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Rehabilitation of post bauxite mine in northern Australia: Controlled experiments on the effect of direct seeding methods, super phosphate fertilization and topsoil handling on the establishment of native species of dry/wet tropics

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Content

ဩစတြေးလျမြောက်ပိုင်းရှိ တူးဖော်ပြီး ဘောဖ့်ဆိုက်သတ္တုတွင်းအား ပြန်လည်ထူထောင်ခြင်း၊ အပူပိုင်းသစ်တော (Wet/Dry tropics) ၏ ဒေသမျိုးများ ပြန်လည်ပေါက်ရောက်မှုအပေါ် တိုက်ရိုက်အစေ့ချစိုက်ပျိုးခြင်း နည်းစနစ်၊ စူပါဖော့စဖိတ်မြေဩဇာသုံးစွဲခြင်းနှင့် မြေပြုပြင်ခြင်း တို့၏ အကျိုးသက်ရောက်မှုကို ထိန်းချုပ်စမ်းသပ်မှုဖြင့် လေ့လာခြင်း

ထင်လင်းအောင်၊ စီမံကိန်းနှင့် စာရင်းဌာန

စာတမ်းအကျဉ်း

သတ္တုတူးဖော်ခြင်းသည် အပင်များနှင့် မြေဆီလွှာများ ရှင်းလင်းခြင်း ဆောင်ရွက်ခြင်း ကြောင့် ဂေဟစနစ်များစွာအပေါ်တွင် တိုက်ရိုက်ဆိုးကျိုးများ သက်ရောက်လျှက်ရှိပါသည်။ အကျိုးဆက်အနေဖြင့် မြေဆီလွှာဖွဲ့စည်းပုံကို ပြောင်းလဲစေပြီး မြေဩဇာဓါတ်များ အဏုဇီဝ ပိုးမွှားများ ဆုံးရှုံးခြင်း၊ မြေဆီလွှာထုတ်လုပ်နိုင်စွမ်း လျော့ကျခြင်းနှင့် မြေအာဟာရ လည်ပတ်မှုအား အနှောက်အယှက်ပေးခြင်းတို့ ဖြစ်ပွားစေပါသည်။ အဆိုပါ ဆိုးကျိုးများကို ကျော်လွှား နိုင်ရန်အတွက် ထိရောက်သော ပြန်လည်ထူထောင်ခြင်း လုပ်ငန်းများကို သစ်တောပြုစုထိန်း သိမ်းရေး ဂေဟဗေဒ အသိပညာများအပေါ် အခြေခံ၍ စနစ်တကျ စီမံဆောင်ရွက် ရန်လိုအပ်ပါ သည်။ ယခုလေ့လာမှု၏ ရည်ရွယ်ချက်မှာ မြေဆီလွှာပြုပြင်ခြင်း၊ မြေဩဇာထည့်ခြင်း၊ တိုက်ရိုက် အစေ့ချခြင်းဖြင့် ဩစတြေးလျမြောက်ပိုင်းရှိ အပူပိုင်းဒေသ ဘောဖ့်ဆိုက်ဒ်(ဒန်) သတ္တုတွင်း တူးဖော်ပြီးစီးသည့်မြေတွင် မျိုးရင်းအပင်များ ပြန်လည်ထောင်ရာတွင် ထိရောက်မှု အရှိဆုံး နည်းလမ်းကို ရှာဖွေဖော်ထုတ်ရန်ဖြစ်ပါသည်။ သုတေသနမှာ ဘောဖ့်ဆိုက် သတ္တုတွင်း အား ဒေသ မျိုးရင်းများဖြင့် ပြန်လည်ထူထောင်ရာတွင် အဆိုပါနေရာမှ မတူညီသော မြေ စုပုံမြေနှင့် ချန်မြေ များပေါ်တွင် တိုက်ရိုက်အစေ့ချနည်းစနစ်(၂) မျိုး(မြေမြှုပ်နှင့် ကျဲဖြန့်) နှင့် စူပါဖော့်စဖိတ် မြေဩဇာကျွေးခြင်းဖြင့် သစ်မျိုး(၅)မျိုး၏ အပင် ပေါက်ရောက်မှု အပေါ် အမျိုးမျိုးသော သက်ရောက်မှုအား လေ့လာခြင်းဖြစ်ပါသည်။ သုတေသနရလဒ်များ အရ စူပါဖော့စဖိတ် မြေဩ ဇာကျွေးခြင်းမှာ အပင်ပေါက်ရောက်မှုအပေါ်တွင် ချက်ချင်း အကျိုးသက် ရောက်မှုမရှိပါ။ စုံပုံမြေနှင့်ချန်မြေများတွင်လည်း သိသာသော ကွဲပြားခြားနားမှုမရှိပါ။ သို့ရာတွင် စိုက်ပျိုးနည်းစနစ်မှာ အပင်တည်ထောင် အောင်မြင်မှု အပေါ်တွင် အကျိုးသက် ရောက်မှု ရှိသည်ကို တွေ့ရှိ ရပါသည်။ *Erythrophlem chlorostachys* နှင့် *Acacia rothii* သစ်မျိုးများမှာ သစ်စေ့ မြေမြှုပ် စိုက်ပျိုးလျှင် အောင်မြင်မှု ပိုမိုကောင်းမွန် သည်ကို တွေ့ရှိရပါသည်။ မြေမျက်နှာပြင်တွင် ဖြန့်ကျဲစိုက်ပျိုးသော သစ်စေ့များမှာ အပြင် ကြမ်းတမ်းသော ပတ်ဝန်းကျင်အခြေအနေနှင့် တိုက်ရိုက်ထိတွေ့ရခြင်း၊ ရေခမ်းခြောက်ခြင်း ကြောင့် ခြောက်၍ သေဆုံးသွားသည်ကို တွေ့ရပါသည်။ *Corymbia ferruginea* သစ်မျိုးမှာ ယေဘူယျအားဖြင့် စိုက်နည်း(၂)မျိုးလုံးတွင် ကောင်းစွာ ဖြစ်ထွန်းသည်ကို တွေ့ရှိရသော်လည်း *Eucalyptus tetrodonta* မှာ ပေါက်ရောက် ရှင်သန်မှု နည်းပါးသည်ကို တွေ့ရပါသည်။ *Adenanthera*

