

1 Quantification of the inevitable: The influence of soil 2 macrofauna on soil water movement in rehabilitated open- 3 cut mine land.

4 **S. Arnold¹ and E. R. Williams^{2,3}**

5 [1]{ Centre for Water in the Minerals Industry, Sustainable Minerals Institute, The University
6 of Queensland, St. Lucia 4072, QLD, Australia }

7 [2]{ Centre for Mined Land Rehabilitation, Sustainable Minerals Institute, The University of
8 Queensland, St. Lucia 4072, QLD, Australia }

9 [3]{ Agri-Science Queensland, Department of Agriculture and Fisheries, Kingaroy 4610,
10 QLD, Australia }

11
12 Correspondence to: S. Arnold (s.arnold@uq.edu.au)




13 14 **Abstract**

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

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

3

4 **1 Introduction**

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

29 Numerical models of environmental processes are a critical component of any planning
30 scheme for the management of human-impacted ecosystems (Arnold et al., 2014; Arnold et
31 al., 2012b), or for the design and construction of facilities aiming to protect ecosystems and
32 local communities from hazardous materials such as mine waste (Arnold et al., 2015; Gwenz

1 et al., 2013; O’Kane and Wels, 2003). For example, modelling of soil water dynamics is
2 essential at the early design stage of mine waste rock storage facilities. However, if model
3 assumptions about material properties are based on their initial state rather than after their
4 temporal evolution, such facilities may fail to attain their long-term design objectives (Taylor
5 et al., 2003). On other hand, a sensible balance between the complexity and uncertainty of
6 numerical models is required to use them as exploratory or management tools (Arnold et al.,
7 2012a). We acknowledge the effects of plant roots on soil hydraulic properties and
8 preferential flow, and the progress in numerical modelling of root system architecture and
9 root water uptake in recent years (Bargués Tobella et al., 2014; Carminati et al., 2011; Javaux
10 et al., 2008; Schröder et al., 2008). However, we believe that macrofauna–soil structure
11 interactions rather than root–soil interactions play a critical role in the soil water distribution
12 at the early stage of soil reconstruction, particularly if plant available water is the predominant
13 abiotic stressor (Arnold et al., 2013).

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

24

25 **2 Socio-ecological impacts of open-cut mining**

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

1 After mining activities are complete, the topography and physical soil properties are re-
2 constructed in an attempt to establish the foundation of a self-sustaining ecosystem. At this
3 initial stage and at the landscape scale, soil biodiversity is reduced and/or disrupted to an
4 extent that could almost be referred to as 'sterile' (Rives et al., 1980; Miller et al., 2011). In
5 addition to this initial sterile conditions, open-cut mining often results in the generation of
6 hazardous wastes in the form of either coarse-grained waste rock that is separated before
7 mineral processing, or of fine-grained processing wastes (tailings) (Lottermoser, 2010). These
8 waste materials are then deposited at the mine site and require rehabilitation. One form of
9 rehabilitation that is increasingly accepted for closure of mining waste facilities is the use of
10 vegetated mine waste cover systems (Arnold et al., 2015; Gwenzi et al., 2013). These
11 evapotranspiration cover systems are also referred to as monolithic alternative covers
12 (Albright et al., 2004), phytocaps (Venkatraman and Ashwath, 2010), or store and release
13 covers (Fourie and Tibbett, 2007; Wilson et al., 2003). Their design aims to minimise
14 drainage into underlying hazardous wastes. Contrary to conventional covers made of
15 compacted clay, geosynthetic clay liners, or polyvinyl chloride (Othman et al., 1994; Benson,
16 2000; Levin and Hammod, 1990), phytocaps serve two purposes: (1) to maximise rainfall
17 interception by vegetation and, if required, a compacted soil layer, and (2) to remove soil
18 water through plant transpiration and evaporation from bare soil (Salt et al., 2011). Through
19 successive rainfall events, the loss of stored soil water through evapotranspiration decreases
20 net percolation through the soil (Hauser et al., 2001; Rock, 2010), and reduces surface runoff
21 and erosion.

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

1 foundation at rehabilitated mine-sites can occur within weeks (Williams, personal
2 observation) and prior to vegetation establishment from seeds.

