microarthropod density up to about 85 000 ind. m^{-2}. During the next 10 to 12 years of succession in the soil eco-subsystems, the microarthropod density adapted to the developing drilosphere and humus layers to a level of about 70 000 ind. m^{-2} with a large variance of ± 44 %.

Tab. 6 Density (1000 ind. m^{-2}, yearly average) and dominance (%) of microarthropod groups during the development of two mine site series (N, T, E, A: deciduous; L: pine to mixed woodland) of the Berzdorf mining district during 46 years (results from soil cores). W: 'native' reference site (*Fraxino-Ulmetum*). For description and code names of mine sites see Tab. 1.

Site/age	NA	T	E	A	L	A	L	A	L	W
deciduous	1	3	7	10		33		46		
prim. pine					10		33		46	
Collembola										
density	3.2	40.5	17.8	8.9	6.5	27.8	35.9	28.2	27.9	30.7
dominance	14.8	31.9	40.0	36.8	5.3	33.2	15.4	40.3	45.6	43.9
Protura										
density	0	1.3	1.4	1.2	0	2.5	2.7	1.9	2.4	0.6
dominance	0	1.0	3.1	4.9	0	3.0	1.2	2.7	4.0	0.8
Oribatida										
density	11.4	51.2	14.3	6.2	102.0	26.5	95.2	26.8	20.2	22.5
dominance	52.8	40.3	32.1	25.6	83.3	31.7	40.9	38.3	33.3	32.1
Trombidiformes										
density	6.1	27.2	8.7	6.5	12.2	18.3	87.6	4.9	2.9	11.7
dominance	28.2	21.4	19.5	26.8	9.9	21.8	37.5	7.0	4.9	16.7
Parasitiformes										
density	0.9	6.8	2.3	1.4	1.8	8.6	11.3	8.2	7.2	4.5
dominance	4.2	5.4	5.2	5.8	1.5	10.3	4.9	11.7	12.0	6.4
Total										
density	21.6	127.0	44.5	24.2	122.5	83.7	232.7	70.0	60.6	70.0

To compare the deciduous series with succession under pine afforestation conditions, the adjacent mine site L (10 to 46) was studied. The site L is identical with A except for being primarily afforested with pine, passing, however, into a mixed forest after about 30 to 35 years (see paragraph 2). Microarthropod succession under these conditions (Dunger 1989, Dunger et al. 2001, Dunger et al. 2004b) is shown in Fig. 3 and Tab. 6. During the first five years, the microarthropod population showed a much slower invasion of the needle layer as could be seen on deciduous sites (‘pioneer optimum’). The same unfavourable effect of *Pinus* was found by Greenslade & Majer (1993) in young Australian mine sites. Later the density rose continuously and reached a very high abundance of about 230 × 10^3 ind. m^{-2} 33 years after rehabilitation. During this period, increasing earthworm activity in the mixed forest drastically reduced the depth of the ectohumus layer and, therefore, of microarthropod density. The last investigations made in 1998 (L46) showed the microarthropod density to be below the level of the deciduous mine site A46. Nevertheless, this conclusion is not tested for significance.

4.3. Collembolan communities

4.3.1. Quantitative development of collembolan density

Collembolan populations began at a low density (NA1; 3.2 ind. m^{-2}, Tab. 6) but only two years later, the very high abundance of springtails comprises nearly a third of the ‘pioneer maximum’ of the mesofauna (T3; 40.5 × 10^3 ind. m^{-2}). During the following years of succession, the contribution made by Collembola to the overall microarthropod density rose again to about 40 %, but abundance declined to 17.8 × 10^3 ind. m^{-2} (E7) and 8.9 × 10^3 ind. m^{-2} (A10) (Tab. 6). In the older series of deciduous sites (A33, A46), no obvious further development took place in the contributions made by Collembolan (33–40 %) nor in absolute lower collembolan density (28–30 × 10^3 ind. m^{-2}). After 46 years of deciduous mine-site development, the collembolan density achieved the level found in the reference ‘native’ woodland (W).

In the site primarily afforested with pine (Berzdorf L) the increase between the 10th and the 33rd year (during the change to a mixed forest) led to a 6-fold increase in collembolan density, but the highest density of microarthropods in L33 was nevertheless from mites (Oribatida and Trombidiformes), not by Collembola. During the following period, collembolan abundance decreased, but not to such a large extent as that of most mites. That resulted in Collembola being the most numerous microarthropods in the late mixed-woodland mine site (L46, Tab. 6).

4.3.2. Changes in collembolan species composition during half a century of succession

Studies made over nearly 50 years in the Berzdorf mine sites with deciduous afforestation (IK, NA, T, H, NB, A) offer the opportunity to evaluate collembolan species composition at the same (or for the first 10 years nearly the same) site (Dunger et al. 2004b). For faunistic comparison, the position of Berzdorf mining region was advantageous because the fauna in the surroundings with 202 species was relatively well known (Schulz & Dunger 1995). Of these species 113 (56 %) were found at the Berzdorf mine sites.

Colonising groups

To distinguish groups of species with equal or at least very similar colonising behaviour, the individual abundances of each species from each of the eight study periods (0, 2, 4, 7, 10, 24, 33, 46 years after rehabilitation) were checked. This was done separately for soil samples (edaphic life forms) as well as for pitfall samples (epedaphic life forms). By the main preference (combined for edaphic and epedaphic species) for one of the eight age stages of mine sites, eight colonising groups could be determined (Tab 7; for detailed information see Dunger et al. 2004b).

Eleven species were combined in the '**Fugitive initial group**', because they were predominantly found on freshly deposited heaps of virgin overburden material. Most of these species showed no distinct ecological preferences but appeared opportunistically. For further information about immigration see Dunger (1991) and Dunger et al. (2002).

Three groups of '**Pioneer species**' were representative of four- to ten-year-old mine sites. Most of these species were entirely absent from the oldest mine sites studied and may be rarely present in the nearest 'native' woodland (W). The '**Pioneer group**' united predominantly epedaphic species with density peaks in the first four years, whereas the '**Post-pioneer group**' consisted of species, the density of which remained high for at least ten years. These species have been reported as pioneers from different parts of the world: Australia (Greenslade & Majer 1980), Siberia (Stebaeva & Andrievskii 1997) or England (Hutson 1981, Moore & Luxton 1986). Between these pioneer groups, three wide-spread euedaphic species are combined as the somewhat problematical '**Bipolar group**' showing an unspecific preference for areas in the young but partly also in the older stages.

The remaining four groups comprised 'Woodland-inhabiting species'. The '**Pioneer woodland group**' was present as early as in the initial site stages but showed a rising density in the oldest studied mine sites and the 'native' woodland. In contrast, the '**Euryoecious woodland group**' clearly preferred older mine sites (scarcely present from the fifth year on) and showed the highest density in the 'native' woodland. These two groups known to colonise more developed mine sites of other geographical regions (Hutson 1981, Moore & Luxton 1986, Materna 1999). The species of the '**Pre-woodland group**' were absent during the first 10 years of mine-site development but present in the oldest studied mine sites and in the nearest 'native' woodland. For these species, few records exist from mine sites of other regions (Dunger 1968, Zerling 1990). The Collembola of the last '**Stenoecious woodland group**' inhabited almost exclusively the 'native' woodland (W). This last group includes widespread species, such as *Folsomia quadrioculata* or *Mesaphorura krausbaueri*, which neither ever occurred on the mine sites during the present investigation nor on mine sites of other regions.

Among the 25 species that could not be grouped because of their uncertain colonising preference in the Berzdorf district, some species have been recorded as mine-site colonisers from other countries. For example, *Orchesella quinquefasciata* and *Hypogastrura vernalis* are numerically dominant on early acid mine sites of Böhlen, Leipzig district (Dunger 1968, 1989). In the Berzdorf district, their place was occupied by *Lepidocyrtus paradoxus* and *Ceratophysella succinea*. *Isotoma anglicana* is also known as a frequent pioneer in the Leipzig and Cottbus mining districts (Zerling 1990, Materna 1999) but the identity of these specimens requires taxonomical verification.

As stated above, the development of collembolan communities during the mine-site succession of deciduous sites in the Berzdorf district can be described by the eight colonising groups with different preferences. There is no developmental stage at which all colonising groups were present. As the study series of the youngest mine sites (IK NA, T, H) is a false-time series, differences should not be overemphasised. The first clear incision was the complete termination of the ‘Fugitive initial group’ and the start of the ‘Pre-woodland group’ after 10 years (A10). A weaker reaction was displayed by the Initial and Pioneer groups as well as the ‘Stenoecious woodland group’ after 24 years (NB24). The 33-year stage was characterised by a minimum of the ‘Post-pioneer-group’ and a maximum of the ‘Stenoecious woodland group’. Outside the succession, the populations of the oldest mine site (A46) and the undisturbed woodland (W) showed the largest differences.