*pavonina သစ်မျိုး*အတွက် ရှင်သန်မှုကောင်းမွန်စေရန် အစေ့မချမီ သင့်လျော်သော ဒေါ်မန်စီပြုစုမှု နည်းလမ်းပေးရန် (Dormancy treatment) လိုအပ်ပါသည်။ အစေ့အရွယ်အစားနှင့် အောင်မြင်မှုသည် စိုက်ပျိုး နည်းစနစ်အပေါ်မူတည်၍ ဆက်စပ်မှု ရှိသည်ကို လေ့လာတွေ့ရှိရပြီး အစေ့ကြီးသော သစ်မျိုးများအတွက် ဖြန့်ကျဲစိုက်ပျိုးပါက မအောင်မြင်ရန် အလားအလာများကြောင်း တွေ့ရှိရပါသည်။ အစေ့သေးသော သစ်မျိုးများ အတွက် မြေဝင်အနက်မှာ အလွန်အရေးကြီးပြီး အစေ့မချခင် ဖော်ထုတ်ရန် လိုအပ်ပါမည်။ သုတေသနရလဒ်များအရ တိုက်ရိုက်အစေ့ချစိုက်ပျိုးခြင်းသည် ဒေသသစ်မျိုးများ တည်ထောင် ရန်အတွက် ထိရောက်သော နည်းလမ်းတစ်ခုဖြစ်ကြောင်း တွေ့ရှိရပြီးစုပုံမြေတွင် အစေ့ချ ပမာဏအား တိုးမြှင့်သင့်ပါသည်။သို့ရာတွင် မြေသြဇာ ကျွေးခြင်း၏ ရေရှည်/လယ် အကျိုး သက်ရောက်မှုအား အဆိုပါဒေသတွင် သုတေသနပြုလုပ်၍ စဉ်ဆက်မပြတ် စောင့်ကြည့် သင့်ပါသည်။