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

13

14 **3 The price to pay for negligence**

15 At post-mining sites, the type of mineral processing initially determines the soil properties,
16 and the depth of overburden and topsoil materials removed from mine pits (Gould, 2012;
17 Erskine and Fletcher, 2013). Likewise, the method and equipment used to reconstruct topsoil
18 affects soil hydraulic properties (Fourie and Tibbett, 2007). However, within weeks after
19 topsoil establishment, the first colonisers such as soil-nesting ants (e.g., *Iridomyrmex* species
20 in Australia) build underground galleries, thereby initiating changes in soil properties (Lee
21 and Foster, 1991). These macrofauna alter the local soil structure and profile characteristics
22 (Jones et al., 1994; De Bruyn and Conacher, 1994), influence soil aggregate stability
23 (Cammeraat and Risch, 2008; Lavelle et al., 2006), water infiltration and mechanical strength
24 (Eldridge, 1994; Frouz and Kuraz, 2013), and increase the field capacity through the
25 formation of holo-organic and organo-mineral aggregates (Frouz and Kuraz, 2013). That is,
26 soil macrofauna introduce or increase heterogeneity of soil properties. Mound building ants,
27 for example, excavate soil material and thereby increase the number of macropores, which
28 leads to a lower bulk density (Dostál et al., 2005; Cammeraat and Risch, 2008; Jones et al.,
29 1994). These changes in soil features lead to increasing infiltration rates under wet conditions
30 (Cammeraat et al., 2002). Some ant species bring soil material from deep soil horizons to the
31 surface (Folgarait, 1998) or damage geotextiles, which can have negative impacts on the
32 functionality of compacted barrier layers through the creation of preferential flow paths

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

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

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

1 soil reconstruction. Any empirical data, be it in form of manipulative experiments under
2 controlled conditions or in-situ field trials, would make a significant contribution to integrate
3 the temporal impact of macrofauna on soil development into numerical soil water models.

4 Although this integration increases model complexity and thereby model uncertainty, it can
5 result in more predictive power and confidence if these interactions are well quantified
6 (Arnold et al., 2012a). In this regard, more complex models provide the opportunity to include
7 the temporal changes in soil material properties due to pedological and biological processes.
8 For example, while some ant species increase infiltration rates (De Bruyn and Conacher,
9 1990; Eldridge, 1993; Cerdà and Jurgensen, 2008), other species may have a contrary impact
10 on infiltration (Sarr et al., 2001; Navarro and Jaffe, 1985). Infiltration rates may vary between
11 different locations or stages of ecosystem development, thereby affecting several aspects of
12 the soil water balance and the availability of plant material for faunal consumption, and in
13 turn the colonisation of the site by different ant species (Williams, 2011). Likewise, while
14 feedbacks between the temporal evolution of macrofauna and soil structure increase model
15 complexity and uncertainty, they could play a critical role in predicting the long-term
16 performance and hence the design of waste cover facilities (Taylor et al., 2003) or post-
17 mining lands (Frouz et al., 2006), which ultimately leads to a higher probability of
18 rehabilitation success and the construction of self-sustaining post-mining landscapes.

19 **4 Conclusions and further directions**

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

27 We suggest two alternative approaches to collect empirical data (Table 1) that can be used to
28 initially quantify these interactions and eventually to reduce uncertainty in modelled
29 hydrological variables such as deep drainage, infiltration, or plant available water (Léonard et
30 al., 2004). For example, manipulative experiments under controlled conditions are effective
31 means to assess the impact of early colonisers on the soil water dynamics. A soil chamber or
32 column (Joschko et al., 1989; Joschko et al., 1992) can be used as a formicarium (Wang et al.,

1 1995), where an ant nest is transplanted (including queen and workers) and food, water and
2 nesting resources provided. Predefined water regimes could then be administered to simulate
3 rainfall events, while the temporal dynamics of soil water potential and content are monitored
4 across the soil profile. Similarly, these small scale experiments are suitable for assessing the
5 colonisation rates and environmental conditions (e.g., pH, temperature, humidity, soil water
6 content) required to colonise soils by ants. At a larger investigative scale (Table 1), field trials
7 in combination with untreated control or reference sites are effective means to assess the
8 impact of macrofauna on soil structure and inter-specific fauna interactions (feedbacks) in
9 relation to soil biodiversity and soil development (Cammeraat et al., 2002). In this regard,
10 open-cut mining lands may provide ideal environments, because the physical properties of re-
11 constructed soils are fundamentally different (and less complex) from those of degraded but
12 physically intact soils.

13 **Acknowledgements**

14 The authors would like to thank David Doley for critical discussions and encouragement to
15 publish this paper, as well as the two anonymous reviewers for constructive comments.

