Quantification of the inevitable: The influence of soil macrofauna on soil water movement in rehabilitated open-cut mine land.

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Abstract

Recolonisation of soil by macrofauna (especially ants, termites, and earthworms) in rehabilitated open-cut mine sites is inevitable. In these highly disturbed landscapes, soil invertebrates play a major role in soil development (macropore configuration, nutrient cycling, bioturbation, etc.) and can influence hydrological processes such as infiltration and seepage. Understanding and quantifying these ecosystem processes is important in rehabilitation design, establishment and subsequent management to ensure progress to the desired end-goal, especially in waste cover systems designed to prevent water reaching and transporting underlying hazardous waste materials. However, soil macrofauna are typically overlooked during hydrological modelling, possibly due to uncertainties on the extent of their influence, which can lead to failure of waste cover systems or rehabilitation activities. We propose that scientific experiments under controlled conditions and field trials on post-mining lands are required to quantify (i) macrofauna – soil structure interactions, (ii) functional dynamics of macrofauna taxa, and (iii) their effects on macrofauna and soil development over time. Such knowledge would provide crucial information for soil water models, which would

increase confidence in mine waste cover design recommendations and eventually lead to higher likelihood of rehabilitation success of open-cut mining land.

1 Introduction

In land restoration, practitioners are principally concerned with the residual physical properties of reconstructed landscape components and their assembly to either resemble the original configurations or in developing novel designs that achieve acceptable functional outcomes (*sensu lato* ecological engineering by Mitsch & Jorgensen (1989)). Typically, the impact of macrofauna (e.g., ants and termites, earthworms) on soil structure is scarcely recognised by these ecological engineers and soil scientists, despite recognition by soil ecologists and entomologists that soil macrofauna significantly contribute to ecosystem services such as soil formation, water availability for vegetation, or flood and erosion control (Lavelle et al., 2006), and soil development (Bottinelli et al., 2015). This omission of macrofauna from landscape design may in part be due to the current lack of quantitative knowledge of their role in the nature and timing of significant alterations to soil physical properties (e.g. the formation of macropores and soil aggregates) at the landscape scale, and their temporal evolution (Bottinelli et al., 2015). Such information is crucial for soil restoration and ongoing ecosystem productivity in degraded lands (Blouin et al., 2013; Jouquet et al., 2014; Frouz and Kuraz, 2013), where biodiversity and material/energy cycles are interrupted and mainly driven by disturbances and land management history (e.g., for agriculture, the history of tillage and pesticide application (Bottinelli et al., 2015; Doley and Audet, 2013)). The perturbation of normal soil forming processes is exacerbated in open-cut mining lands, where topographical and geological ecosystem elements are disrupted at the landscape-scale (Fig. 1). In this regard, and throughout this article, we refer to “ecosystem rehabilitation” as the process of attempting to re-instate ecosystem functions and services (Seastedt et al., 2008; Audet et al., 2013; Doley and Audet, 2013; Aronson et al., 1993) as opposed to “ecosystem restoration” that aims to re-instate the structure, functioning, and dynamics of historical (pristine) ecosystems (Aronson et al., 1993; Hobbs et al., 2006).

Numerical models of environmental processes are a critical component of any planning scheme for the management of human-impacted ecosystems (Arnold et al., 2014; Arnold et al., 2012b), or for the design and construction of facilities aiming to protect ecosystems and local communities from hazardous materials such as mine waste (Arnold et al., 2015; Gwenzi et al., 2013; O'Kane and Wels, 2003). For example, modelling of soil water dynamics is essential at the early design stage of mine waste rock storage facilities. However, if model assumptions about material properties are based on their initial state rather than after their temporal evolution, such facilities may fail to attain their long-term design objectives (Taylor et al., 2003). On other hand, a sensible balance between the complexity and uncertainty of numerical models is required to use them as exploratory or management tools (Arnold et al., 2012a). We acknowledge the effects of plant roots on soil hydraulic properties and preferential flow, and the progress in numerical modelling of root system architecture and root water uptake in recent years (Bargués Tobella et al., 2014; Carminati et al., 2011; Javaux et al., 2008; Schröder et al., 2008). However, we believe that macrofauna–soil structure interactions rather than root–soil interactions play a critical role in the soil water distribution at the early stage of soil reconstruction, particularly if plant available water is the predominant abiotic stressor (Arnold et al., 2013).

