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1 **The potential of earthworms to restore ecosystem services after opencast mining**
2 **– A review**

3

4 **Running head: Earthworms in opencast mine restoration**

5

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14

14 **Abstract**

15 Opencast coal mining has several environmental impacts, which require land
16 rehabilitation when mining operations are finished. For that reason, restoration after
17 such extractive industries' work is common and has been well studied. However,
18 many ecological restoration schemes do not examine to what extent complete and
19 functioning ecosystems have been restored above and below ground. While the aim
20 should be to restore functioning ecosystems, most restoration plans focus only on
21 vegetation and above ground macro-fauna.

22 Among the potential species that are likely to be important early in mine land
23 restoration, earthworms are particularly good candidates. They provide several
24 ecosystem services that are likely to accelerate soil restoration, improve primary
25 production and facilitate the restoration of a functional ecosystem in mining areas.
26 These services include: increase in topsoil fertility, food for a wide range of predators
27 and recycling of waste organic materials on rehabilitated areas.

28 Here, we outline some of the challenges specifically facing opencast mining
29 restoration and describe how the ecosystem services provided by earthworms may
30 address some of these challenges.

31

32 **Keywords:** Earthworm introduction; soil rehabilitation; ecological restoration;
33 functioning ecological ecosystems; waste bio-stabilisation

34

35

36 **Introduction**

37 The fundamental role of earthworms in the formation of soils was largely
38 acknowledged by Darwin (1881): "It may be doubted whether there are many other
39 animals which have played so important a part in the history of the world, as have
40 these lowly organised creatures". In a recent review of the potential role of soil
41 macro-invertebrates in ecological restoration, Snyder & Hendrix (2008) highlighted
42 the importance of earthworms in accomplishing restoration goals in various degraded
43 soils. Here we outline some of the challenges specifically facing opencast mining
44 restoration and describe how the ecosystem services provided by earthworms may
45 address some of these challenges. The unique emphasis of this review is a focus on a
46 specific type of land restoration (opencast mining) for which the potential of
47 earthworms has been scarcely investigated. There are no examples of large-scale use
48 of earthworms for such restoration programmes. This review will address why this
49 ecosystem approach needs to be carried out and discusses the role of functioning
50 earthworm communities in such a restoration programme.

51

52 **Environmental issues associated with opencast mining**

53 Opencast mining usually consists of removing vegetation and soil and, when
54 necessary, blasting the underlying rocks to gain access to the desired resource. During
55 this process, several environmental impacts occur that require land restoration when
56 mining operations are finished. The main long-term environmental issues caused by
57 opencast mining include direct vegetation destruction, soil deterioration and water
58 acidification. For that reason, attempts at restoration are common (Plass & Vogel,
59 1973; Lyle, 1987; Hossner, 1988; Sengupta, 1993; Smyth & Dearden, 1998) but are
60 not always based on a sound ecological knowledge.

61

62 *Direct vegetation destruction*

63 The vegetation is either cut down or removed with the soil. The resulting denuded
64 landscape is favourable for pioneer, early successional, often introduced species but
65 not for mid- to late-successional plant and animal populations to re-colonise.

66

67 *Deterioration caused by soil displacement and long-term stockpiling*

68 Before opencast mining begins, soil is usually removed and stored in stockpiles,
69 sometimes for several years, then spread again at the original place or elsewhere after
70 mining activities have been completed (Lyle, 1987; Scullion, 2002). The soil fauna
71 and flora experience extreme conditions during this phase, as most of the pile is
72 compacted and anaerobic (Abdul-Kareem & McRae, 1984). Furthermore, structure of
73 soils spread after stockpiling is likely to be destroyed by the bulking process, partly
74 because topsoil is mixed with subsoil overburden materials (Schwenke, Mulligan &
75 Bell, 2000).