16

1 References


- 2 Albright, W. H., Benson, C. H., Gee, G. W., Roesler, A. C., Abichou, T., Apiwantragoon, P.,
3 Lyles, B. F., and Rock, S. A.: Field water balance of landfill final covers, *Journal of*
4 *Environmental Quality*, 33, 2317-2332, 2004.
- 5 Arnold, S., Lechner, A., and Baumgartl, T.: Merging modelling and experimental approaches
6 to advance ecohydrological system understanding., in: *Revisiting experimental catchment*
7 *studies in forest hydrology.*, edited by: Webb, A. A., Bonell, M., Bren, L., Lane, P. N. J.,
8 McGuire, D., Neary, D. G., Nettles, J., Scott, D. F., Stednick, J. D., and Wang, Y., IAHS
9 Publications, 117-124, 2012a.
- 10 Arnold, S., Thornton, C., and Baumgartl, T.: Ecohydrological feedback as a land restoration
11 tool in the semi-arid Brigalow Belt, QLD, Australia, *Agriculture, Ecosystems & Environment*,
12 163, 61-71, <http://dx.doi.org/10.1016/j.agee.2012.05.020>, 2012b.
- 13 Arnold, S., Audet, P., Doley, D., and Baumgartl, T.: Hydropedology and Ecohydrology of the
14 Brigalow Belt, Australia: Opportunities for Ecosystem Rehabilitation in Semiarid
15 Environments, *gsvadzone*, 12, -, 10.2136/vzj2013.03.0052, 2013.
- 16 Arnold, S., Attinger, S., Frank, K., Baxter, P., Possingham, H., and Hildebrandt, A.:
17 Ecosystem management along ephemeral rivers: Trading off socio-economic water supply
18 and vegetation conservation under flood regime uncertainty, *River Research and*
19 *Applications*, n/a-n/a, 10.1002/rra.2853, 2014.
- 20 Arnold, S., Schneider, A., Doley, D., and Baumgartl, T.: The limited impact of vegetation on
21 the water balance of mine waste cover systems in semi-arid Australia, *Ecohydrology*, 8, 355-
22 367, 10.1002/eco.1485, 2015.
- 23 Aronson, J., Floret, C., Le Floc'h, E., Ovalle, C., and Pontanier, R.: Restoration and
24 Rehabilitation of Degraded Ecosystems in Arid and Semi-Arid Lands. I. A View from the
25 South, *Restoration Ecology*, 1, 8-17, 10.1111/j.1526-100X.1993.tb00004.x, 1993.
- 26 Audet, P., Gravina, A., Glenn, V., McKenna, P., Vickers, H., Gillespie, M., and Mulligan, D.:
27 Structural development of vegetation on rehabilitated North Stradbroke Island:
28 Above/belowground feedback may facilitate alternative ecological outcomes, *Ecological*
29 *Processes*, 2, 20, 2013.
- 30 Bargués Tobella, A., Reese, H., Almaw, A., Bayala, J., Malmer, A., Laudon, H., and Ilstedt,
31 U.: The effect of trees on preferential flow and soil infiltrability in an agroforestry parkland in
32 semiarid Burkina Faso, *Water Resources Research*, 50, 3342-3354, 10.1002/2013wr015197,
33 2014.
- 34 Bengough, A. G., Bransby, M. F., Hans, J., McKenna, S. J., Roberts, T. J., and Valentine, T.
35 A.: Root responses to soil physical conditions; growth dynamics from field to cell, *Journal of*
36 *Experimental Botany*, 57, 437-447, 10.1093/jxb/erj003, 2006.
- 37 Bengough, A. G., McKenzie, B. M., Hallett, P. D., and Valentine, T. A.: Root elongation,
38 water stress, and mechanical impedance: a review of limiting stresses and beneficial root tip
39 traits, *Journal of Experimental Botany*, 62, 59-68, 10.1093/jxb/erq350, 2011.
- 40 Benson, C. H.: Liners and covers for waste containment, 4th Kansai International
41 Geotechnical Forum, Japan, 2000, 1-40,
- 42 Blouin, M., Hodson, M. E., Delgado, E. A., Baker, G., Brussaard, L., Butt, K. R., Dai, J.,
43 Dendooven, L., Peres, G., Tondoh, J. E., Cluzeau, D., and Brun, J. J.: A review of earthworm

