Science of the Total Environment 621 (2018) 744–752

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Native-plant amendments and topsoil addition enhance soil function in post-mining arid grasslands

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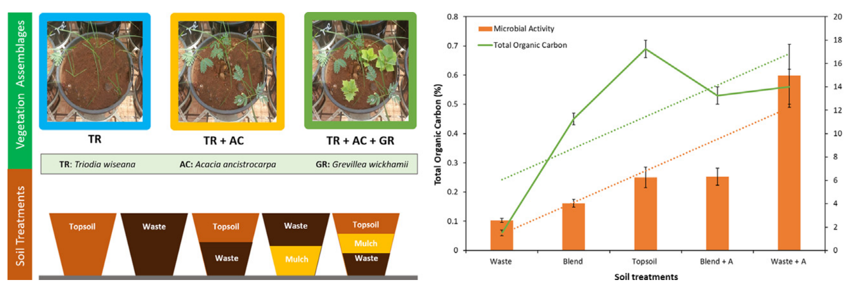
HIGHLIGHTS

- A native-plant based amendment increased C and N contents of reconstructed soils.
- High microbial activity and C mineralisation were found in the amended mine waste.
- Low N mineralisation in amended soils suggests N immobilisation by soil microbes.
- The amendment did not increase emergence, survival or growth of native plants.
- Adding topsoil to reconstructed soils increase native plants' survival and growth.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 4 October 2017
Received in revised form 19 November 2017
Accepted 19 November 2017
Available online xxxx

Editor: D. Barcelo

Keywords:
Arid zone restoration
Triodia (Spinifex)
Land degradation
Organic amendment
Soil organic carbon
Microbial activity
Pilbara

ABSTRACT

One of the most critical challenges faced in restoration of disturbed arid lands is the limited availability of topsoil. In post-mining restoration, alternative soil substrates such as mine waste could be an adequate growth media to alleviate the topsoil deficit, but these materials often lack appropriate soil characteristics to support the development and survival of seedlings. Thus, addition of exogenous organic matter may be essential to enhance plant survival and soil function. Here, we present a case study in the arid Pilbara region (north-west Western Australia), a resource-rich area subject to intensive mining activities. The main objective of our study was to assess the effects of different restoration techniques such as soil reconstruction by blending available soil materials, sowing different compositions of plant species, and addition of a locally abundant native soil organic amendment (*Triodia pungens* biomass) on: (i) seedling recruitment and growth of *Triodia wiseana*, a dominant grass in Australian arid ecosystems, and (ii) soil chemical, physical, and biological characteristics of reconstructed soils, including microbial activity, total organic C, total N, and C and N mineralisation. The study was conducted in a 12-month multifactorial microcosms setting in a controlled environment. Our results showed that the amendment increased C and N contents of re-made soils, but these values were still lower than those obtained in the topsoil. High microbial activity and C mineralisation rates were found in the amended waste that contrasted the low N mineralisation but this did not translate into improved emergence or survival of *T. wiseana*. These results suggest a short- or medium-term soil N immobilisation caused by negative priming effect of fresh un-composted amendment on microbial communities. We found similar growth and survival rates of *T. wiseana* in topsoil and a blend of topsoil and waste (50:50) which highlights the importance of topsoil, even in a reduced amount, for plant establishment in arid land restoration.

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https://doi.org/10.1016/j.scitotenv.2017.11.219
0048-9697/

1. Introduction

Dryland regions, including arid and semi-arid areas, occupy over 40% of the global land surface, store 45% of the active global carbon, and support 40% of the global population (Millenium Ecosystem Assessment, 2005). Around 20% of these regions are currently degraded and will continue to degrade at a rate of 12 million ha per year (Kildisheva et al., 2016). Intensive land uses, including extractive activities such as mining, and natural disturbances in extreme environmental conditions (Keesstra et al., 2017), have largely contributed to degradation of these arid and semi-arid lands worldwide, leading to a substantial decrease in the services provided by soils at a global scale (Anaya-Romero et al., 2016; Pereira et al., 2015, 2017). Restoring these disturbed areas has become a pressing international priority in order to maintain ecosystem function, conserve biodiversity, and improve ecosystem resilience to climate change (Menz et al., 2013; Keesstra et al., 2016, 2018).

One of the most critical challenges faced in post-disturbance restoration of arid lands, particularly in post-mining, is the limited availability of topsoil, i.e. the upper 5–10 cm of the soil profile prior to extraction operations (Golos and Dixon, 2014; Muñoz-Rojas et al., 2016a). Stripping, stockpiling and re-spreading of topsoil are common practices in mining operations. During these processes topsoil may be buried, eroded and/or degraded, leading to a topsoil deficit for use in restoration (Luna et al., 2016; Merino-Martín et al., 2017). A possible approach to overcome this deficit is the reconstruction of soil profiles using alternative substrates, including mine waste generated during the mining process and, where topsoil is available, a blend of topsoil and waste material (Machado et al., 2013; Brevik and Lazari, 2014; Muñoz-Rojas et al., 2016a; Merino-Martín et al., 2017).

