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Transitioning from phosphate mining to agriculture: Responses to urea and slow release fertilizers for *Sorghum bicolor*

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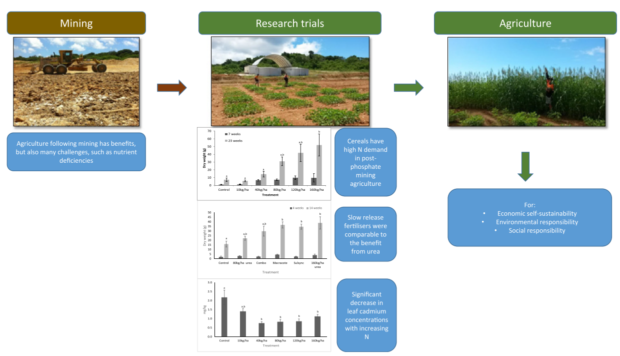
HIGHLIGHTS

- Agriculture following mining has many abiotic and biotic challenges.
- We tested growth response of a key cereal to urea and slow release fertilizers.
- *Sorghum bicolor* has a high N demand in post-phosphate mining agriculture.
- Slow release fertilizers were comparable to the benefit from 160 kg/ha urea.
- High biomass and a reduction in Cd can be attained with appropriate levels of urea.

GRAPHICAL ABSTRACT



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ABSTRACT

Globally, land-use transition from mining to agriculture is becoming increasingly attractive and necessary for many reasons. However, low levels of necessary plant nutrients, and high levels of heavy metals, can hamper plant growth, affecting yield, and potentially, food safety. In post-phosphate mining substrates, for example, nitrogen (N) is a key limiting nutrient, and, although legumes are planted prior to cereals, N supplementation is still necessary. We undertook two field trials on Christmas Island, Australia, to determine whether *Sorghum bicolor* could be grown successfully in a post-phosphate mining substrate. The first trial investigated N (urea) demand (amount of N required for adequate crop growth) for *S. bicolor*, and whether N addition could reduce the naturally occurring cadmium (Cd) concentrations in the crop. The second trial examined whether slow release nitrogen fertilizers (SRF) could replace urea to increase biomass and reduce Cd concentrations. Our first trial demonstrated that *S. bicolor* has a high N demand, with the highest biomass being recorded in the 160 kg/ha urea treatment. However, plants treated with 80, 120 and 160 kg/ha were not significantly different from one another. After 7 weeks of growth, leaf Cd concentrations were significantly lower for all urea treatments compared with the control plants. However, after 23 weeks, seed Cd concentrations did not differ across treatments. Our second trial demonstrated that the application of SRF (Macracote® and Sulsync®) and 160 kg/ha urea significantly increased biomass above the control plants. There was, however, no treatment response in terms of Cd or N concentrations in the seed at final harvest. Thus, we have shown that N is currently critical for *S. bicolor*, even following legume cropping, and

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that high biomass and a significant reduction in Cd can be attained with appropriate levels of urea. Our work has important implications for cereal growth and food safety in post-mining agriculture.

1. Introduction

Globally, land-use transition from mining to agriculture is becoming increasingly attractive and necessary for many reasons (Godfray et al., 2010; McHenry and Persley, 2015); there is an appreciation that one industry replacing another is critical for community stability, economic self-sufficiency and environmental responsibility (Davies et al., 2012; Stacey et al., 2010). However, abiotic and biotic challenges hamper plant growth in a post-mining substrate, including low nutrient availability (Rowland et al., 2009; Ruthrof, 1997; Singh and Singh, 2001; Tischew and Kirmer, 2007), heavy metals (Gnandi et al., 2006; Singh and Singh, 2001; Singh et al., 2016), altered hydrological conditions such as low soil water availability, soil erosion and compaction (Rowland et al., 2009), and lack of beneficial soil microbes such as mycorrhizal fungi and rhizobia (Brundrett et al., 1985; Giller et al., 2016; Jasper et al., 1991). Following phosphate mining, for example, nutrients other than phosphate can be limiting: one year after phosphate mining on Nauru Island, Pacific Ocean, soils have very low N levels (0.03–0.04%) (Manner and Morrison, 1991). Such challenges must be overcome for post-mining agriculture to be viable, commercial, and sustainable.

Nitrogen is critical in agriculture for improving yield, particularly in cereal crops (Bockman and Olfs, 1998; Unkovich et al., 2010). Nitrogen may be delivered through a legume rotation, however, at the onset of the agricultural process following mining, N may be so deficient that a legume rotation provides insufficient N (Howieson et al., 2016). Thus at least in the short term, providing sufficient N requires fertilizer application. Approximately 100 megatons of N fertilizer are applied to crops globally each year in response to the ever increasing pressure to produce high quantities of high quality food for an exponentially increasing human population (Lehnert, 2015; Scialabba and Muller-Lindenlauf, 2010). However, N applied as urea is vulnerable to volatilization and leaching into fresh water and marine environments (Angus, 2001; Lehnert, 2015). In Australia, for example, the Great Barrier Reef receives 65,989 t/yr total N, 5.8 times more than it did before European settlement (Kroon et al., 2010). Such leaching can cause eutrophication, acidification, algal blooms, loss of dissolved oxygen and death of aquatic animals, and thus has broad-scale and multiple economic, social and environment impacts (Lehnert, 2015; Vitousek et al., 1997).