- 1 impact on soil function and ecosystem services, *European Journal of Soil Science*, 64, 161-
2 182, 2013.
- 3 Blüthgen, N., and Feldhaar, H.: Food and shelter: How resources influence ant ecology, in:
4 Ant ecology, edited by: Lach, L., Parr, C., and Abbott, K., Oxford University Press, Oxford,
5 2009.
- 6 Bottinelli, N., Jouquet, P., Capowiez, Y., Podwojewski, P., Grimaldi, M., and Peng, X.: Why
7 is the influence of soil macrofauna on soil structure only considered by soil ecologists?, *Soil
8 and Tillage Research*, 146, Part A, 118-124, <http://dx.doi.org/10.1016/j.still.2014.01.007>,
9 2015.
- 10 Brooks, R. H., and Corey, A. T.: Hydraulic properties of porous media, *Hydrol. Paper No. 3*,
11 Colorado State University, Fort Collins, CO, 1964.
- 12 Cammeraat, E. L. H., and Risch, A. C.: The impact of ants on mineral soil properties and
13 processes at different spatial scales, *Journal of Applied Entomology*, 132, 285-294,
14 10.1111/j.1439-0418.2008.01281.x, 2008.
- 15 Cammeraat, L. H., Willott, S. J., Compton, S. G., and Incoll, L. D.: The effects of ants' nests
16 on the physical, chemical and hydrological properties of a rangeland soil in semi-arid Spain,
17 *Geoderma*, 105, 1-20, [http://dx.doi.org/10.1016/S0016-7061\(01\)00085-4](http://dx.doi.org/10.1016/S0016-7061(01)00085-4), 2002.
- 18 Carminati, A., Schneider, C. L., Moradi, A. B., Zarebanadkouki, M., Vetterlein, D., Vogel,
19 H.-J., Hildebrandt, A., Weller, U., Schüler, L., and Oswald, S. E.: How the Rhizosphere May
20 Favor Water Availability to Roots gsvadzone, 10, 988-998, 10.2136/vzj2010.0113, 2011.
- 21 Cerdà, A., and Jurgensen, M. F.: The influence of ants on soil and water losses from an
22 orange orchard in eastern Spain, *Journal of Applied Entomology*, 132, 306-314,
23 10.1111/j.1439-0418.2008.01267.x, 2008.
- 24 Czarnes, S., Hallett, P. D., Bengough, A. G., and Young, I. M.: Root- and microbial-derived
25 mucilages affect soil structure and water transport, *European Journal of Soil Science*, 51, 435-
26 443, 10.1046/j.1365-2389.2000.00327.x, 2000.
- 27 De Bruyn, L., and Conacher, A.: The role of termites and ants in soil modification - a review,
28 *Soil Research*, 28, 55-93, <http://dx.doi.org/10.1071/SR9900055>, 1990.
- 29 De Bruyn, L., and Conacher, A.: The bioturbation activity of ants in agricultural and naturally
30 vegetated habitats in semiarid environments, *Soil Research*, 32, 555-570,
31 <http://dx.doi.org/10.1071/SR9940555>, 1994.
- 32 Doley, D., and Audet, P.: Adopting novel ecosystems as suitable rehabilitation alternatives for
33 former mine sites, *Ecological Processes*, 2, doi:10.1186/2192-1709-2-22, 2013.
- 34 Dostál, P., Březnová, M., Kozlíčková, V., Herben, T., and Kovář, P.: Ant-induced soil
35 modification and its effect on plant below-ground biomass, *Pedobiologia*, 49, 127-137,
36 <http://dx.doi.org/10.1016/j.pedobi.2004.09.004>, 2005.
- 37 Durner, W.: Hydraulic conductivity estimation for soils with heterogeneous pore structure,
38 *Water Resources Research*, 30, 211-223, 10.1029/93wr02676, 1994.
- 39 Edwards, W. M., Shipitalo, M. J., Owens, L. B., and Norton, L. D.: Effect of *Lumbricus*
40 *terrestris* L. burrows on hydrology of continuous no-till corn fields, *Geoderma*, 46, 73-84,
41 [http://dx.doi.org/10.1016/0016-7061\(90\)90008-W](http://dx.doi.org/10.1016/0016-7061(90)90008-W), 1990.