Rehabilitation of Post Bauxite Mine in Northern Australia: Controlled Experiments on the Effect of Direct Seeding Methods, Super Phosphate Fertilization and Topsoil Handling on the Establishment of Native Species of Dry/Wet Tropics

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Abstract

Mining has direct impacts on many ecosystems due to the removal of vegetation and soil profile. The subsequent impacts due to changing soil structure include extensive loss of nutrients and soil microorganisms, reduced soil productivity, and interrupted nutrient cycling. To overcome these adverse effects, an efficient and cost-effective method of rehabilitation is required through systematic integration and planning, based on sound ecological and silvicultural knowledge. The aim of this study is to determine the most effective way of re-establishing native plant communities in a degraded post-bauxite mine through an improved early rehabilitation process of topsoil handling, direct seeding, and fertilization. The study investigated the different effects of various soils stockpiled and fallow from a tropical bauxite mine, two direct seeding methods (burial and broadcast), and superphosphate fertilization on the germination and establishment success of five native species of wet/dry tropic, northern Australia. The results indicated that soil types and superphosphate fertilization had no significant effects on the seedling emergence in the native species tested. However, the different seeding methods were found to have a significant effect on establishment success. The germination and establishment of *E. chlorostachys* and *A. rothii* increased when the seeds were buried in the soil. The broadcasted seeds were found to be dried and dead due to desiccation and direct contact to adverse atmospheric conditions. Seeds of *C. ferruginea* performed well with both seeding methods while *E. tetrodonta* germination was relatively low. The dormancy pre-treatment was found to be critical to the successful establishment of *A. pavonina* and considered an essential prerequisite before seeding. The association between seed size and germination was clearly observed in relation to seeding methods and large seeded species were most likely to fail when they were broadcasted. The results suggest that direct seeding is an effective method for the establishment of native species selected and seeding amounts should be increased in the stockpiled soils. The burial depth is very important for small seeded species and thus, optimum planting depth should be identified before seeding. Mid-term and long-term effects of fertilization should be monitored through continuous research in the field study area.

Keywords: Rehabilitation, Seed size, Seeding methods, Fertilization, Northern Australia

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1. Introduction

1.1 Research Background

Mining is an extensive form of anthropogenic disturbance to many ecosystems because of the removal of both vegetation and the soil profile. However, the areas impacted by surface mining is relatively small compared to other areas cleared for agriculture, logging, and construction of infrastructure such as roads and hydropower. Nevertheless, surface mining impacts on the surrounding environment through erosion, sedimentation, and pollution of nearby rivers and water sources (Parrotta and Knowles, 2001). There is also often a significant change in soil structure and distribution of nutrients within the re-established soil profile due to the soil removal and the replacement of the topsoil during post-mining rehabilitation activities (Daws et al., 2013). The consequences of this includes extensive losses of nutrients and soil microorganisms, lower soil productivity, and diminished nutrient cycling (Short et al., 2000, Schwenke et al., 2000). To overcome these adverse environmental impacts, effective forest rehabilitation is needed with a systematic and integrated planning of mining and rehabilitation operations based on sound ecological and silvicultural knowledge. This study outlines the review of current rehabilitation efforts and an investigation of proper techniques for the improvement of the early establishment of native plant communities through proper soil handling and silvicultural practices.

The effective management of mine-site landscape rehabilitation requires appropriate site preparation, soil handling, rapid replacement of topsoil and subsoil, soil ripping, and fertilizer application, to ensure the vigorous establishment of planted tree species and natural regeneration of viable seeds contained in the topsoil. A key challenge in restoring many ecosystems is to develop effective and low-cost techniques which can be applied to land rehabilitation at large geographical scales (Campos-Filho et al., 2013, Cole et al., 2005, Holl and Aide, 2011). The optimized use of all sources of regenerative materials, including the topsoil seedbank as well as efficient seed usage, may reduce the financial cost of seed collection, storage, and sowing and avoid wastage of seed during rehabilitation. While there has been an increased demand for the restoration of degraded forests across the world, the average seed loss has been identified at between 90-95% globally with a relatively low percentage of plant recruitment from seeds. Therefore, proper direct seeding techniques with optimised seed usage may assist with the successful establishment of desired tree species. In addition, effective topsoil management including direct replacement of topsoil with a viable seed bank will provide a more balanced and dynamic restored plant community (Grant et al., 2007).

