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Young calcareous soil chronosequences as a model for ecological restoration on alkaline mine tailings

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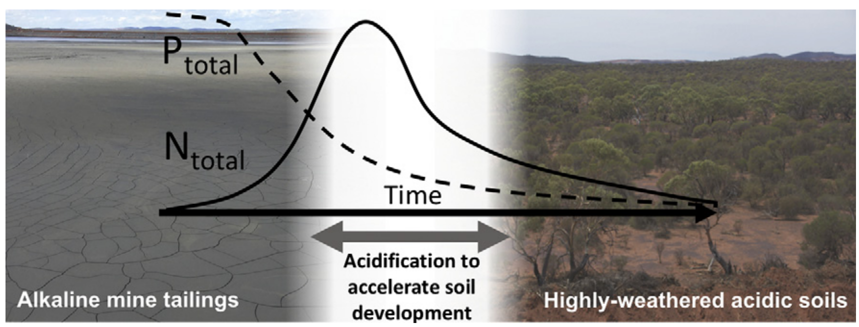
HIGHLIGHTS

- Time frames for natural soil development on tailings are at odds with community expectations.
- Calcareous-soil chronosequences inspire acceleration of soil development on alkaline tailings.
- Soil acidification may improve the timeliness and cost-effectiveness of ecological restoration.

GRAPHICAL ABSTRACT



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ABSTRACT

Tailings are artificial soil-forming substrates that have not been created by the natural processes of soil formation and weathering. The extreme pH environment and corresponding low availability of some macro- and micronutrients in alkaline tailings, coupled with hostile physical and geochemical conditions, present a challenging environment to native biota. Some significant nutritional constraints to ecosystem reconstruction on alkaline tailings include i) predominant or complete absence of combined nitrogen (N) and poor soil N retention; ii) the limited bioavailability of some micronutrients at high soil pH (e.g., Mn, Fe, Zn and Cu); and iii) potentially toxic levels of biologically available soil phosphorus (P) for P-sensitive plants. The short regulatory time frames (years) for mine closure on tailings landforms are at odds with the long time required for natural pedogenic processes to ameliorate these factors (thousands of years). However, there are similarities between the chemical composition and nutrient status of alkaline tailings and the poorly-developed, very young calcareous soils of biodiverse regions such as south-western Australia. We propose that basic knowledge of chronosequences that start with calcareous soils may provide an informative model for understanding the pedogenic processes required to accelerate soil formation on tailings. Development of a functional, stable root zone is crucial to successful ecological restoration on tailings, and three major processes should be facilitated as early as possible during processing or in the early stages of restoration to accelerate soil development on alkaline tailings: i) acidification of the upper tailings profile; ii) establishment of appropriate and resilient microbial communities; and iii) the early development of appropriate pioneer vegetation. Achieving successful ecological restoration outcomes on tailings landforms is likely one of the greatest challenges faced by restoration ecologists and the mining industry, and successful restoration on alkaline tailings likely depends upon careful management of substrate chemical conditions by targeted amendments.

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1. Introduction

The restoration of vegetation on mine tailings, the fine-particulate residue wastes of ore processing, represents one of the greatest challenges faced by the mining industry and restoration practitioners in the 21st century (Jamieson, 2011). The successful reinstatement within reasonable time scales of biodiverse, representative and self-sustaining communities on tailings landforms is a stringent closure requirement of many mine sites in biodiverse regions such as Western Australia (e.g., EPA, 2009a, 2009b), and is an aspiration of newly-formulated international standards for the practice of ecological restoration (McDonald et al., 2016). However, the global increase in tailings production in recent decades has occurred asynchronously with our understanding of the processes by which vegetation on tailings landforms can be effectively restored. Though the accumulative footprint of tailings storage facilities is already estimated to cover millions of hectares and continues to rise (Huang et al., 2012), successful ecological restoration to full ecosystem recovery (the point at which all ecosystem attributes closely resemble those of a reference ecosystem; McDonald et al., 2016) on a tailings landform has not yet been achieved anywhere in the world. A lack of practical, cost-effective restoration solutions impacts upon biodiversity, jeopardises the economic viability of mining, and compromises the social and environmental license of industry to mine.

Tailings are commonly produced as a byproduct of the extraction and processing of primary minerals such as iron, gold, aluminium, copper, lead and zinc (Jamieson, 2011). These minerals are often associated with geologically ancient landforms in very old, climatically-stable, low-rainfall landscapes such as South Africa, south-western Australia, Brazil, and southern North America (e.g., Gordon et al., 1958; Beukes, 1973; Sadleir and Gilkes, 1976; Schidlowski et al., 1976; Anand and Payne, 2002; Hopper, 2009). Annual tailings production in south-western Australia, for example, a global biodiversity hotspot supporting a mining industry worth approximately $100 billion employing over 100,000 people (DMP, 2016), is now estimated to significantly exceed a billion tonnes (Mudd, 2009; Geoscience Australia, 2013). Tailings production is frequently associated with unique novel landforms in geologically-ancient regions such as Western Australia, and the vegetation assemblages of ecosystems in old and climatically stable landscapes often comprise diverse suites of well-adapted plant and microbial communities on shallow, acidic and deeply-weathered soils (Anand and Payne, 2002; Hopper, 2009; Hopper et al., 2016). These communities often comprise many endemic, range-restricted, and highly-specialised taxa, to which unweathered tailings represents a very different, challenging, and potentially hostile substrate (Fig. 1). Though previous studies have examined the geochemical factors limiting plant establishment and growth in acidic tailings (e.g., Shu et al., 2001; Jurjovec et al., 2002; Paradis et al., 2007; Huang et al., 2011, 2012), many mining operations are producing extremely large volumes of highly-alkaline material that poses a different yet equally hostile environment to native biota (Jamieson, 2011; Santini and Banning, 2016; Santini and Fey, 2016).