- 1 Eldridge, D.: Effect of ants on sandy soils in semi-arid eastern Australia - Local distribution
2 of nest entrances and their effect on infiltration of water, *Soil Research*, 31, 509-518,
3 <http://dx.doi.org/10.1071/SR9930509>, 1993.
- 4 Eldridge, D. J.: Nests of ants and termites influence infiltration in a semiarid woodland,
5 *Pedobiologia*, 38, 481-492, 1994.
- 6 Erskine, P., and Fletcher, A.: Novel ecosystems created by coal mines in central Queensland's
7 Bowen Basin, *Ecological Processes*, 2, 33, 10.1186/2192-1709-2-33, 2013.
- 8 Folgarait, P.: Ant biodiversity and its relationship to ecosystem functioning: a review,
9 *Biodiversity and Conservation*, 7, 1221-1244, 10.1023/a:1008891901953, 1998.
- 10 Fourie, A., and Tibbett, M.: Post-mining landforms - engineering a biological system, *Mine*
11 *Closure Santiago, Chile*, 2007.
- 12 Frouz, J., Elhottová, D., Kuráž, V., and Šourková, M.: Effects of soil macrofauna on other soil
13 biota and soil formation in reclaimed and unreclaimed post mining sites: Results of a field
14 microcosm experiment, *Applied Soil Ecology*, 33, 308-320,
15 <http://dx.doi.org/10.1016/j.apsoil.2005.11.001>, 2006.
- 16 Frouz, J., and Kuraz, V.: Soil fauna and soil physical properties, in: *Soil Biota and Ecosystem*
17 *Development in Post Mining Sites*, edited by: Frouz, J., CRC Press, Boca Raton, 265-278,
18 2013.
- 19 Gould, S. F.: Comparison of Post-mining Rehabilitation with Reference Ecosystems in
20 Monsoonal Eucalypt Woodlands, Northern Australia, *Restoration Ecology*, 20, 250-259,
21 10.1111/j.1526-100X.2010.00757.x, 2012.
- 22 Gwenzi, W., Hinz, C., Bleby, T. M., and Veneklaas, E. J.: Transpiration and water relations of
23 evergreen shrub species on an artificial landform for mine waste storage versus an adjacent
24 natural site in semi-arid Western Australia, *Ecohydrology*, 7, 965-981, 10.1002/eco.1422,
25 2013.
- 26 Hauser, V., Weand, B., and Gill, M.: Natural Covers for Landfills and Buried Waste, *Journal*
27 *of Environmental Engineering*, 127, 768-775, 10.1061/(asce)0733-9372(2001)127:9(768),
28 2001.
- 29 Hinsinger, P., Bengough, A. G., Vetterlein, D., and Young, I.: Rhizosphere: biophysics,
30 biogeochemistry and ecological relevance, *Plant Soil*, 321, 117-152, 10.1007/s11104-008-
31 9885-9, 2009.
- 32 Hobbs, R. J., Arico, S., Aronson, J., Baron, J. S., Bridgewater, P., Cramer, V. A., Epstein, P.
33 R., Ewel, J. J., Klink, C. A., Lugo, A. E., Norton, D., Ojima, D., Richardson, D. M.,
34 Sanderson, E. W., Valladares, F., Vilà, M., Zamora, R., and Zobel, M.: Novel ecosystems:
35 theoretical and management aspects of the new ecological world order, *Global Ecology and*
36 *Biogeography*, 15, 1-7, 10.1111/j.1466-822X.2006.00212.x, 2006.
- 37 Hölldobler, B., and Wilson, E.: *The Ants*, Harvard University Press, Cambridge, 1990.
- 38 Javaux, M., Schröder, T., Vanderborght, J., and Vereecken, H.: Use of a Three-Dimensional
39 Detailed Modeling Approach for Predicting Root Water Uptake Vadose Zone J., 7, 1079-
40 1088, 10.2136/vzj2007.0115, 2008.
- 41 Jones, C. G., Lawton, J. H., and Shachak, M.: Organisms as ecosystem engineers, *Oikos*, 69,
42 373-386, 1994.