76

77 *Water acidification following the oxidation of sulfide*

78 During excavation, sulfide minerals, such as pyrite (FeS_2), are exposed to oxygen.
79 Pyrite occurs in nearly all types of geological environments and is commonly
80 associated with coal and metallic ore. Oxidation of pyrite leads to the formation of
81 acid in the environment, resulting in low pH and releasing other metals such as
82 aluminium, iron and trace metals (Lu, Wang, Chen, Xue, Zhang et al., 2005).
83 Rainwater coming into contact with these oxidized minerals then becomes severely
84 acidified and loaded with heavy metals (Lottermoser, 2007).

85

86 **Opencast mining restoration**

87 While the aim should be to restore a functioning ecosystem (Bradshaw & Hüttl,
88 2001), most restoration plans focus only on vegetation and above-ground macro-
89 fauna, which are more visible and more easily manageable. Soil communities, which
90 are less accessible and less visible, are usually ignored (Langer, Davis & Ross 1999;
91 Majer, Brennan & Moir, 2007). The reconstruction of an appropriate plant community
92 is essential for the restoration of most degraded land ecosystems and attempts to
93 restore most other aspects of ecosystem structure and function cannot succeed without
94 a functioning ecological community of primary producers (Perrow & Davy, 2002).
95 Therefore, environmental criteria for restoration success after opencast mining
96 operations are traditionally related to re-vegetation success and plant biomass
97 production (e.g., Smyth & Dearden, 1998; Koch, 2007). It is usually assumed that the
98 production of self-sustaining vegetation comprising a variety of native plants will in
99 turn support native fauna (Schwenke et al., 2000). However, the enhancement of
100 populations or the addition of other species groups may be necessary in many cases to
101 accelerate ecological succession, ensure native fauna re-colonisation and improve the
102 restoration of a functioning ecosystem (Frouz, Elhottova, Pizl, Tajovsky, Sourkova et
103 al., 2007). Because soil is the component most dramatically altered by opencast
104 mining, soil fauna should be a major focus with regard to the re-establishment of
105 ecosystems on mine sites (Dunger, 1968; Hüttl & Weber, 2001; Topp, Simon, Kautz,
106 Dworschak, Nicolini et al., 2001; Majer et al., 2007).

107

108

109 **The potential roles of earthworms in restoration ecology**

110 **Earthworms as soil improvers**

111 Among the potential groups that are likely to be important early in mine-site
112 restoration, earthworms are particularly good candidates. Because they play a major

113 role in the comminution and mineralisation of organic matter and greatly influence
114 soil structure and chemistry, the presence of a flourishing earthworm community is
115 likely to accelerate soil restoration and improve primary production (Edwards &
116 Bohlen, 1996). Therefore, earthworms have frequently been used for soil restoration
117 purposes (for a review, see: Butt, 2008; Snyder & Hendrix, 2008), but never for large-
118 scale restoration of opencast mine sites. By their burrowing activity, earthworms mix
119 and aggregate soil (Blanchart, 1992) and minimize surface water erosion by
120 enhancing soil macroporosity (Francis & Fraser 1998) and water-holding capacity
121 (Topp et al. 2001). Earthworms consume organic matter and mineral particles and
122 many of the species egest casts that are microbially very active and contain nutrients,
123 which are readily usable by plants (Edwards, 2004). By doing so, they accelerate the
124 topsoil creation process. Sandhu, Wratten, Cullen & Hale (2005) quantified the value
125 of exotic earthworms' ecosystem services in terms of topsoil creation in pastures in
126 Canterbury, New Zealand (125,000 ha of arable land). The benefits were estimated at
127 between 4 and 65 million USD per year, depending on field type and history. This
128 figure is probably underestimated since it is based on the current low market price of
129 topsoil, which ignores the complex and lengthy processes that created it as well as the
130 direct and indirect costs associated with substituting oil-based input for soil ecosystem
131 functions.