One of the aims of this long-term study was to describe distinct phases of the succession, marked by different steps in the colonisation by Collembola. The results show that there was no simple indication but a continuum of colonisation by specific groups of Collembola. A clearer distinction might be apparent using mathematical descriptions of community characters.

4.3.3. Changes in collembolan community characters

The alpha-diversity of collembolan communities rose during the first four years of succession very strongly, whereas it remained nearly constant over the following forty years (Tab. 7). That can be seen from the species numbers (10–38 and 40–43, resp.), the Shannon-Wiener index (0.557–1.954 and 2.262–2.371, resp.) and the Simpson-index (0.290–0.814 and 0.836–0.879, resp.) Species numbers as well as the Shannon and Simpson indices allow no differentiation of the development later than 10 years after restitution.

Species turnover (Tab. 8) was distinctly divided into a first phase of a continuous decrease over the first 10 years and a second phase of continuously high values. This indicates that the greatest changes in species composition occurred during the first 10 years of succession as already indicated. Between the 10th and the 24th year a very large jump occurred, initiating a new high level of species turnover with low variability during the second half of the succession studied. That held true even for the comparison with the undisturbed woodland. That means that the number, but not the composition of species was nearly the same at the first and the second phase of the studied succession. The higher proportion of species turnover during this period was linked with the longer time period between the observations.

Tab. 7 Species richness, abundance and diversity of Collembola and collembolan colonising groups in deciduous mine sites of the Berzdorf district 1960–1998. Dominance values: DD eudominant, D dominant, SD subdominant, R recedent, SR subrecedent. For description and code names of mine sites see Tab. 1.

site /age	IK1		NA2		T4		H7		A10		NB24		A33		A46		W_{native}	
sampling method	m^{-2}	tr	m^{-2}	tr	m^{-2}	tr	m^{-2}	tr	m^{-2}	tr	m^{-2}	tr	m^{-2}	tr	m^{-2}	tr	m^{-2}	tr
average individuals. per m^{-2} and pitfall traps	1276	15.2	4146	11.9	26945	93.0	10637	132.0	7060	86.6	14850	104.4	24183	62.5	16612	64.2	23235	41.1
species number	10		23		38		40		32		40		43		43		64	
Shannon–Wiener index	0.557		1.673		1.954		2.262		2.050		2.371		2.209		2.168		2.240	
Simpson index	0.290		0.713		0.814		0.836		0.801		0.879		0.844		0.801		0.842	
Colonisation groups: (mean numbers of individuals per group)																		
1 Fugitive initial group: 11 species	932	14.7	83	1.4	9	3.0	0	0.5	0	0	50	0.1	50	0.1	23	0	0	0.2
Mesaphorura florae Simon et al., 1994	DD	–	–	–	–	–	–	–	–	–	–	–	–	–	+	–	–	–
Entomobrya lanuginosa (Nicolet, 1841)	–	DD	–	D	SR	R	–	SR	–	+	SR	–	–	+	–	–	–	SR
Bourletiella pistillum Gisin, 1946	SD	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
2 Pioneer group: 5 species	0	0	1331	4.4	9394	54.1	554	0.5	476	0.9	300	0	183	0.1	206	0	125	0.2
Hypogastrura assimilis (Krausbauer, 1889)	–	–	DD	R	DD	DD	R	+	R	SR	–	–	–	+	–	–	+	+
Ceratophysella succinea (Gisin, 1949)	–	–	DD	D	D	DD	+	+	+	SR	–	–	–	–	–	–	–	–
Isotomodes productus (Axelson, 1906)	–	–	R	–	SD	–	R	–	R	–	–	–	+	–	SR	–	+	–
3 Bipolar group: 3 species	288	0	2479	0	16472	0.1	6446	0.1	4530	0.1	5800	0.3	13217	0.5	9360	0	4901	0.2
Mesaphorura macrochaeta Rusek, 1976	SR	–	DD	–	DD	–	DD	–	DD	–	DD	–	DD	–	DD	–	SD	–
Parisotoma notabilis (Schäffer, 1896)	DD	–	D	+	DD	+	DD	+	DD	SR	DD	+	DD	SR	DD	–	DD	SR
Protaphorura armata (Tullberg, 1869)	–	–	D	+	D	–	D	–	D	–	SD	–	DD	–	SD	–	D	+

Tab. 7 cont.

site/age	IK1		NA2		T4		H/		A10		NB24		A33		A46		W_{native}	
sampling method	m^{-2}	tr	m^{-2}	tr	m^{-2}	tr	m^{-2}	tr	m^{-2}	tr	m^{-2}	tr	m^{-2}	tr	m^{-2}	tr	m^{-2}	tr
4 Post–pioneer group: 18 species	36	0.3	208	5.3	727	35.2	1857	130.1	1208	81.2	150	3.7	33	0.1	91	–	1276	8.4
Lepidocyrtus cyaneus Tullberg, 1871	–	+	R	R	SR	SD	R	SD	SR	SD	R	–	–	–	+	–	SD	DD
Lepidocyrtus paradoxus Uzel, 1891	–	+	–	R	–	D	SR	SD	SR	DD	–	–	–	–	–	–	–	SR
Isotoma viridis Bourlet, 1839	R	–	SD	D	R	DD	R	SR	D	DD	–	SD	–	–	–	–	SR	SD
5 Pioneer woodland group: 8 species	0	0.2	21	0.3	60	0.5	214	0.1	363	1.8	6775	97.1	6817	39.2	1503	39.3	297	8.2
Megalothorax minimus Willem, 1900	–	–	–	–	–	–	SR	–	SD	–	D	–	DD	–	SD	–	SR	–
Tomocerus flavescens (Tullberg, 1871)	–	–	–	+	–	+	–	+	–	SR	SR	DD	R	DD	R	DD	–	DD
Mesaphorura hylophila Rusek, 1982	–	–	–	–	SR	–	SR	–	SD	–	DD	–	SD	–	R	–	SR	–
6 Euryoecious woodland group: 7 species	4	0	0	0.4	227	0.1	1536	0.7	435	2.6	1250	2.9	2300	17.2	3726	21.6	2271	19.4
Isotomiella minor (Schäffer, 1896))	–	–	–	–	SR	–	D	–	SD	–	R	–	SD	–	DD	–	SD	–
Stenaphorurella quadrispina (Börner, 1901)	SR	–	–	–	SR	–	SR	–	SR	–	SD	–	SR	–	R	–	R	–
Pseudosinella alba (Packard, 1873)	–	–	–	–	–	–	+	–	SR	–	D	+	SD	SD	R	–	SD	–
7 Pre–woodland group: 20 Species	0	0	21	0	0	0	0	0	12	0	500	0.2	1450	5.3	1680	3.3	844	0
Mesaphorura tenuisensillata (Rusek, 1974)	–	–	–	–	–	–	–	–	–	–	–	–	R	–	SD	–	SD	–
Xenylla grisea Axelson, 1900	–	–	–	–	–	–	–	–	–	–	–	–	+	–	SD	–	–	–
Neonaphorura dungeri Schulz, 1994	–	–	–	–	–	–	–	–	–	–	–	–	–	–	R	–	–	–
8 Stenoecious woodland group: 16 species	16	0	21	0.1	56	0	30	0	36	0	25	0.1	133	0	23	0	13531	4.5
Folsomia manolachei Bagnall, 1939	–	–	–	+	SR	–	–	–	+	–	–	–	–	–	–	–	DD	+
Folsomia quadrioculata (Tullberg, 1871)	–	–	SR	–	SR	–	–	–	+	–	–	–	–	–	–	–	DD	+
Mesaphorura krausbaueri Börner, 1901	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	SD	–

Tab. 8 Species turnover rates of collembolan communities between successive stages of the Berzdorf mine sites. For description and code names of mine sites see Tab. 1.

Sites	Species turnover rate
IK:NA2	0.545
NA2:T4	0.295
T4:H7	0.231
H7:A10	0.100
A10:NB24	0.444
NB24:A33	0.432
A33:A46	0.409
A46:W	0.454

Indices of species similarity gave some additional information. The Sørensen-index (Fig. 4), the Baroni-Urbani Buser-quotient, and the dominance similarity by the Renkonen-index were all calculated separately for edaphic and epedaphic life forms. The clusters of similarity for all three indices and the life forms were nearly identical, which confirmed the situation as expected from the alpha-diversity and species turnover values. There were three groups: firstly from the earliest stage of colonisation (IK), secondly from the young mine sites, including the youngest stage NA2 with very sparse vegetation somewhat separated from the stages with more or less complete vegetation cover (T4, H7, and A10), and thirdly from the combination of the older deciduous woodland mine sites (NB24, A33 and A46). Unexpectedly and particularly interesting was the position of the undisturbed reference woodland community (W), which was close to the group of young mine sites. The high similarity of the collembolan community of the adjacent undisturbed forest (W) with the younger stages of Berzdorf mine sites was relevant to assess the direction of the later phase of succession on Berzdorf mine sites (Dunger et al. 2004b).