- 1 Joschko, M., Diestel, H., and Larink, O.: Assessment of earthworm burrowing efficiency in
2 compacted soil with a combination of morphological and soil physical measurements, *Biol*
3 *Fert Soils*, 8, 191-196, 10.1007/BF00266478, 1989.
- 4 Joschko, M., Söchtig, W., and Larink, O.: Functional relationship between earthworm
5 burrows and soil water movement in column experiments, *Soil Biology and Biochemistry*, 24,
6 1545-1547, [http://dx.doi.org/10.1016/0038-0717\(92\)90148-Q](http://dx.doi.org/10.1016/0038-0717(92)90148-Q), 1992.
- 7 Jouquet, P., Blanchart, E., and Capowiez, Y.: Utilization of earthworms and termites for the
8 restoration of ecosystem functioning, *Applied Soil Ecology*, 73, 34-40, 2014.
- 9 Kosugi, K. i.: Lognormal Distribution Model for Unsaturated Soil Hydraulic Properties,
10 *Water Resources Research*, 32, 2697-2703, 10.1029/96wr01776, 1996.
- 11 Lavelle, P., Decaëns, T., Aubert, M., Barot, S., Blouin, M., Bureau, F., Margerie, P., Mora, P.,
12 and Rossi, J. P.: Soil invertebrates and ecosystem services, *European Journal of Soil Biology*,
13 42, Supplement 1, S3-S15, <http://dx.doi.org/10.1016/j.ejsobi.2006.10.002>, 2006.
- 14 Lee, K., and Foster, R.: Soil fauna and soil structure, *Soil Research*, 29, 745-775,
15 <http://dx.doi.org/10.1071/SR9910745>, 1991.
- 16 Léonard, J., Perrier, E., and Rajot, J. L.: Biological macropores effect on runoff and
17 infiltration: a combined experimental and modelling approach, *Agriculture, Ecosystems &*
18 *Environment*, 104, 277-285, <http://dx.doi.org/10.1016/j.agee.2003.11.015>, 2004.
- 19 Levin, S., and Hammod, M.: Application of PVC in a 'Top Cap' application in: *Geosynthetic*
20 *Testing for Waste Containment Applications*, edited by: Robert, M., American Society for
21 *Testing and Materials*, Philadelphia, PA, 1990.
- 22 Lottermoser, B.: *Mine Wastes: Characterization, Treatment and Environmental Impacts*, 3
23 ed., Springer, Berlin Heidelberg, 400 pp., 2010.
- 24 Manassero, M., Dominijanni, A., Foti, S., and Musso, G.: *Coupled phenomena in*
25 *environmental geotechnics*, CRC Press, 2013.
- 26 Miller, C., Franklin, J., and Buckley, D.: Effects of soil amendment treatments on American
27 chestnut performance and physiology on an East Tennessee surface mine, *National Meeting*
28 *of the American Society of Mining and Reclamation*, Bismarck, ND, 2011.
- 29 Mitsch, W. J., and Jorgensen, S. E.: Introduction to Ecological Engineering, in: *Ecological*
30 *Engineering: An Introduction to Ecotechnology.*, edited by: Mitsch, W. J., and Jorgensen, S.
31 E., John Wiley & Sons, New York, 3-12, 1989.
- 32 Navarro, J. G., and Jaffe, K.: On the Adaptive Value of Nest Features in the Grass-Cutting
33 *Ant Acromyrmex landolti*, *Biotropica*, 17, 347-348, 10.2307/2388602, 1985.
- 34 O'Kane Consultants Inc.: *Evaluation of the long-term performance of dry cover systems -*
35 *Phase 2 Final Report*, 2003.
- 36 O'Kane, M., and Wels, C.: Mine waste cover system design - linking predicted performance
37 to groundwater and surface water impacts, *6th International Conference on Acid Rock*
38 *Drainage (ICARD)*, Cairns, 2003.
- 39 Othman, M., Benson, C., Chamberlain, E., and Zimmie, T.: Laboratory testing to evaluate
40 changes in hydraulic conductivity caused by freeze thaw: state of the art, in: *Hydraulic*
41 *Conductivity and Waste Containment Transport in Soils*, edited by: Trautwein, S., and Daniel,
42 D., 227-254, 1994.