While the recent review article of Bottinelli et al. (2015) advocates collaboration between soil ecologists and physicists in order to increase understanding of soil-plant water relations, their review is limited to natural and agricultural ecosystems subjected to low or moderate levels of disturbance. As an extension of their work, we propose that interactions between soil fauna and soil structure dynamics are even more critical for severely disturbed ecosystems such as in open-cut mining lands. Therefore, in this short communication article, we (i) consider the impact of macrofauna on the rehabilitation of open-cut mine lands, specifically the effects of ants/termites and mine waste facilities, and (ii) indicate how further research on feedbacks between macrofauna and soil structure may help to reduce uncertainties in the prediction of soil water movement in rehabilitated mine environments, especially toxic waste covers.

2 Socio-ecological impacts of open-cut mining

Both biotic (e.g., fauna, vegetation, microbes) and abiotic (e.g., water, soil material, meteorological variables) ecosystem components are fundamental drivers of material and energy cycles, and thereby govern ecosystem structure and function. During open-cut mining, many ecosystem components, including these material and energy cycles, undergo significant physical and chemical disturbances and may be irreversibly disrupted to at least some extent (Fig. 1).

After mining activities are complete, the topography and physical soil properties are re-constructed in an attempt to establish the foundation of a self-sustaining ecosystem. At this initial stage and at the landscape scale, soil biodiversity is reduced and/or disrupted to an extent that could almost be referred to as 'sterile' (Rives et al., 1980; Miller et al., 2011). In addition to this initial sterile conditions, open-cut mining often results in the generation of hazardous wastes in the form of either coarse-grained waste rock that is separated before mineral processing, or of fine-grained processing wastes (tailings) (Lottermoser, 2010). These waste materials are then deposited at the mine site and require rehabilitation. One form of rehabilitation that is increasingly accepted for closure of mining waste facilities is the use of vegetated mine waste cover systems (Arnold et al., 2015; Gwenzi et al., 2013). These evapotranspiration cover systems are also referred to as monolithic alternative covers (Albright et al., 2004), phytocaps (Venkatraman and Ashwath, 2010), or store and release covers (Fourie and Tibbett, 2007; Wilson et al., 2003). Their design aims to minimise drainage into underlying hazardous wastes. Contrary to conventional covers made of compacted clay, geosynthetic clay liners, or polyvinyl chloride (Othman et al., 1994; Benson, 2000; Levin and Hammod, 1990), phytocaps serve two purposes: (1) to maximise rainfall interception by vegetation and, if required, a compacted soil layer, and (2) to remove soil water through plant transpiration and evaporation from bare soil (Salt et al., 2011). Through successive rainfall events, the loss of stored soil water through evapotranspiration decreases net percolation through the soil (Hauser et al., 2001; Rock, 2010), and reduces surface runoff and erosion.

Regardless of the rehabilitation design, soil macrofauna are particularly important in this initial stage of rehabilitation (Frouz and Kuraz, 2013), due to their rapid recolonisation, particularly by generalist taxa that have long-distance (relative to macrofauna) dispersal strategies. For example, the typical dispersal strategy for many ant species is by nuptial flights (Peeters and Molet, 2009), where copulation occurs in the air after specific climatic cues and queens fly from 100 m to 10 km from their originating nest to find suitable habitat before dropping their wings and establishing a new nest (Hölldobler and Wilson, 1990). Initially, a limited number of individuals are produced from newly laid eggs and colony survival depends on food resources, which for ants (omnivores) include seeds (e.g. from topsoil spreading or revegetation activities), other fauna (invertebrates or vertebrates and their products) or other organic matter (Blüthgen and Feldhaar, 2009). As these newly established colonies are small, not much food is required for survival until further resources become available. Thus, colony foundation at rehabilitated mine-sites can occur within weeks (Williams, personal observation) and prior to vegetation establishment from seeds.

However, deterioration in cover performance and even failure can be caused by increased soil permeability resulting from (i) the formation of shrinkage cracks, and (ii) macropores associated with root channels, (iii) ant and termite galleries (Taylor et al., 2003) or (iv) burrowing macrofauna such earthworms (Edwards et al., 1990; Frouz and Kuraz, 2013). While the importance of the first two causes has been accepted by soil scientists (e.g., Bengough et al. (2011), Bengough et al. (2006), Czarnes et al. (2000), Hinsinger et al. (2009), Ranatunga et al. (2008)), the contribution of soil macrofauna to waste cover failure has been largely overlooked (Taylor et al., 2003). For example, in their report about the deterioration in performance of a waste rock cover facility in tropical Australia, Taylor et al. (2003) concluded that, amongst (i) and (ii), the formation of termite galleries played a critical role.