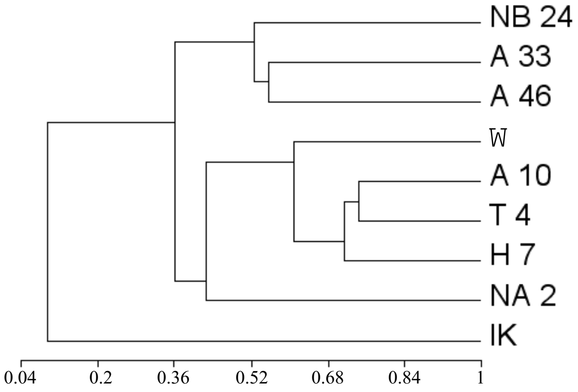


Fig. 4 Cluster analysis (UPGMA constrained) of the collembolan communities of Berzdorf mine sites and a ‘native’ woodland (W) according to species similarity using the Sørensen index (based on soil samples; edaphic life forms). For description and code names of mine sites see Tab. 1.

4.3.4. Do collembolan communities become gradually similar to those of an undisturbed woodland during the mine-site development?

There are different influences affecting results on collembolan succession at mine sites. On the one hand, results depend on the length of the observation period; on the other hand the ecological characteristics of the sites are important. Results from short-term investigations (Bode 1975, Greenslade & Majer 1993, Stebaeva & Andrievskii 1997) indicate a direct development of the collembolan community towards an equilibrium state similar to that expected for native soils. This corresponds to observations at Berzdorf mine sites up to ten years after recultivation. Only the results from the long-term observation (between 24 und 46 years) at Berzdorf mine sites indicate that the collembolan species composition becomes more divergent from undisturbed woodlands with increasing mine-site age. The niches occupied by Collembola, existing in an ectohumus layer, apparently changed 10 to 20 years after rehabilitation because of the dominant impact of earthworm activity, creating new ecological (endohumic) conditions (cf. Scullion & Malik 2000). That is reflected by the fact that a total of 38 species behaved differently on the older mine sites (A33, 46) compared to the undisturbed woodland (W). Typical observations concern the absence of very common ubiquists such as *Folsomia quadrioculata* at mine sites. There is no immigration barrier, as the species had been found twice (NA2, A33) with only few specimens that obviously were unsuccessful at colonising (Dunger et al. 2004b). The same results were published by Bode (1975) from central German mine sites. Materna (1999) only found the species in Czech red-oak mine sites.

These observations support the hypothesis that soil ecological processes become partially worse with the aging of mine sites. This is suggested by laboratory tests, which found that the activities of both earthworms and springtails are essential for plant nutrition (Scheu & Setälä 2002). However, these experiments were carried out with only few collembolan species selected opportunistically (Partsch et al. 2005). Such results cannot give any information as to whether the collembolan species composition of older mine sites is sufficiently diverse to fulfil its functions in the nutrient cycle. There is no evidence to deny the soil biological success of the mine-site development after fifty years. Nevertheless, the gap in the species composition of Collembola in the older mine sites and its ecological significance remains obscure.

5. Macroarthropods

Studies in macroarthropods colonising Berzdorf mine sites were carried out also on myriapods (see below), beetles (Vogel & Dunger 1991, Brunk et al. 2007), spiders and harvestmen (Kobel-Lamparski in Dunger & Wanner 1999, Zulka in Dunger et al. 2001, Balkenhol & Nährig 2007), ants (Seifert in Dunger et al. 2001), and other groups.

We do not intend to summarise the results of all these investigations here but confine the review of our studies to myriapods. This group, combining saprophagous (Diplopoda or millipedes), and zoophagous (Chilopoda or centipedes) taxa, is of a particularly high importance in soil ecology and was therefore studied very intensively.

5.1. Diplopoda

5.1.1. Immigration

Immigration by millipedes takes place mainly through active locomotion (Dunger 1967, 1998, Dunger & Voigtländer 1990, Wanner et al. 1998). Wind has been suggested as a mechanism of dispersal only for small species or juveniles (Haacker 1968). Air immigration tests, carried out on Berzdorf mine sites (see paragraph 4.1), never contained juvenile millipedes or centipedes. Dispersal ability varies considerably between species. Some species more or less remain in their optimum habitat, whereas others have a marked tendency to migrate. Many species have life strategies (parthenogenesis, periodomorphosis), which allow them to invade new habitats rapidly (Blower 1969).

5.1.2. Colonising process

True pioneer species, i.e., colonisers that appear only in the first ten years after rehabilitation, do not exist within millipedes. However, we can distinguish between ‘early’ and ‘late’ colonisers.

Early colonisers. *Craspedosoma rawlinsii* and *Polydesmus inconstans* occur at first in the 1st (IK) to 4th (T4) years of succession at sites with deciduous afforestation only. The high densities found at T4 (Fig. 5) suggest an earlier starting point at one or two years, as observed on IK and on mine sites of the Sokolov region (Tajovský 2001). *C. rawlinsii* reached its highest densities during the first 8 years, and *P. inconstans* after 10 years (Tab. 9). Both species decreased in abundance in a stepwise fashion during the following years and were totally absent after 46 years from pitfall traps, but sporadically present in soil cores. Juveniles (found by minicontainer tests) indicate that populations still exist at site A46. *Craspedosoma rawlinsii* as well as *P. inconstans* are part of the millipede fauna of surrounding ‘native’ woodlands of the Berzdorf region. *J. scandinavius* also belongs to the group of early colonisers. In the Sokolov and Rhenanian mining district this species already appeared in 1- or 2-year-old afforestations (Tajovský 2001, Topp et al. 1992, 1998), as well as in newly developed vineyard areas in southern Germany (Kobel-Lamparski & Lamparski 1995). In the Berzdorf mining district *J. scandinavius* needs 8 years to immigrate (Tab. 9). All these investigations have in common, that the abundances and dominances reached their maximum during the phase of biocoenotic regulation (Dunger 1991), in mine sites after 20 to 25 years, in vineyard areas possibly some years earlier. At mine sites in Lower Lusatia with unfavourable site conditions (afforested with *Quercus rubra* on poor sandy soils), this species appears not earlier than 20 years after afforestation (Voigtländer & Balkenhol 2006).

The group of late colonisers is composed of species preferring woody habitats. The first-listed occurrences of the following species were: *Nopoiulus kochii*: A18, *Proteroiulus fuscus*: A34, *Polydesmus denticulatus*: A34, *Polyzonium germanicum*: A34, L34, *Melogona voigtii:* NB24, *Glomeris hexasticha*: A46, L46. Some species tried to settle on Berzdorf mine sites earlier, but without success: *Glomeris tetrasticha* at L10, *Unciger foetidus* at H7 (in Fig. 5 overlaid) and *Brachydesmus superus* at A18 and N18. Of these, only *U. foetidus* was able to establish itself later (from H22 on), whereas the other two species never colonised the Berzdorf mine sites.

The blaniulid species *Blaniulus guttulatus* (found by field samplings and soil cores only), *N. kochii* and *P. fuscus* usually live under bark, in dead wood and leaf litter where large amounts of wood are present. Such conditions were found only in older afforestations, in the Berzdorf mine sites starting with site A34, when the planted *Robinia*-trees began to break down. In the Lower Lusatian mining district, *P. fuscus* also occurs in the oldest red oak mine sites and in the *Q. petraea* woodlands older than 40 years (Voigtländer & Balkenhol 2006). All blaniulids are often highly aggregated (e.g. Gromysz-Ka³kowska & Tracz 1977) without a tendency to active migration or epigeic activity. Their abundance per square metre can therefore not be measured efficiently by the usual quantitative methods. *Polydesmus denticulatus*, preferring cool and humid habitats (e.g. Blower 1985, Spelda 1999), was found for the first time about 30 years after the recultivation of mine sites in the Lower as well as Upper Lusatian mining district (only by field sampling).