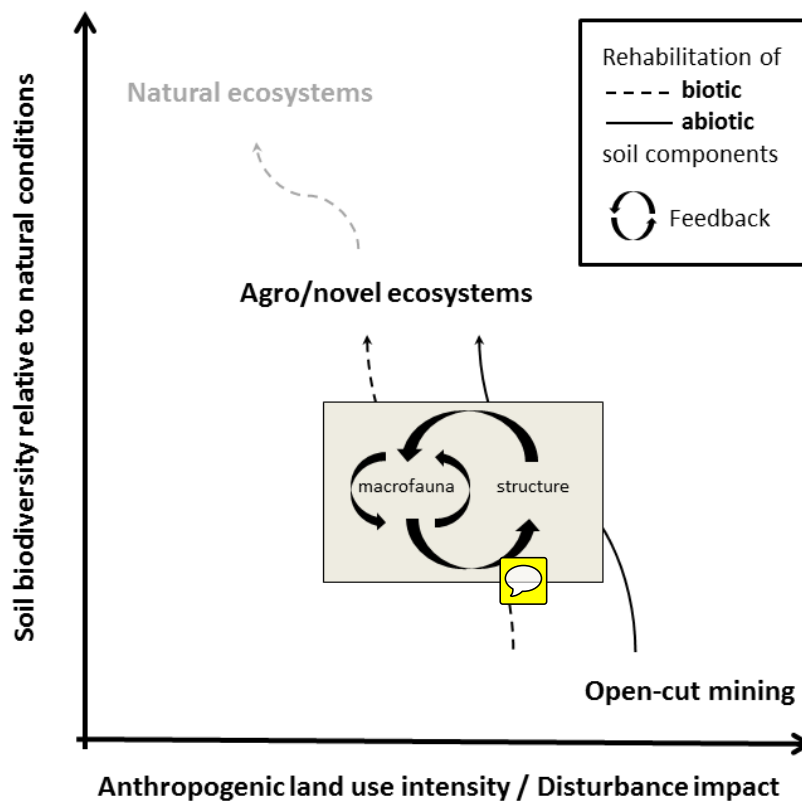
- 1 Peeters, C., and Molet, M.: Colonial reproduction and life histories, in: *Ant ecology*, edited
2 by: Lach, L., Parr, C., and Abbott, K., Oxford University Press, Oxford, 2009.
- 3 Perring, M., Audet, P., and Lamb, D.: Novel ecosystems in ecological restoration and
4 rehabilitation: Innovative planning or lowering the bar?, *Ecological Processes*, 3, 8,
5 doi:10.1186/2192-1709-3-8, 2014.
- 6 Ranatunga, K., Nation, E. R., and Barratt, D. G.: Review of soil water models and their
7 applications in Australia, *Environmental Modelling & Software*, 23, 1182-1206,
8 <http://dx.doi.org/10.1016/j.envsoft.2008.02.003>, 2008.
- 9 Richards, L. A.: Capillary conduction of liquids through porous mediums, *Journal of Applied*
10 *Physics*, 1, 318-333, doi:<http://dx.doi.org/10.1063/1.1745010>, 1931.
- 11 Rives, C., Bajwa, M., Liberta, A., and Miller, R.: Effect of topsoil storage during surface
12 mining on the viability of VA Mycorrhiza, *Soil Science*, 129, 253-257, 1980.
- 13 Rock, S.: Evapotranspiration covers for landfills, in: *Application of Phytotechnologies for*
14 *Cleanup of Industrial, Agricultural, and Wastewater Contamination*, edited by: Kulakow, P.,
15 and Pidlisnyuk, V., Springer, Dordrecht, 189-198, 2010.
- 16 Salt, M., Lightbody, P., Stuart, R., Albright, W., and Yeates, R.: Guidelines for the
17 assessment, design, construction and maintenance of phytocaps as final covers for landfills,
18 2011.
- 19 Sarr, M., Agbogba, C., Russell-Smith, A., and Masse, D.: Effects of soil faunal activity and
20 woody shrubs on water infiltration rates in a semi-arid fallow of Senegal, *Applied Soil*
21 *Ecology*, 16, 283-290, [http://dx.doi.org/10.1016/S0929-1393\(00\)00126-8](http://dx.doi.org/10.1016/S0929-1393(00)00126-8), 2001.
- 22 Schröder, T., Javaux, M., Vanderborght, J., Körfgen, B., and Vereecken, H.: Effect of Local
23 Soil Hydraulic Conductivity Drop Using a Three-Dimensional Root Water Uptake Model,
24 *Vadose Zone J.*, 7, 1089-1098, 10.2136/vzj2007.0114, 2008.
- 25 Seastedt, T. R., Hobbs, R. J., and Suding, K. N.: Management of novel ecosystems: are novel
26 approaches required?, *Frontiers in Ecology and the Environment*, 6, 547-553,
27 10.1890/070046, 2008.
- 28 Taylor, G., Spain, A., Nefiodovas, A., Timms, G., Kuznetsov, V., and Bennet, J.:
29 Determination of the reasons for deterioration of the Rum Jungle waste rock cover, Brisbane,
30 2003.
- 31 van Genuchten, M. T.: A Closed-form Equation for Predicting the Hydraulic Conductivity of
32 Unsaturated Soils, *Soil Science Society of America Journal*, 44, 892-898,
33 10.2136/sssaj1980.03615995004400050002x, 1980.
- 34 Venkatraman, K., and Ashwath, N.: Field performance of a phytocap at Lakes Creek landfill,
35 Rockhampton, Australia, *Management of Environmental Quality: An International Journal*,
36 21, 237-252, doi:10.1108/14777831011025571, 2010.
- 37 Vogel, T., Cislerova, M., and Hopmans, J. W.: Porous Media With Linearly Variable
38 Hydraulic Properties, *Water Resources Research*, 27, 2735-2741, 10.1029/91wr01676, 1991.
- 39 Wang, D., McSweeney, K., Lowery, B., and Norman, J. M.: Nest structure of ant *Lasius*
40 *neoniger* Emery and its implications to soil modification, *Geoderma*, 66, 259-272,
41 [http://dx.doi.org/10.1016/0016-7061\(94\)00082-L](http://dx.doi.org/10.1016/0016-7061(94)00082-L), 1995.
- 42 Williams, E.: Ant community response to management practices on rehabilitated mine sites.,
43 Doctorate of Philosophy Thesis, The University of Queensland, 2011.