132 Three different ecological guilds of earthworms are commonly differentiated: those
133 inhabiting the leaf-litter, the topsoil or the subsoil (Bouché, 1972; Lee, 1985).
134 Earthworms in different guilds have different feeding preferences and burrowing
135 behaviours that affect their impact on and creation of soil. There is little functional
136 redundancy between groups as each affects the soil structure and nutrient dynamics in
137 a different way. As a result, the impact of all groups is not a reflection of the sum of
138 their individual contributions but is synergistic (Sheehan, Kirwan, Connolly &
139 Bolger, 2006). Therefore an optimal restoration scheme should focus on species from
140 the three guilds.

141

142 **The role of earthworms in community function**

143 Because earthworms are integral to the functioning of terrestrial ecosystems, they
144 have the ability to influence plant and soil communities. As an example, seed
145 ingestion and excretion by earthworms have the potential to alter seed germination of
146 numerous plant species (Eisenhauer, Schuy, Butenschoen & Scheu, 2009). In most
147 cases earthworm digestion was shown to accelerate seed germination by breaking
148 seed dormancy (Ayanlaja et al., 2001) and increasing water permeability of the seed
149 surface (Tomati, Grappelli & Galli, 1988). However, for some plant species,
150 germination success decreases after digestion by earthworm (e.g., Decaens, Mariani,
151 Betancourt & Jimenez, 2003). The effect of earthworm excreta on seeds appears to be
152 earthworm and plant species-specific and suggests that plants might have adapted to
153 the ingestion by local earthworms (Eisenhauer et al. 2009). These relationships are
154 likely to contribute to earthworm-mediated changes in vegetation structure (Regnier,
155 Harrison, Liu, Schmoll, Edwards et al. 2009) such as those observed in the recent
156 invasion of European earthworm species in the temperate forests of the North-eastern
157 United States (James & Hendrix, 2004; Hale, Frelich & Reich, 2006; Hendrix, Baker,
158 Callaham, Damoff, Fragoso et al., 2006).

159 In addition to their key role in soil structure and chemistry, and their influence on
160 plant communities, earthworms represent a substantial biomass capable of supporting
161 large communities of vertebrate (e.g., Macdonald, 1983) and invertebrate (e.g., Judas,
162 1989; Boyer & Wratten, 2009) predators. Duvigneau (1980) estimated that the

163 earthworm biomass in a deciduous oak-hornbeam (*Quercus-Carpinus*) forest in
164 Belgium to be 600 kg/ha. This can represent more than 98% of all animal biomass in
165 forest ecosystems (Brockie & Moeed, 1986) and leads to indirect ecosystem services,
166 as their predators may have positive impacts on seed dispersal (Wall, 2004), reduction
167 of pests (Landis, Wratten & Gurr, 2000; Symondson, Glen, Erickson, Liddell &
168 Langdon, 2000; Araj, Wratten, Lister & Buckley, 2009) and weed-seed populations
169 (Navntoft, Wratten, Kristensen & Esbjerg, 2009).

170

171 **Earthworms in opencast mine soils**

172 **Impact of mining activities on earthworms**

173 Soils disturbed and/or moved after mining are particularly hostile to earthworms
174 because of the lack of structure, the compaction during the stockpiling process, low
175 organic matter content, unfavourable moisture conditions and very low pH (Pizl,
176 2001; Curry, 2004). However, natural re-colonisation of soils after mining can occur
177 at a slow rate. Only a few studies in the United Kingdom and Eastern Europe have
178 focused on the impact of opencast mining on earthworm populations. They show that
179 the survival rate of earthworms in the surface of the soil stockpiles can be high
180 enough to act as a reservoir for re-colonisation of re-spread soils (Armstrong &
181 Bragg, 1984). Because stockpiles are mainly anaerobic and very compact, only the
182 top layer of the pile is suitable for earthworms to survive until the soil is spread again.
183 Individuals surviving the stockpiling process can re-colonise rehabilitated soils within
184 10 to 30 years (Scullion, Mohammed & Ramshaw, 1988; Hüttnl & Weber, 2001 Pizl,
185 2001). Earthworm biomass is then similar to that of the pre-mining state but species
186 composition may differ. Best results are obtained in conjunction with efficient plant
187 restoration programmes. Indeed, the presence of vegetation accelerates the natural re-
188 colonisation process because plant roots enhance earthworm burrowing activity
189 (Springett, Gray, Barker, Lambert, Mackay et al., 1998) and more importantly,
190 decaying plant parts provide the necessary food resource.