One response to nitrogen volatilization and leaching has been to increase the efficient use of nutrients use efficiency through the development and application of slow release fertilizers (SRF) (Azeem et al., 2014; Bockman and Olfs, 1998; Shaviv, 2001). These SRF prolong nutrient release and extend availability to plants significantly longer than traditional, fast release fertilizers, and, ideally, nutrients are released in synchrony with the needs of the plants being targeted (Azeem et al., 2014; Yang et al., 2016). One of the mechanisms by which nutrient release is delayed from water soluble fertilizers such as urea, is through coating with organic hydrophobic polymers, or inorganic coatings of sulfur (S) (Azeem et al., 2014). For example, the physical intromission of urea granules in a coating material is one such technique that produces controlled release coated urea (Azeem et al., 2014). Slow release fertilizers have other environmental, economic and social benefits, particularly for remote communities. Their use can potentially: optimise nutrient input and maximise yield and hence decrease reliance on food and animal feed imports; reduce the amount and frequency of fertilizer application, and hence decrease the cost of fertilizer and labour; reduce transportation costs of large quantities of fertilizer; and, decrease volatilization and hence waste and runoff into the environment (Shaviv, 2001). However, the use of SRFs in agriculture remains hampered by lack of data on their efficacy in different soil types and environmental conditions (Azeem et al., 2014).

Christmas Island (10°29′06″S, 105°37′38″E), Australia, situated in the Indian Ocean, provides an important opportunity to undertake research on the transition from mining to agriculture. The leading industry on the tropical island is rock phosphate mining, and, given that the phosphate ore may be depleted by ~2030, there is critical need to provide ongoing employment for the island community of ~1500. Furthermore, there is no history of large-scale agriculture on the island, and there is a heavy reliance on expensive imported airfreighted produce. Thus, increasing food security for this remote community is vital.

Our overall study aim is to investigate methods of introducing commercial, sustainable, high quality agriculture under post-phosphate mining conditions on Christmas Island. Nutrient field trials previously undertaken suggest that N is a major limiting nutrient for cereals such as sorghum (*Sorghum bicolor*), dryland rice (*Oryza sativa*), maize (*Zea mays*) and sweet corn (*Zea mays* var. *saccharata*), and that S, P and trace elements were not limiting (Howieson et al., 2016). Although the long term aim is to rotate legumes prior to cereal production to deliver N to cereals, N demand for cereal crops in these substrates remains unclear. Furthermore, a fundamental challenge for agriculture in these, and other post-phosphate mining substrates globally, is to reduce the uptake of the naturally occurring heavy metals such as cadmium (Cd). Given the tropical conditions with high humidity and high rainfall on Christmas Island, and thus the potential for leaching of nutrients, SRFs could benefit plant growth and have a greater longevity over a longer period than traditional, fast release fertilizers. To fill these knowledge gaps, we ask the following questions using *Sorghum bicolor*, which is a globally important cereal crop species for millions of people (Taylor et al., 2006).

1. What is the growth response to N (urea) addition in a post phosphate mining substrate and can this N addition reduce cadmium concentrations?
2. Can slow release fertilizers (SRF) replace urea for increasing biomass and reducing cadmium concentrations in a post-phosphate mining substrate?

2. Methodology

2.1. Study site

Christmas Island (10°29′06″S, 105°37′38″E), Australia, Indian Ocean, is located 2623 km NW of Perth, Western Australia, and 380 km south of Jakarta, Indonesia. The climate is tropical with a wet season from November to May when the NW monsoon prevails, and an average annual rainfall of 2183.0 mm. However, when the study was conducted in 2016, the island received 5120.8 mm (BOM, 2017). Temperatures range between approximately 26–27 °C during the day from May to November and 28 °C from December to April (BOM 2016, Christmas Island Airport, #200790, 10°26′60.00″S, 105°41′24.00″E). The vegetation ranges from tropical rainforest to coastal heath and open woodland (Gray, 1981). Soils on Christmas Island are phosphatic derived from limestone or basalt with a pH 7.0–8.0.

Mining during the past ~100 years has utilised 3000 ha of the 13,500 ha island, resulting in a post-mined area of 400 ha with a soil depth appropriate for rehabilitation back to rainforest and 2600 ha with shallower soils that necessitate an alternative end land-use (Beeton et al., 2010). The phosphate mining process on Christmas Island involves clearing of secondary (i.e. previously cleared or disturbed) vegetation