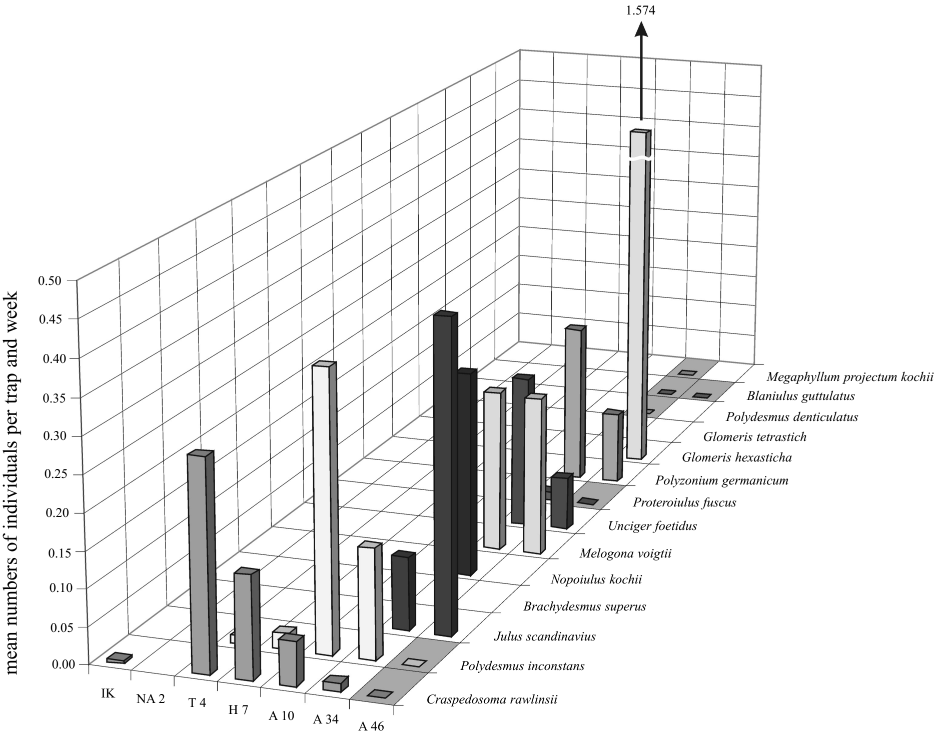


Fig. 5 Millipedes trapped on Berzdorf deciduous mine sites and on the vegetationless site IK during intensive investigation periods between 1960 and 1998. Grey areas: results from special field samplings with minimal numbers of individuals. For description and code names of mine sites see Tab. 1.

Quantitative development at deciduous afforested mine sites. Over 46 years of development at the Berzdorf deciduous mine sites (NA2, T4 and A10 to A46), species numbers and abundances increased in relation to site conditions (Figs 7, 8). Activity and abundance increased strongly at the beginning of the pre-woodland stage (A10) and reached its maximum after 46 years with 2.4 ind./trap/week. This is clearly a higher activity than was found in the neighbouring 'native' deciduous woodland NVd (1.8 ind./trap/week), whereas species numbers are much higher in NVd.

Population development at mine sites afforested with *Pinus.* Under the conditions at the Berzdorf mine site, the pioneer *Pinus*-phase (L10, L14) was characterised by only two typically early-colonising species (*C. rawlinsii* and *P. inconstans*), but at lower densities than in deciduous afforestations (Figs 5, 6). During the following years the *Pinus*-forest has developed into a mixed forest (see paragraph 2) and therefore species number and density of millipedes increased above the level found at coniferous forests on undisturbed soils (see below).

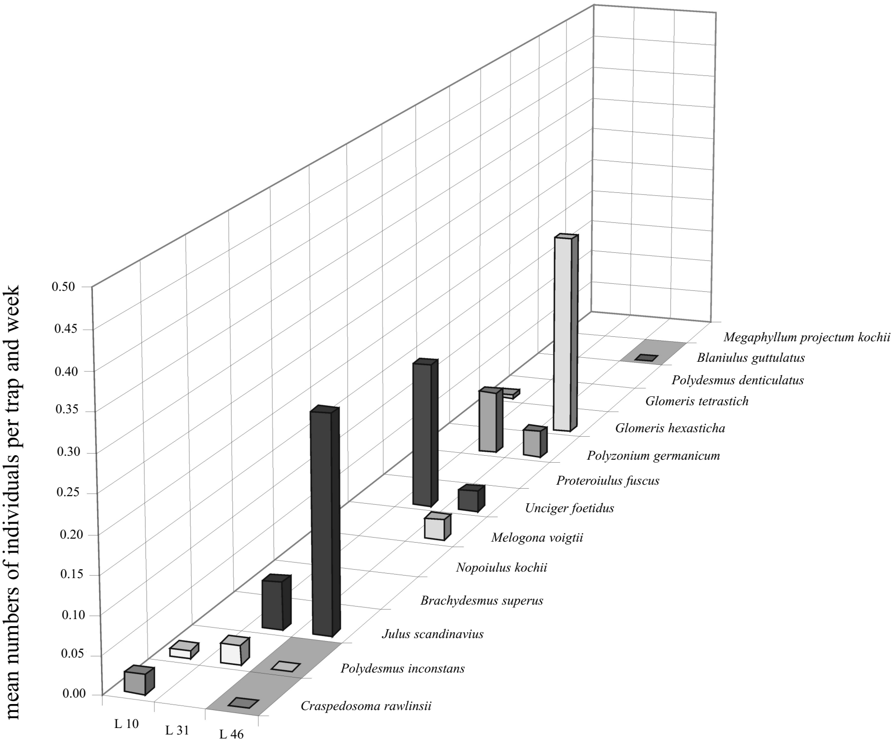


Fig. 6 Millipedes trapped on Berzdorf primarily coniferous afforested mine sites during intensive investigation periods between 1960 and 1998. Grey areas: results from special field samplings with minimal numbers of individuals. For description and code names of mine sites see Tab. 1.

Pinus sites under unfavourable soil conditions (Tertiary sands on mine sites as well as on native soils; DoKie, DH), are found to be inhabited by only 1 to 3 species at low densities (Figs 7, 8).

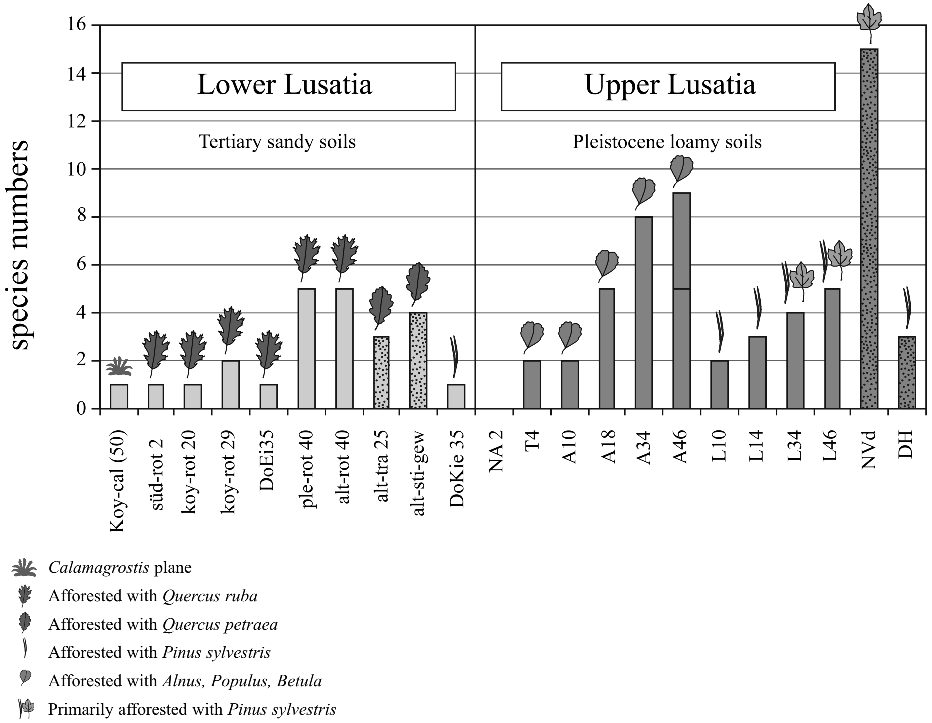


Fig. 7 Millipede species numbers at mine sites of the Cottbus (Lower Lusatia) and Berzdorf (Upper Lusatia) mining district of different soil conditions, ages and vegetation cover in comparison to ‘native’ sites (NVd, DH). For description and code names of mine sites see Tab. 1. (After Voigtländer & Balkenhol 2006).