191

192 **Introduction of earthworms to mining soils**

193 Unlike some microorganisms (Jasper, 2007), arthropods (Majer et al., 2007), birds,
194 reptiles and mammals (Nichols & Grant, 2007), earthworms have limited dispersal
195 capacities (Dunger, 1989; Marinussen & van den Bosh, 1992) and may require
196 extensive re-introduction in areas requiring restoration following intensive
197 commercial or industrial use. Introduction of earthworms facilitates the creation of
198 topsoil and the establishment of vegetation (Butt, Frederickson & Morris, 1995;
199 Baker, Brown, Butt, Curry & Scullion, 2006) as well as the provision of other
200 ecosystem services; see above. Therefore, earthworms have often been targeted as
201 organisms to introduce in restoration programmes involving macro-invertebrates
202 (Butt, 2008; Snyder & Hendrix, 2008). Introduction of earthworms has been rarely
203 attempted in restored mine soils, however, when it has been attempted, substantial
204 improvements in ecosystem services have been achieved. For example, in an opencast
205 coal mine in Ohio, there was a faster degradation rate of leaf litter within six months
206 after the introduction of *Lumbricus terrestris* (L.) to small mesocosms in mine spoils
207 (Vimmerstedt, 1983). On a larger scale (400 m²) in the UK, the introduction of six
208 local earthworm species (70 individuals m⁻²) in restored coal mine soils led to an
209 increase in soil aggregation, microbial biomass and carbohydrate content and more
210 generally to higher primary production over a five-year study (Scullion & Malik,
211 2000).

212 The choice of which species to introduce is of primary importance, as several
213 examples of earthworm introductions in landfills and colliery spoils resulted in poor
214 re-colonisation success when unsuitable species were used (see Butt, 2008 for a
215 review). Moreover, the introduction of exotic earthworms can significantly affect
216 other soil organisms and plant communities, as earthworms are integral to the
217 functioning of terrestrial ecosystems within which they have evolved (James &
218 Hendrix, 2004; Hale et al., 2006; Hendrix et al., 2006). Therefore, it is essential to
219 introduce only those earthworms, which are native or endemic to mine restoration
220 areas if the aim is to restore native ecosystems.

221

222 **Bio-stabilisation of waste organic materials in mining soil**

223 Increasing worldwide production of city and industrial waste motivates the research
224 for disposal and recycling options methods alternative to the traditional land filling
225 and open dumping practices. Earthworms have been used to recycle wastes from
226 various origins such as textile (Rosa, Giuradelli, Corrêa, Rörigand, Schwingel et al.,
227 2007), distillery (Suthar & Singh, 2008), paper (Garg, Gupta & Satya, 2006) and food
228 industries (Schuldt, Rumi, Gutiérrez-Gregoric, Caloni, Bodnar et al., 2005), as well as
229 city sewage (Neuhauser, Loehr & Malecki, 1988; Suthar, 2009); see Kale (2004) for a
230 review. Most of these studies have involved only one epigeic species such as *Eisenia*
231 *fetida* (Savigny), *Eisenia andrei* Bouché, *Eudrilus eugeniae* (Kinberg), *Perionyx*
232 *excavatus* (Perrier) or *Perionyx sansibaricus* (Perrier), although remediation
233 efficiency may vary according to the species as well as waste composition and
234 concentration (Neuhauser et al., 1988; Butt, 1993; Emmerling & Paulsch, 2001;
235 Khwairakpam & Bhargava, 2009). In a restoration programme context, knowledge
236 acquired from single-species laboratory or small mesocosm studies needs to be
237 extrapolated to large-scale application of waste directly to the soil, with the aim of
238 benefitting to the whole earthworm community. The supplementary addition of
239 organic waste may be required until decaying plant parts from the rehabilitated
240 vegetation produce enough organic matter.