3 The price to pay for negligence

At post-mining sites, the type of mineral processing initially determines the soil properties, and the depth of overburden and topsoil materials removed from mine pits (Gould, 2012; Erskine and Fletcher, 2013). Likewise, the method and equipment used to reconstruct topsoil affects soil hydraulic properties (Fourie and Tibbett, 2007). However, within weeks after topsoil establishment, the first colonisers such as soil-nesting ants (e.g., *Iridomyrmex* species in Australia) build underground galleries, thereby initiating changes in soil properties (Lee and Foster, 1991). These macrofauna alter the local soil structure and profile characteristics (Jones et al., 1994; De Bruyn and Conacher, 1994), influence soil aggregate stability (Cammeraat and Risch, 2008; Lavelle et al., 2006), water infiltration and mechanical strength (Eldridge, 1994; Frouz and Kuraz, 2013), and increase the field capacity through the formation of holo-organic and organo-mineral aggregates (Frouz and Kuraz, 2013). That is, soil macrofauna introduce or increase heterogeneity of soil properties. Mound building ants, for example, excavate soil material and thereby increase the number of macropores, which leads to a lower bulk density (Dostál et al., 2005; Cammeraat and Risch, 2008; Jones et al., 1994). These changes in soil features lead to increasing infiltration rates under wet conditions (Cammeraat et al., 2002). Some ant species bring soil material from deep soil horizons to the surface (Folgarait, 1998) or damage geotextiles, which can have negative impacts on the functionality of compacted barrier layers through the creation of preferential flow paths

(Manassero et al., 2013; O'Kane Consultants Inc., 2003). Later during ecosystem rehabilitation, burrowing macrofauna such as earthworms affect the soil structure and profile characteristics in a similar manner by modifying the pore and aggregate size distribution, the soil bulk density, and soil organic matter, eventually affecting the soil water holding capacity and infiltration rates (Blouin et al., 2013; Jouquet et al., 2014; Frouz and Kuraz, 2013). The qualitative and quantitative impact of macrofauna on hydrological variables (e.g., infiltration) depends on the taxa and species involved, the soil type, the successional stage of the ecosystem, and the initial soil water conditions (Cammeraat and Risch, 2008; Cammeraat et al., 2002).

Additional uncertainties with respect to soil properties arise during ecosystem development. Specifically, unlike static engineered structures such as bridges, water levees, or dam walls, the re-construction of soil for the purpose of ecosystem rehabilitation or waste cover systems must allow for structural and functional changes. The temporal evolution of soils on post-mining lands is affected by various biotic taxa during recolonisation and compositional changes over time, including vegetation and soil macrofauna such as ants and termites (Taylor et al., 2003).

Numerical models of the one-dimensional water movement through a vertical unsaturated soil column are typically based on the Richards equation (Richards, 1931), which requires knowledge of the effective soil hydraulic properties. A range of hydraulic models are suitable to describe unimodal soil-water retention curves (Brooks and Corey, 1964; Kosugi, 1996; van Genuchten, 1980; Vogel et al., 1991); however, in open-cut mining lands where the formation of secondary pore systems is common (e.g., in waste rock materials), multimodal soil-water retention curves are an appropriate means to describe soil moisture and hydraulic conductivity characteristics in relation to soil water pressure conditions (Durner, 1994). Hence at the early stage of soil reconstruction, model uncertainty is relatively low (Fig. 2) because the models include well quantified soil parameters, and in reality, macrofauna contribute minimally to the hydraulic soil properties. However, even at a low level of complexity, these models tend to lose their predictive power over time due to pedological processes that may be ignored in the initial soil water model, but later lead to significant material changes such as increasing saturated hydraulic conductivities (Fourie and Tibbett, 2007), particularly in layers of low permeability (Taylor et al., 2003). Even more critical is the lack of quantitative knowledge about the role of macrofauna processes for soil hydraulic properties at subsequent stages of soil reconstruction. Any empirical data, be it in form of manipulative experiments under controlled conditions or in-situ field trials, would make a significant contribution to integrate the temporal impact of macrofauna on soil development into numerical soil water models.