5.1.3. Factors influencing the colonisation process

Nutrient supply. As for other saprophagous soil animals, the quality of food (tree species, herb layer) influences the settlement and development of populations of millipedes. Pine needles and ‘hard-leaf’ litter (*Quercus, Fagus*) are a very unsuitable food for them. This accounts (in combination with soil conditions) for the poor development of millipedes at sites afforested with *Quercus petraea*, *Q. rubra* or coniferous trees (Figs 7, 8) in comparison with deciduous tree sites with more palatable litter (*Populus*, *Robinia*, *Alnus*). The existence of a herb layer of *Calamagrostis* does not ameliorate conditions in unfavourable leaf litter (koy-cal-50, DoKie), because these grasses are only a tolerated, but not preferred food for millipedes (Schmidt 1952, Voigtländer 1987).

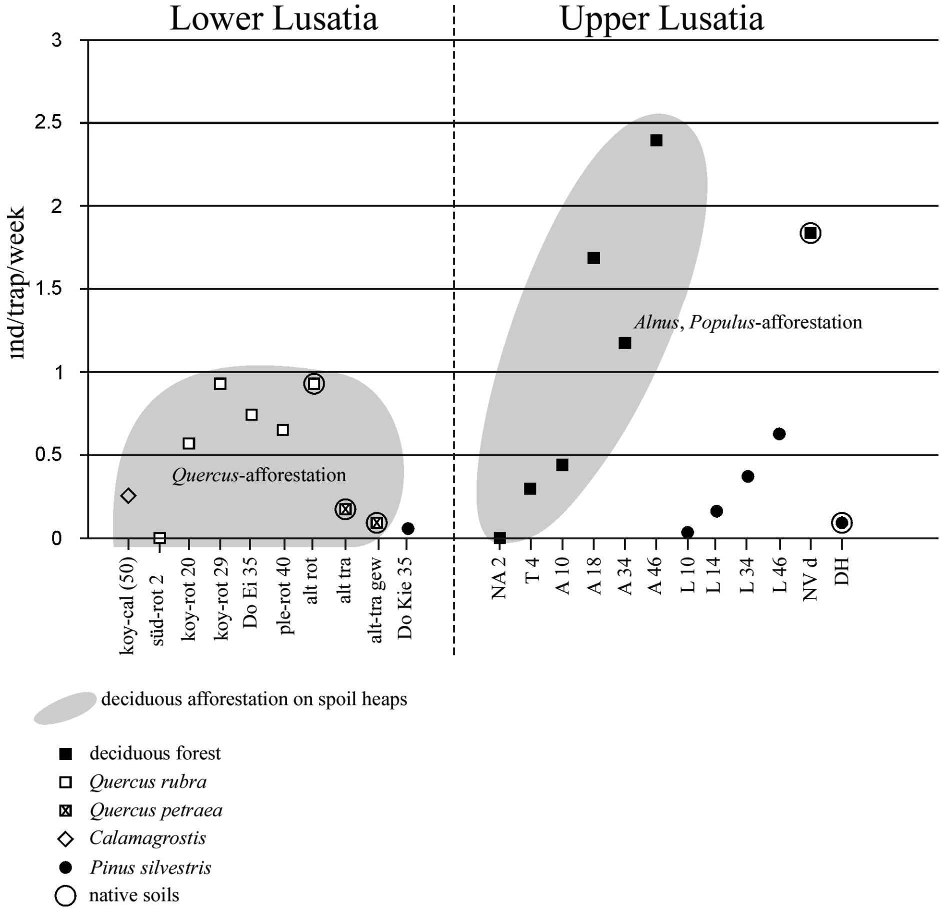


Fig. 8 Activity abundance (mean number of individuals per trap per week) of millipedes at mine sites of the Cottbus (Lower Lusatia) and Berzdorf (Upper Lusatia) mining district of different soil conditions, ages and vegetation cover in comparison to 'native' sites. For descriptions and code names of mine sites see Tab. 1. (After Voigtländer & Balkenhol 2006).

Soil quality. The same soil conditions are relevant for millipedes as for other saprophagous soil animals. The mining districts in Upper and Lower Lusatia offer good conditions to compare the influence of the substratum on the colonising process and further population development.

The Tertiary, nutrient-poor sandy mine sites in Lower Lusatia with low water retention, low content of organic matter and high acidity (Scherzer 2001, Düker 2003) are not favourable for colonisation by millipedes (Voigtländer & Balkenhol 2006), compared with conditions in Upper Lusatia (Berzdorf) or in Bohemia (Sokolov) (Dunger & Voigtländer 1990, Tajovský 2001) with a more loamy, Pleistocene substrata. The diversity and activity density of millipedes on Tertiary substrata never reached that of Pleistocene mine sites (Figs 7, 8).

Additionally, pine forests are generally poor in millipedes with not more than 8 (mainly 3 dominant) species and an average activity of 0.05 ind./trap/week because of soil acidity and poor humus and nutrient quality (Voigtländer 1995a, b, Voigtländer & Balkenhol 2006, Weigmann et al. 1989, Wytwer 1992, 2000).

Species inventory and invasion capacity. The species composition of the surroundings and the colonising activity of species have main influences on colonisation process. Different resources in the surrounding habitats result in different species composition on the sites studied (Neumann 1971, Kobel-Lamparski 1989, Scheu 1996, Tajovský 1999, Dauber et al. 2005). For example, *Polydesmus testaceus, Leptoiulus cibdellus* and *Megaphyllum unilineatum* migrated from surrounding woods into the Most mining district (ÈR) (Tajovský & Voženílková pers. comm.), but these species were never found in mine sites of Sokolov (ÈR) or Berzdorf. Correspondingly, the 'sand species' *Ommatoiulus sabulosus* migrated from surrounding open land into Lower Lusatian mining districts (Voigtländer & Balkenhol 2006).

5.1.4. Diplopods as indicators

Dominance structure. During the studied first 46 years of the Berzdorf deciduous mine site succession, the diplopod fauna was subjected to important changes in species composition (Figs. 5, 6) and dominance structure (Tab. 9). Four developmental stage with fluid transitions were distinguished:

The early pioneer stage (0 to 6 years after rehabilitation) is characterised by the occurrence of *C. rawlinsii* (1st year) and *P. inconstans* (4th year). *C. rawlinsii* was the predominant species. Only these two species were able to tolerate the extremely unfavourable conditions of young mine sites.

The late pioneer stage (shrub and grass phase; 5 to 10 years) allowed the settlement of *J. scandinavius* in small numbers with further growth of vegetative cover and increase in litter production (Tab. 9). The dominance of *C. rawlinsii* decreased in favour of *P. inconstans* during the following years.

Pre-woodland stage (10 to 18 years): This stage is clearly dominated by *P. inconstans* and of *C. rawlinsii* in smaller amounts. Improvements in site conditions (closing of the canopy, well-developed herb layer, better microclimatic conditions and stepwise enrichment of a humic A-horizon) also allowed species with stricter ecological requirements (*N. kochii*) to establish. With the change over to the 'woodland stage' in the 18th to 22nd year after afforestation *J. scandinavius* reached high dominances.

Woodland stage (more than 22 years): Widespread species (*G. hexasticha*, *P. denticulatus*) and woodland species (Blaniulidae-species, *P. germanicum*, *M. voigtii*) became more important. The early colonisers *C. rawlinsii* and *P. inconstans* persisted, but decreased to a minimum (at A46 only a few individuals could be recorded in soil cores).

Diplopod assemblages. One of the aims of reclamation and recultivation is the adaption of the sites to conditions of the 'predisturbed level' (Dunger 2004). This possibly means that the following conditions should be met: a high biodiversity, an increased environmental capacity and the transition to a natural cycle of ecological processes. The stepwise development in millipede assemblages over the long investigation period of 46 years can best be compared using faunistic similarity.

Tab. 9 Dominance of selected diplopod species at Berzdorf deciduous-afforested mine sites during 46 years and at an adjacent deciduous ‘native’ woodland according to pitfall trapping.