- 1 Wilson, G. W., Williams, D. G., and ykaart, E. M.: Integrity on Cover Systems - An Update,
- 2 6th International Conference on Acid Rock Drainage, Cairns, Australia, 2003.
- 3

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

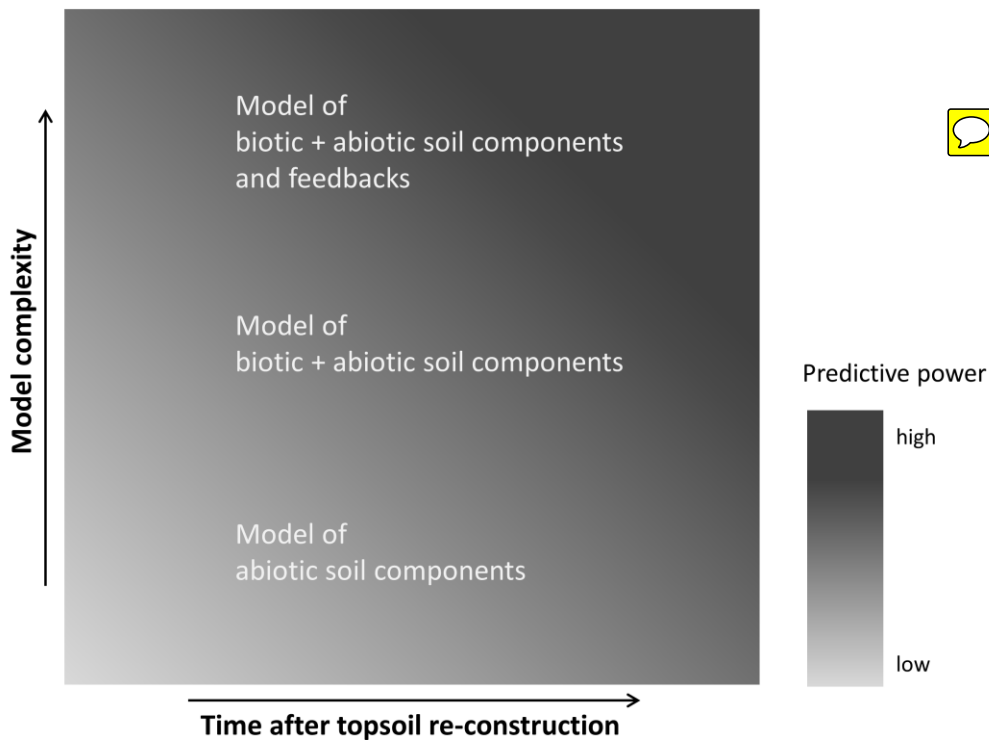
	Glasshouse / Laboratory	Post-mining land
Methodology^a	Controlled/manipulative experiments	Field trials with control site
Investigative Scale^a	Small	Medium
Knowledge gap	Quantity and conditions of colonisation rates	Inter-specific interactions
	Effects on soil hydraulics	Succession of colonisation
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

2 ^a Arnold et al. (2013)



1
2
3
4
5
6
7
8
9
10
11
12

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.



1

2

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

12

13