Although this integration increases model complexity and thereby model uncertainty, it can result in more predictive power and confidence if these interactions are well quantified (Arnold et al., 2012a). In this regard, more complex models provide the opportunity to include the temporal changes in soil material properties due to pedological and biological processes. For example, while some ant species increase infiltration rates (De Bruyn and Conacher, 1990; Eldridge, 1993; Cerdà and Jurgensen, 2008), other species may have a contrary impact on infiltration (Sarr et al., 2001; Navarro and Jaffe, 1985). Infiltration rates may vary between different locations or stages of ecosystem development, thereby affecting several aspects of the soil water balance and the availability of plant material for faunal consumption, and in turn the colonisation of the site by different ant species (Williams, 2011). Likewise, while feedbacks between the temporal evolution of macrofauna and soil structure increase model complexity and uncertainty, they could play a critical role in predicting the long-term performance and hence the design of waste cover facilities (Taylor et al., 2003) or post-mining lands (Frouz et al., 2006), which ultimately leads to a higher probability of rehabilitation success and the construction of self-sustaining post-mining landscapes.

4 Conclusions and further directions

Soil colonisation by macrofauna such as ants and termites on post-mining rehabilitation sites is inevitable. Due to the significant effects of these macrofauna on soil structure, we conclude that macrofauna need to be considered by ecological engineers when designing and reconstructing lands after open-cut mining. In this regard, rehabilitation plans should include numerical soil water models that consider the temporal evolution of (i) macrofauna – soil structure interactions, and (ii) feedbacks between macrofauna taxa, and macrofauna and soil development over time.

We suggest two alternative approaches to collect empirical data (Table 1) that can be used to initially quantify these interactions and eventually to reduce uncertainty in modelled hydrological variables such as deep drainage, infiltration, or plant available water (Léonard et al., 2004). For example, manipulative experiments under controlled conditions are effective means to assess the impact of early colonisers on the soil water dynamics. A soil chamber or column (Joschko et al., 1989; Joschko et al., 1992) can be used as a formicarium (Wang et al., 1995), where an ant nest is transplanted (including queen and workers) and food, water and nesting resources provided. Predefined water regimes could then be administered to simulate rainfall events, while the temporal dynamics of soil water potential and content are monitored across the soil profile. Similarly, these small scale experiments are suitable for assessing the colonisation rates and environmental conditions (e.g., pH, temperature, humidity, soil water content) required to colonise soils by ants. At a larger investigative scale (Table 1), field trials in combination with untreated control or reference sites are effective means to assess the impact of macrofauna on soil structure and inter-specific fauna interactions (feedbacks) in relation to soil biodiversity and soil development (Cammeraat et al., 2002). In this regard, open-cut mining lands may provide ideal environments, because the physical properties of re-constructed soils are fundamentally different (and less complex) from those of degraded but physically intact soils.

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Table 1. Proposed approaches to collect empirical data in relation to ant – soil interactions.

	Glasshouse / Laboratory	**Post-mining land**
Methodology[a]	Controlled/manipulative experiments	Field trials with control site
Investigative Scale[a]	Small	Medium
Knowledge gap	Quantity and conditions of colonisation rates	Inter-specific interactions
	Effects on soil hydraulics	Succession of colonisation
		Long-term water availability for plants

[a] Arnold et al. (2013)