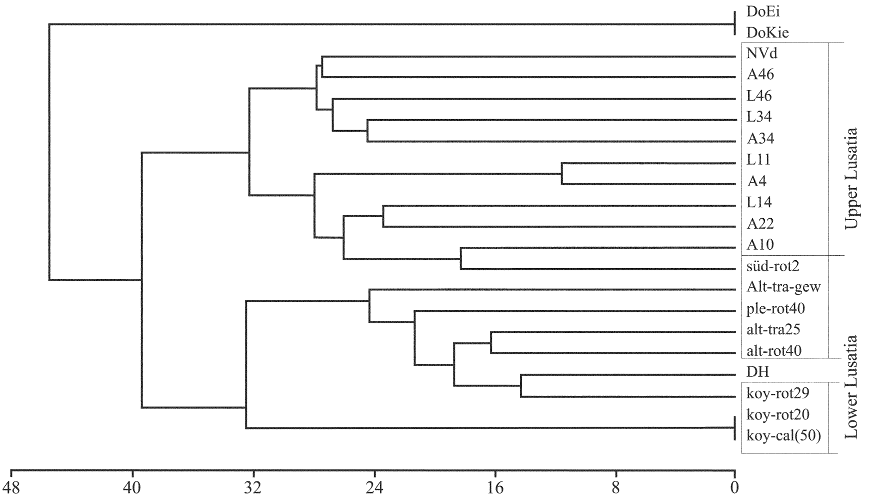
	pioneer stage			grass and shrub stage		pre-woodland stage				woodland stage				‘native’ wood
years after recultivation	1	2	4	7	8	10	11	14	18	22	24	34	46	NVd
C. rawlinsii	100		96.6	66.7	66.7	18.5	13.7	80	▥	12.2		▤		
P. inconstans			▥	26.7	21.6	81.5	81.8	20	59.1	20		12.8		
J. scandinavius					11.8		▥		13.6	62.5		▥	17.6	18.1
further species				▥					20.5	▥	100	77,7	82.4	80.7
intensive investigations	x	x	x	x		x						x	x	x

■	eudominant (32.0–100.0 %), white typed
▒	dominant (10.0–31.9 %), black typed
▥	subdominant (3.2–10.0 %)
▤	recedent (1.0–3.1 %)
□	subrecedent (< 1 %)

The cluster of similarities shows three related complexes (Fig. 9): I ‘Upper Lusatian-complex’, II ‘Lower Lusatian-complex’ and III the outsider complex (DoEi, DoKie) with the least similarity (because of the sole presence of *O. sabulosus*).

The clear differentiation between the Upper and Lower Lusatian complex is mainly caused by soil conditions and secondly by food supply (see above). In the ‘younger Upper Lusatian-complex’, the similarity between the already developed site A10 and the young süd-rot-site (Lower Lusatian-complex) is remarkable. This is perhaps explicable by the high dominance of *P. inconstans* at these sites. Under the poor soil conditions in Lower Lusatia the development of assemblages is arrested at an underdeveloped stage, differing quite distinctly from the Berzdorf mine sites with better conditions.

Within the ‘Upper Lusatian-complex’ the diplopod assemblages cluster into two groups: the younger afforested sites up to 22 years were separated from the older afforestations and the ‘native’ site NVd.



UPGMA: Average Distance

Fig. 9 Biocoenotical similarity of the diplopod coenoses using the Wainstein index. Clustering method: UPGMA. For description and code names of mine sites see Tab. 1.

With the progressive change of the initial *Pinus* afforestation into a mixed woodland, the millipede assemblages of this site became more similar to those of the deciduous sites of the same age (A34:L34 and A46:L46). Both types of sites came closer to undisturbed woodlands with increasing age. The fauna of the surroundings is well known (Voigtländer & Dunger 1992, Voigtländer & Hauser 1999, Voigtländer 2001). As a representative 'native' site for comparison, the Neiße Valley (NV) is chosen. The high number of common species (7), and similar densities (but a different dominance structure) are reflected in the relatively high similarity (but not identity). Nevertheless, characteristic species, which occur frequently and in high numbers in the surroundings, are still absent even in the oldest mine sites, especially *Strongylosoma stigmatosum*, but also *Mycogona germanica*, *Mastigona bosniense*, *Ochogona caroli, Polydesmus complanatus* and *Megaphyllum projectum kochi.* This indicates that the succession to a 'regionally typical' woodland has not yet been achieved.

5.2. Chilopoda

5.2.1. Immigration

As to the millipedes, active immigration and first establishment of centipedes are influenced by the surrounding fauna, the invasion capacity, dispersal ability and particular life strategies.

Investigations with drift-protected and normal pitfall traps (Dunger & Engelmann 1978) at an open kaolin-covered area at a Berzdorf dumped mine (see paragraph 4.1; Dunger et al. 2002) suggest that an active immigration of *Lamyctes emarginatus* and *Lithobius forficatus* from a neighbouring young *Populus* afforestation (with small populations of these species) took place. Records of very young juveniles (stages III and IV) of *L. emarginatus* – having a small locomotion activity – suggest the existence of an already established population at the young mine site.

In the Cottbus mining district colonisation by chilopods was much delayed. *L. emarginatus* occurred only after 26 years of recultivation. This is due to the isolated location of the investigation sites within the very large mining district without population-source areas in the direct neighbourhood (Balkenhol et al. 2006).

Soil cores taken at freshly dumped test plots never contained centipedes, nor did outdoor experimental plots with 'sterile' Pleistocene substratum (see paragraph 4.1) at Berzdorf mine sites give any evidence for centipedes being transported as aerial plankton, although this may be possible for light juveniles (approx. 0.2 mg, Voigtländer 2000) but surely not for the much heavier adults.

5.2.2. Centipede assemblages

Changes in species composition and dominance structure. Very early immigrating microarthropods (e.g. *Proisotoma*, *Entomobrya*; Dunger 1968, 1998) provide the first food for invading predaceous living chilopods. As the first species, *Lamyctes emarginatus* occurs after 1 to 2 years (Tab. 10), being a real pioneer with a short generation cycle (only 1 year or shorter), parthenogenetic propagation and a high mobility. In consequence of the high fecundity (several generations per year), the species is able to increase its populations rapidly (Zulka 1991). *L. emarginatus* is characterised by a high tolerance to stress, which allows it to resist the poor site conditions which are typical for the first years. Other early colonisers, but not pioneers s. str., are *Lithobius forficatus* and *Lithobius microps*. They were found at mine sites after 1 and 7 years respectively, and still dominated after 46 years.

Tab. 10 Dominance of four selected centipede species at Berzdorf deciduous-afforested mine sites during 46 years and at an adjacent deciduous 'native' woodland. For dominance classes see Tab. 9.

	pioneer stage			grass and shrub stage		pre-woodland stage				woodland stage				'native' wood
years after recultivation	1	2	4	7	8	10	11	14	18	22	25	34	46	NVd
Lamyctes emarginatus	99.9	100	62.5	88.2	65.1	▥								
Lithobius forficatus			25	▥	18.6	64.9	69.1	71.4	87.5	66.7	28.6	32.6	12.9	▤
Lithobius microps						29.7	25	28.6	12.5		42.8	52.2	77	▤
Lithobius mutabilis			12.5										▥	86.7
further species						▤	▥			33.3	28.6	15.2	▥	▥
intensive investigation	x	x	x	x		x						x	x	x

For some other centipedes, only estimates of establishment can be made. The open land and dry woodland-inhabiting species *Lithobius calcaratus* (H22, soil cores; A34; L34) and L. crassipes (L34, soil cores) are of this type as well as species preferring open and ruderal habitats such as *L. melanops* (H7; H11, soil cores; A10; A46). The woodland-inhabitant species *Schendyla furcidens* was only found for one time at L34 and *L. mutabilis* at T4 and L10. Of these species, only *L. mutabilis* was able to build up populations at mine sites after 46 years (A46, L46), in high densities (Figs 10, 11), but in a subdominant position (Tab. 9). This seems to be an indication of successful settlement, in contrast to *L. melanops*, which occurred only in low numbers of individuals at A46.

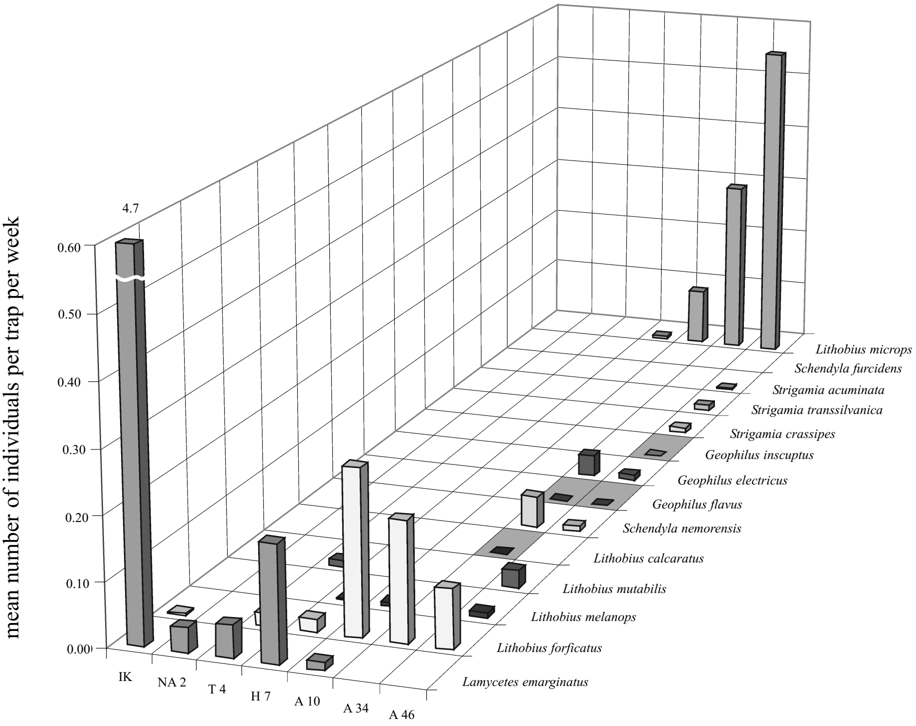


Fig. 10 Centipedes trapped at Berzdorf deciduous mine sites of different ages from intensive investigation periods between 1960 and 1998. Grey areas: results from special field samplings with minimal numbers of individuals. For description and code names of mine sites see Tab. 1.