Given the absence of topsoil that contain valuable nutrients and seedbank, direct seeding is often needed for reinstating biodiverse vegetation communities (Bateman et al., 2016; Kildisheva et al., 2016; Erickson et al., 2017). However, seedling emergence is a critical stage of the plant life-cycle in dryland ecosystems, with rates of seed mortality frequently exceeding 90% (James and Carrick, 2016). Reconstructed soils using alternative mine substrates often lack the necessary soil characteristics to support the development and survival of seedlings. Issues include poor soil structure, low water retention, inadequate levels of organic matter, nutrients and microbial activity (Merino-Martín et al., 2017). Thus, investigation into restoration strategies that re-establish both plant communities and soil health after mining has gained momentum in recent years (Maisto et al., 2010; Luna et al., 2016, 2017; Muñoz-Rojas et al., 2016b; Wubs et al., 2016). Plant diversity can improve soil carbon (C) and nitrogen (N) levels, increase microbial biomass and activity, as well as recover overall soil fertility (Breulmann et al., 2012; Lange et al., 2015). Therefore, promoting plant diversity in soil restoration and reconstruction practices could enhance belowground ecosystem recovery and consequently ecosystem functioning (Klopf et al., 2017).

Several soil characteristics have been proposed as indicators of soil fertility, quality, health or function in restored soils (Anaya-Romero et al., 2015; Costantini et al., 2016; Muñoz-Rojas et al., 2016b, 2016c). Specifically, soil organic C has been extensively used to assess soil quality in amended soils as it reflects the nutrients and water reservoir of soils and strongly influences plant growth (Luna et al., 2016; Francaviglia et al., 2017). In recent years, biochemical processes and biological indicators such as microbial activity and C and N decomposition have been the focus of numerous studies due to the immediate and precise information that these bio-markers provide on soil and ecosystem recovery following management practices (Maisto et al., 2010; Bastida et al., 2015; Wang et al., 2015).

Organic amendments from different sources, including compost, organic wastes and mulches have been broadly used to promote plant growth, improve soil fertility and structure, reduce erosion and improve the overall hydrological condition of degraded and/or disturbed soils (Maisto et al., 2010; Luna et al., 2016; Yazdanpanah et al., 2016). Several studies have focused on the use of organic soil amendments in restoration (including compost or mulches) to enhance plant performance and soil functions (Bastida et al., 2008; Jordán et al., 2011; Benigno et al., 2013; Parras-Alcántara et al., 2016; Gebhardt et al., 2017). Adding external sources of organic C has shown to improve water availability for plants, recover soil structure and enhance the biochemical and biological status via the exogenous input of plant litter (You et al., 2016; Yanardağ et al., 2017). But, despite this extensive research on the general use of organic amendments, the effects of native-plant amendments combined with alternative soil materials on the quality and functionality of reconstructed soils is largely unknown.

Triodia spp., also referred to as 'Spinifex', are key restoration targets in the Australian arid zone due to their inability to successfully re-establish following land rehabilitation operations (Erickson et al., 2016a; Lewandrowski et al., 2017). These dominant plant species of the Pilbara region cover one-third of the Australian continent, making them a readily available resource for multiple uses (Gamage et al., 2012). Yet, their use as a plant-based amendment to increase soil quality in dryland restoration has not been explored.

Visual indicators such as above-ground diversity and coverage have been used as primary indicators for successful land rehabilitation (Shackelford et al., 2017). However, soil chemical, physical and biological parameters, including nutrient contents and microbial activity, can provide immediate and precise indication of ecosystem responses to stress and recovery (Costantini et al., 2016). Some of these parameters have been extensively used to assess soil quality and health and are strongly associated with ecosystem functions, e.g. biological productivity, nutrient cycling, or physical stability and support for plant growth (Doran and Zeiss, 2000; Muñoz-Rojas et al., 2016c; Griffiths et al., 2016; Francaviglia et al., 2017). Understanding the effects of soil modifications on native species recruitment, growth and soil quality indicators, is essential to improve current restoration practices to overcome critical challenges in mine rehabilitation.

Here, we present a case study in the arid Pilbara region (north-west Western Australia), an animal and flora biodiversity hotspot subject to intensive mining activities (Department of Environment and Heritage, 2003; Brueckner et al., 2013). The main objective of our study was to assess the effects of different restoration techniques on (i) seedling recruitment and growth parameters of *Triodia wiseana*, a dominant grass in Australian arid ecosystems, and (ii) soil chemical and biological characteristics (e.g. microbial activity, total organic C, total N, and C and N mineralisation) of reconstructed soils. The combined strategies included: (i) the creation of soil blends from available soil materials in mining operations, including topsoil and mine waste; (ii) sowing of different compositions of native plant species used in restoration (e.g. monoculture of *T. wiseana*, a mixture of *T. wiseana* and *Acacia ancistrocarpa*, and a combination of the former species with *Grevillea wickhamii*), and (iii) the addition of *T. pungens* dry biomass as a locally abundant native soil organic amendment.

2. Materials and methods

2.1. Study area

This study was conducted over 12 months, from December 2015 to December 2016, in Kings Park and Botanic Garden's controlled glasshouse facilities, (Perth, Western Australia). Glasshouse environmental conditions mimicked those from the Pilbara biogeographical region (north-west Western Australia, 22°03S, 118°07E to 23°19S 119°43E), characterised by a semi-arid climate with a mean annual precipitation ranging from 250 to 400 mm. In the Pilbara, most rainfall occurs during the wet-season (December–March) when extreme temperatures, commonly over 40 °C, are reached (Bureau of Meteorology, 2016). The interim Pilbara biogeographical region covers 178,060 km^2 and soils in this area are red shallow stony soils on hills and ranges and sands on plains comprising Red Kandosols, Red Ferrosols and Leptic Rudosols