Organisms are sometimes naturally exposed to the challenge of recolonising new substrates following catastrophic disturbance events such as landslides, glacial retreat, volcanic activity or tsunamis (Sousa, 1984; Łaska, 2001). The physical and geochemical characteristics of newly formed substrates following disturbances such as these can contrast starkly with the surrounding undisturbed landscape, but the geochemical environment is affected over time by natural weathering processes resulting in soil chronosequences: a sequence of soils derived from the same parent material and developed on similar relief under the effect of constant climatic and biotic factors (Stevens and Walker, 1970). Analysis of nutrient dynamics during pedogenesis along chronosequences in many regions of the world indicates that pedogenesis follows a general pattern in a dynamic process closely linked with vegetation dynamics (Walker and Syers, 1976; Wardle et al. 2004; Laliberte et al. 2012; Turner and Laliberté, 2015). However, natural shifts in nutrient dynamics during pedogenesis occur over hundreds, thousands or even millions of years (Walker and Syers, 1976; Wardle et al. 2004; Laliberté et al. 2012; Turner and Laliberté, 2015); time scales that contrast starkly with the mandated expectations of mine-site restoration projects (5–7 years) provided by regulatory bodies (e.g., EPA, 2009a, 2009b). So, how might thousands of years of pedogenesis and vegetation development on alkaline tailings be achieved in under a decade, taking advantage of the basic knowledge available on soil chronosequences? We propose that soil chronosequences, particularly those of marine origin along the coast of Western Australia, provide guidance for a methodological approach toward achieving this challenging target.

2. Pedogenesis on young alkaline soils

The biogeochemical changes in soils during pedogenesis follow a relatively predictable pattern over long geological time scales, with a shift in nutrient status from nitrogen (N) limitation of primary productivity on young soils to extreme phosphorus (P) limitation on old soils (Walker and Syers, 1976; Lambers et al., 2008a; Turner and Condron, 2013). Pedogenesis is mainly driven by changes in pH, organic matter and nutrient availability resulting from chemical and biological transformations (Turner and Laliberté, 2015; Turner et al., 2017). Chronosequences of soils along coastal sand dunes in old and climatically-buffered landscapes in south-western Australia indicate that soils develop slowly from calcareous sand (<6500 years old) to deeply weathered decalcified sand (>2 million years old), although the rate of soil development depends on parent material and processes such as erosion, root metabolism and microbial activity, which are influenced primarily by rainfall and temperature (Laliberté et al., 2013; Turner

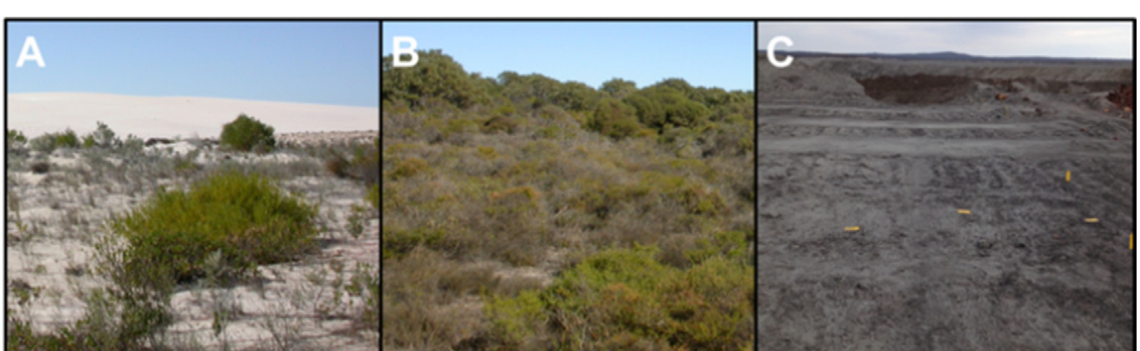

Fig. 1. Native vegetation on young calcareous primary (A) and secondary (B) dunes of the Quindalup dunes along a 2-million year old dune chronosequence, Jurien Bay, Western Australia, and unweathered dry stacked tailings produced during the processing of magnetite ore from Banded Ironstone Formations in the Midwest region of Western Australia (C). The Quindalup dunes are the youngest dunes along the chronosequences (Hayes et al. 2014). Photos by Hans Lambers (A, B) and Adam T. Cross (C).