The fourth group, composed of Geophilomorphs, was never dominate but was characteristic of ‘woodland-like stages’ of mine sites. Unlike the litter-layer-inhabiting Lithobiomorphs, Geophilomorphs are predators hunting within the soil pores. Thus, they require a developed A-horizon (Dunger & Voigtländer 2005). Among them, the most surface-active species of Geophilomorphs, *Geophilus flavus* (A14) and *Schendyla nemorensis* (A14, soil cores), immigrate not earlier than 14 years after recultivation (Figs 10, 11). *Geophilus electricus* needed much more time, first arriving after 34 years, and *Strigamia crassipes, Strigamia acuminata* and *Geophilus alpinus (=insculptus)* were first found after 46 years.

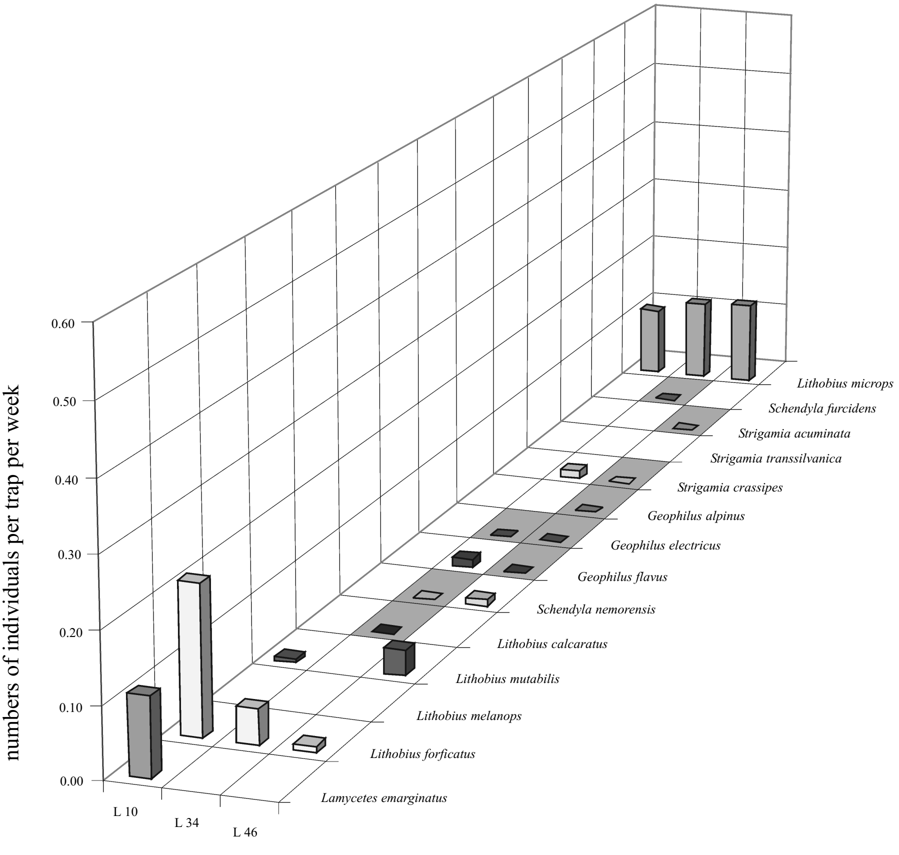


Fig. 11 Centipedes trapped at Berzdorf coniferous-afforested mine sites during intensive investigation periods between 1960 and 1998. Grey areas: results from special field samplings with minimal numbers of individuals. The occurrence of *L. crassipes* at L34 (only 1 ind.) is not shown in the figure. For description and code names of mine sites see Tab. 1.

The dominance of each of four lithobiid species was found to indicate three stages of primary succession over the 50 years (Tab. 10). The pioneer stage is well characterised by *L. emarginatus*. The predominance of this pioneer lasted till the 8th year after rehabilitation, i.e., to the end of the late pioneer stage. At that time the ecolimatic conditions of the habitat – as a result of vegetation development – allow *L. forficatus* to establish itself. This euryoecious species, having a weak preference for open and dryer habitats in eastern Germany (Voigtländer 2005), was best suited to the 'pre-woodland stage'. After 25 years a further change in dominance structure takes place. *L. microps*, which is also present earlier but with only few specimens (recedently), becomes and eudominant remains for the following years. Both species are subordinate inhabitants of surrounding undisturbed deciduous woodlands, where *L. mutabilis* dominates.

Quantitative development. The density ('activity abundance' as registered by pitfall trapping) and species numbers of centipedes were investigated in a totally vegetationless (IK), in deciduous (NA, T, H, NB and A) and in coniferous (L) Berzdorf mine sites for 46 years (Tab. 11). Within the succession, the vegetation-free site IK took a special position with extremely high activity abundance of pioneers and early colonisers (see also Fig. 10).

In the deciduous forests, increasing abundances were estimated in correlation with different developmental stages of the sites: The early pioneer stage (2 to 6 years) was characterised by the lowest activity abundances and species numbers. During the following stages, up to the start of the woodland stage, the increase in abundances and species numbers was relatively small. At first, the developing woodland stage (after 34 years) offers good conditions for a high number of species to be abundant.

Under *Pinus* plantation, the latest pioneer phase (L8–10) is characterised by a very high density of centipedes. This comprised high densities of *L. forficatus* together with *L. emarginatus* which is still present, and the first occurrence of *L. microps* in a subordinate role. During the following years (L14, short investigations) abundance decreased and the species number was reduced to only one (*L. forficatus*). After the transition of the *Pinus*-forest into a mixed forest (see paragraph 2.) species number and density of centipedes increased again.

Tab. 11 Species numbers and activity abundances (mean numbers of individuals per trap and week) of centipedes at mine sites of the Berzdorf mining district of different ages and vegetation cover in comparison to adjacent 'native' sites (grey fields). For description and code names of mine sites see Tab. 1.

Deciduous-afforested sites	IK	NA2	T4	H7	A10	A 14–18	NB24	A34	A46	NVd	W
species number	2	1	3	4	4	4	3	7	10	16	7
activity abundance	4.85	0.08	0.008	0.211	0.201	0.1533	0.175	0.575	0.731	1.09	0.41

Coniferous-afforested sites	L 10	L 34	L 46	NVs
species number	4	6	8	8
activity abundance	0.439	0.2	0.185	0.601

Similarity between chilopod assemblages at mine sites and surrounding ‘native’ sites

The estimation of similarity in composition between centipede assemblages at mine sites in comparison with ‘native’ surrounding woodlands was based on the species records (using the Jaccard-index of similarity), because differences in sampling methods for Lithobiomorpha and Geophilomorpha only allow a comparison of species numbers.

On this basis, the cluster of similarities showed two groups of sites (Fig. 12): Group I consists of young site assemblages, up to 10 years for deciduous and up to 18 years for coniferous afforestations. The slower development of coniferous forests was seen by the similarity between younger deciduous afforested sites and older coniferous afforested sites: (L10 to T4; L14–18 to A 10).