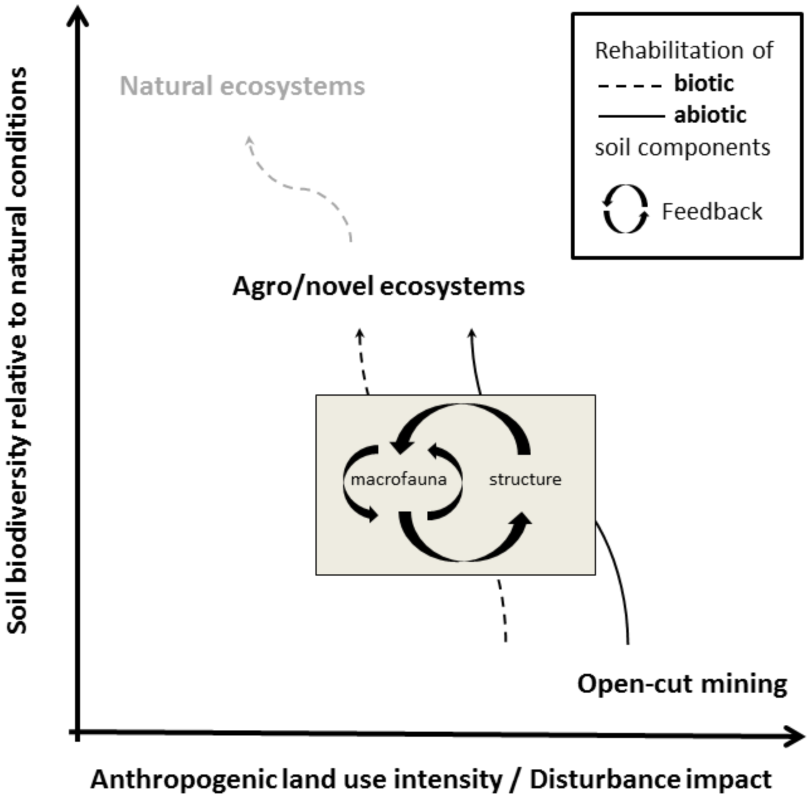

Figure 1. Relation between land use intensity / disturbance impact and soil biodiversity of natural ecosystems, conventional agriculture, and open-cut mining lands (modified after Bottinelli et al. (2015), and Doley and Audet (2013)). While the transition from conventional agriculture to natural ecosystems mainly requires restoration of biotic soil components, the transition of open-cut mining land to novel (Perring et al., 2014), agricultural or native ecosystems (if possible) requires rehabilitation of both biotic and abiotic soil components. Feedbacks between different macrofauna taxa, and macrofauna and soil structure might be critical drivers of the temporal transition of open-cut mining land to novel or agricultural ecosystems.

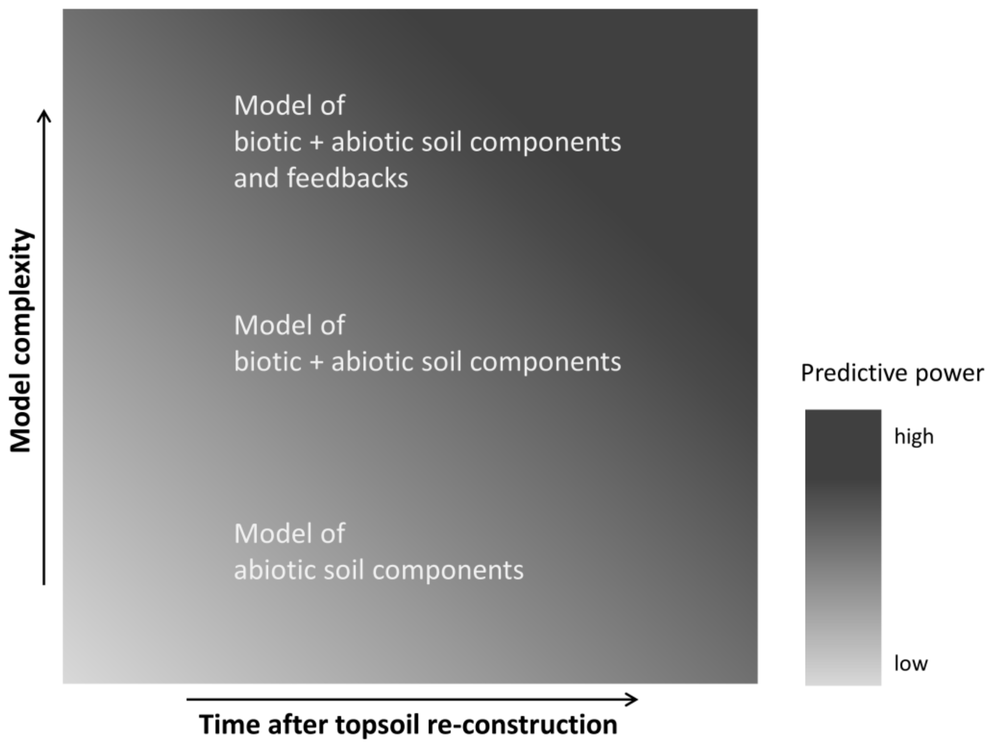

Figure 2. Conceptual scheme of predictive power of soil water models at different levels of complexity. While uncertainty of hydrological variables such as deep drainage or plant available water is lowest for traditional models that only consider abiotic soil components, these models may also have low predictive power due to omission of critical macrofauna – soil structure interactions. Integration of biotic components and feedbacks between macrofauna taxa, and macrofauna and soil development increases model complexity and thereby uncertainty. However, quantification of macrofauna – soil interactions by controlled scientific experiments reduces these uncertainties, thereby increasing the predictive power to a level acceptable to assess the risk of potential failure of post-mining land rehabilitation.