241 The addition of organic waste such as sewage sludge to mine re-spread soil could be
242 an optimal solution for land restoration. Indeed, sludge could provide the local
243 earthworm community with the organic matter that it lacks because of the absence of
244 vegetation in the early phase of land restoration. At the same time this waste could be
245 recycled naturally by the earthworms. The use of sewage sludge in this way at
246 restored mine sites in Germany led to an increase in earthworm population density,
247 biomass and burrowing activity (Emmerling & Paulsch, 2001). In the treated areas,
248 which received 10 to 25 t of sludge per hectare, earthworm population density had
249 doubled after two years compared to the control which had only mineral fertilizer
250 added. Similar results were obtained by Barrera, Andrés & Alcañiz (2001). However,
251 the authors highlighted the accumulation of heavy metals in earthworm tissue and
252 faeces. Although they are sometimes useful to detoxify soils, the propensity of
253 earthworms to accumulate heavy metals and other toxic materials may present a
254 significant risk of bioaccumulation through the food web (Suthar & Singh 2009).

255

256 **Conclusions**

257 There is a high current interest in the relationship between ecosystem function and
258 biodiversity because the economic value of ecosystem function (ecosystem services)
259 is of global importance (Constanza, d'Arge, de Groot, Farber, Grasso et al., 1997;
260 Daily, 1997). However, biodiversity is declining worldwide at the greatest rate since
261 the last Ice Age (Wilson, 1988) and species extinction rate is expected to continue to

262 increase dramatically during the next 50 years if ‘biodiversity hotspots’ are not
263 protected (Pimm & Raven, 2000). Because restoration schemes cannot focus on every
264 species in an ecosystem, priority groups are usually selected based on their important
265 role in the ecosystem (keystone species), their high resource requirements and habitat
266 needs (umbrella species), their capacity to arouse public interest and sympathy
267 (flagship species) or their threatened status (Simberloff, 1998; Hunter & Gibbs, 2007).
268 In mining areas, the restoration of earthworm communities could greatly accelerate
269 land restoration and the re-establishment of a functioning ecosystem. Indeed,
270 earthworm populations have an important impact on several ecosystem services,
271 including direct services and indirect services due to the sustaining of a wide range of
272 predators. Also, the use of earthworms in mine soils can enhance the disposal and
273 stabilisation of organic wastes. Measurement of all these ecosystem services may be
274 necessary to have an accurate idea of the ecological and economic value of
275 rehabilitating earthworm fauna in post-mining land. An appropriate approach to this
276 will require a multi-disciplinary programme (see Sandhu, Wratten, Cullen & Case,
277 2008), which includes measuring ecosystem function in the field using a range of
278 experimental methods, which are rapidly becoming available (see Navntoft et al.
279 2009; Porter, Costanza, Sandhu, Sigsgaard & Wratten, 2009).
280 Despite their ecological importance, the services that earthworms provide have been
281 poorly considered in mine land restoration, even in the well-studied mines of eastern
282 Germany (Hüttl & Weber, 2001) and Western Australia (Majer et al., 2007). With a
283 rapidly-increasing world human population and consequent reductions in biodiversity,
284 such approaches are increasingly important. Research of the type reviewed here on
285 ecosystem services provided by earthworms needs to be provided to end-users in the
286 form of Service Providing Units (SPUs; Luck, Harrington, Harrison, Kremen, Berry
287 et al., 2009). Such units of information inform users about what type of biodiversity is
288 needed to improve ecosystem services by how much ecosystem services thereby
289 improved and how, where and when to deploy the functional biodiversity. Producing
290 such SPUs is a vital requirement for sustainable future mine restoration using
291 earthworms.

292

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298

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