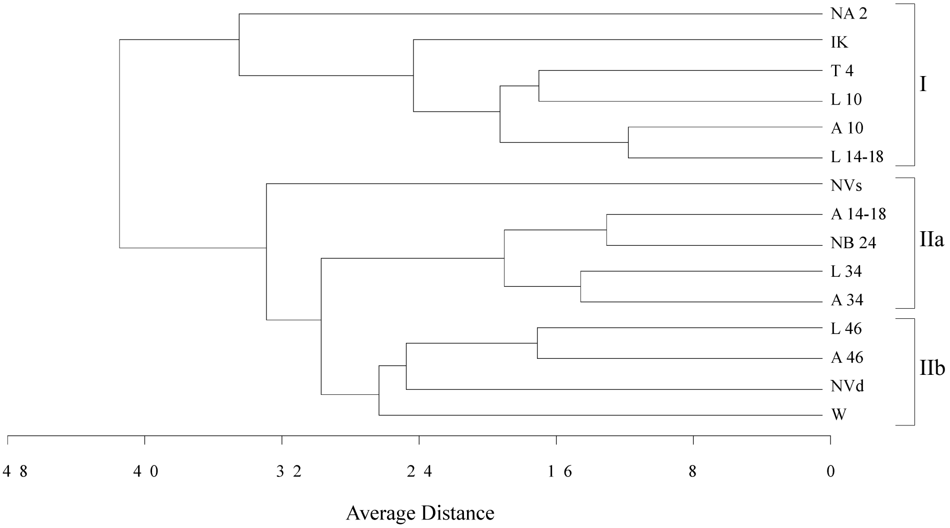


Fig. 12 Biocoenotical similarity of the chilopod coenoses using the Jaccard index. Clustering method: UPGMA. For description and code names of mine sites see Tab. 1.

Group II, divided into a and b, consists on the one hand of sites older than 14 years (deciduous afforestation only) to 34 years (group IIa) and on the other hand, of the mine sites older than 46 years together with the ‘native’ deciduous woodlands (NVd and W; group IIb).

The high similarity between L 34 and A 34 (within group IIa) and the affiliation of L46 with the group IIb are explicable by the changes in site conditions of site L after about 30 years.

The oldest afforested mine sites look natural and the vegetation composition is close to that of ‘native’ forests. However, on the oldest mine sites many species of natural and regionally typical centipede assemblages were still lacking: *L. dentatus*, *L. nodulipes*, *L. austriacus*, *L. macilentus*, *L. valesiacus* and *L. agilis.*

The centipede fauna of the ‘native’ reference spruce forest (NVs) is intermediate between groups I and II.

In neither deciduous nor coniferous forests do species numbers and abundances reach the level of ‘native’ adjacent woodlands (NVd, NVs).

6. Conclusions

The soil-faunal colonisation of dump mines, deposited after brown coal open cast mining, was investigated because of its considerable high economic interest and the opportunity to use an extensive field experiment for soil ecological science. An investigation extending over such a long period as half a century should provide significant conclusions regarding revitalisation processes.

In order to reintegrate such a big dump area into the landscape, among others the evolution of a soil fauna onto the primarily dead surface of mine sites – a result of the activity of an open cast mining industry – is essential.

6.1. Immigration and colonisation

As experiments showed by controlling the arrival of aerial plankton, first species to invade appear by chance, dependant on the species composition of the vagile parts of the fauna of the surrounding environments. For members of the soil microfauna, that is probably the first real step in colonisation. Higher animals (e.g. microarthropods) are very seldom seen to found in the ‘airborne’ population, but aerial plankton distribution may be one way (of many) to invade mine sites.

6.2. Quantitative and qualitative development of the soil fauna

Basic factors controlling soil faunal development are the soil fauna of the surrounding environment, the mineral and chemical composition of the substratum and the local climate. These factors were found to cause – mainly based on the development of the vegetation – large differences between the studied mine site districts Berzdorf (loamy Pleistocene substrata) and Cottbus (poor sandy, Tertiary substrata). In particular, the decomposition of soft leaves with high nitrogen content (from deciduous plants) favours the development of a saprophagous soil fauna.

Species of the soil mesofauna (microarthropods) with short generation periods, requiring only small microhabitats, are able to reproduce soon after invasion and to build up high densities (10^5 ind. m^{-2}) rapidly (over 3 to 6 years). The loss of their microhabitats (litter layer) by earthworm feeding competition drastically decreased their densities, and recovery takes about 30 years.

The species diversity of microarthropods rises rapidly to a high level and retains this level for 50 years.

Species of the soil macrofauna, especially earthworms, need 20 years or more to build up a ‘normal’ population density, then it can rise to be higher than normal by overshooting after 30 to 40 years, but decreases later. Species diversity of earthworms is generally low but their soil-ecological importance is dominant over all other groups of soil fauna.

6.3. Importance of soil animals in the formation of a new soil eco-subsystem

As is generally known, saprophagous soil animals are of a high importance in initiating and intensifying the decomposition processes by means of several steps (primary decomposition by soil macrofauna, secondary decomposition by soil meso- and microfauna). Whereas micro- and mesofaunal animals invade during early stages of the succession, members of the macrofauna immigrate later and therefore are acting in most cases about from the 10th year on. As an exception, dipteran larvae were found in the litter layer of young open mine sites without earthworms. Isopods could very seldom be found to contribute to litter decomposition at early stages of the studied mine sites. Only after 50 yearss, Berzdorf deciduous mine sites were invaded by the normal wood-inhabiting isopod species.

A quantitative measure of the significance of the macrofauna, especially of earthworms, to litter decomposition is only possible using the contribution to the energy flow by respiration related to the individual biomass (see paragraph 3.5, Tab. 5). Using this method, the potential level of zoogenic decomposition (DLZpot) can be related to the energy yield of the yearly production of litter to the soil layer by the vegetation. From the 10th year after recultivation onwards, the saprophagous soil macrofauna of deciduous afforested Berzdorf mine sites is able to decompose about 70 % of the yearly litter input. Of the total SOM decomposition, the contribution of earthworms is about 95 %, so that the role of millipedes and dipteran larvae can be ignored from the quantitative viewpoint. At mine sites with a poor substratum and vegetation quality (Lower Lusatian district), 4.5 to 7 times less decomposition was measured and the contribution made by other groups, especially dipteran larvae, was higher (Dunger 1989, 2004, Dunger & Voigtländer 2005).

The activity of earthworms and millipedes in bioturbation has not been measured, but their effectiveness could be observed studying soil sections from afforested Berzdorf mine sites. Some investigators (Parr 1978) are convinced that even microarthropds such as Collembola, may considerably influence the structure and species composition of the vegetation. Results of the present study gave no direct indication of such an effect.

6.4. Suitability of taxonomical and ecofunctional groups as indicators of biological soil quality

The length of the investigation period (about 50 years), and the study of many different groups (saprophagous and predaceous groups of soil macro-, meso- and microfauna) with large differences in the individual life span, allow an assessment of the suitability of each animal group to indicate the mine-site development and especially improvements of soil-biological quality.

Indication is of high relevancey to characterise the process of decomposition and – as a consequence – the origin, development and quality of humus. Lumbricids or – in a wider sense – the decomposer assemblage (with Enchytraeidae and microarthropods) were considered to be the most suitable group for qualitative and even quantitative indication (zootic decomposition level).

Another aim of mine-site reclamation is the improvement of biodiversity. A suitable group for checking diversity should have many (>100) regional, taxonomically well-known species and an integrated relationship with other organisms. For these reasons, the microbiophagous, species-rich Collembola (springtails) were considered suitable for investigation. The results showed details of the quite different and alternating species composition over half a century, but no clear improvement of Collembolan species diversity during the period 20 to 25 years after rehabilitation. In order to solve this particular question, further studies in ecophysiology of some species will be necessary.

The division of the dynamic succession on mine sites into biologically relevant periods can be made based on the development of different groups. The best correspondence between plant and animal succession was found for centipedes and millipedes as far as typical species were present in the stages as early pioneers, late pioneers, pre-woodland and woodland assemblages. Therefore, using myriapods as indicators for biological stages of mine site development an unambiguous, compatible and economical method.

6.5. Is there a stepwise reapprochment to the 'pre-disturbance level'?

The (not yet published) study on plant development over half a century on Berzdorf mine sites shows a succession resulting in a woodland plant assemblage typical of the region. The same can be stated for the (partly new) results from soil- animal decomposer assemblages and decomposition activity (earthworms).

Other conclusions could be drawn from data obtained by the study of the species-rich groups of soil microarthropods, especially springtails, as well as from myriapods. Within the springtails, 38 common and woodland-inhabiting species that were present in the adjacent woodlands, could not be found in the 50-year-old woodland mine sites. In parallel, 5 species of millipedes and 6 species of centipedes – all members of the Myriapod fauna of native woodlands near the mine sites – did not colonise the mine sites. Exceptionally, single immigrants of these species were found on the mine sites, so that immigration barriers cannot be the cause of their absence. At present, the gaps in the species composition of these groups of micro- and macroarthropodes and their significance for the ecological capacity of 50-year-old mine sites are not understood. It is not possible to conclude that the development of the soil fauna of the studied mine sites have arrived at a 'pre-disturbance level' in general, whereas important ecological functions (e.g. soil organic matter decomposition) do take place without question. Nevertheless, the time required for an ecologically optimal restoration 'may be extremely long' (Greenslade & Majer 1993).

7. Acknowledgements

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