Bauxite mining has been operating continuously since the 1960s in the Weipa plateau, the world's largest bauxite resource located on the northwest coast of Cape York Peninsula, Queensland, Australia (Taylor et al., 2008). Bauxite ore is usually discovered at less than 1 m under the surface and requires the complete removal of all surface vegetation (Koch, 2007).

The areas to be mined are generally cleared one or two years before mining commences and the top 50cm of soil are stockpiled for future rehabilitation (Comalco Mining and Refining 2004). Mining at Weipa is a strip-mining operation in which the native forest is removed and burnt one or two years before mining. When the area is revegetated with native vegetation, either freshly stripped top soils or stockpiled soil is spread on the mine floor and cultivated, fertilized, and direct-seeded with a mix of native species (Gould, 2011). The post-mining areas of Weipa region had been rehabilitated since 1981 with the aim to build self-sustaining systems in which established vegetation comprises a plant community with various native species, which in turn support native fauna (Gould, 2012).

With recent global targets aiming to restore 15% of degraded ecosystems by 2020 (CBD, 2012), rehabilitation is increasingly being promoted to restore the vegetation and ecosystems that have been destroyed by mining operations. In Queensland, Australia, the *Environmental Protection Act 1994* (Qld) outlines the legal requirement that post-mining rehabilitation should be "able to sustain an agreed land use" (Environmental Protection Agency, 2008). Native vegetation is designated as the post mining land use, given the rehabilitation should be similar to the pre-existing ecosystem prior to any disturbance. Rehabilitation of post bauxite mine in Weipa, focuses on a re-establishing self-sustaining native vegetation community, which resembles unmined neighbouring forests resilient to fire or drought, supporting habitats for recolonization by flora and fauna and reducing mining impacts and erosion (Green Coast Resources, 2014).

1.2 Study Location

Germination experiments took place in the SMI laboratory (Sustainable Mineral Institute) laboratory and the glasshouse trials at Glasshouse 7, St Lucia campus, the University of Queensland. The soils and seeds used in glasshouse experiments were brought from the Hey Point Bauxite Mine site. The Hey Point Bauxite project (HPBP) is situated approximately 10 km south of the township of Weipa which is 1200 km east of Darwin and 700 km north-west of Cairns (Figure 1). The recent use of the nearby areas has historically been cattle grazing but grazing pressure was not likely significant due to unimproved pastures and low stocking rates (Green Coast Resources, 2014). Generally, Weipa experiences tropical equatorial or monsoonal climate with a dry and wet season. The annual rainfall is two meters with most rain falling during December to March and rarely from May to September (BOM, 2018). The mean daily maximum temperatures range from 31-35 degrees and the minimum overnight temperatures are 18-19 degrees during the winter months and nearly 24 degrees during summer. The cyclone season extends from December to April (BOM, 2018).

The study site is located entirely within the Batavia Landscape of Weipa. The landform comprises of a generally flat to undulating bauxite plateau, which contains a network of small creeks and rivers (Green Coast Resources, 2014). The area is surrounded by slightly elevated uplands at about 35 to 40 mAHD (meters Australian Height Datum), which gradually slope towards the Hey River on the east and north east. The lowest elevations in the region are between 0 to 5 mAHD with the highest elevations ranging from about 50 to 55 mAHD (RTA, 2011). Soils in Weipa are mostly aluminous in nature and infertile with low moisture holding capacity due to the presence of pisoids of bauxite or ironstone and the nature of their light texture (Green Coast Resources, 2014).

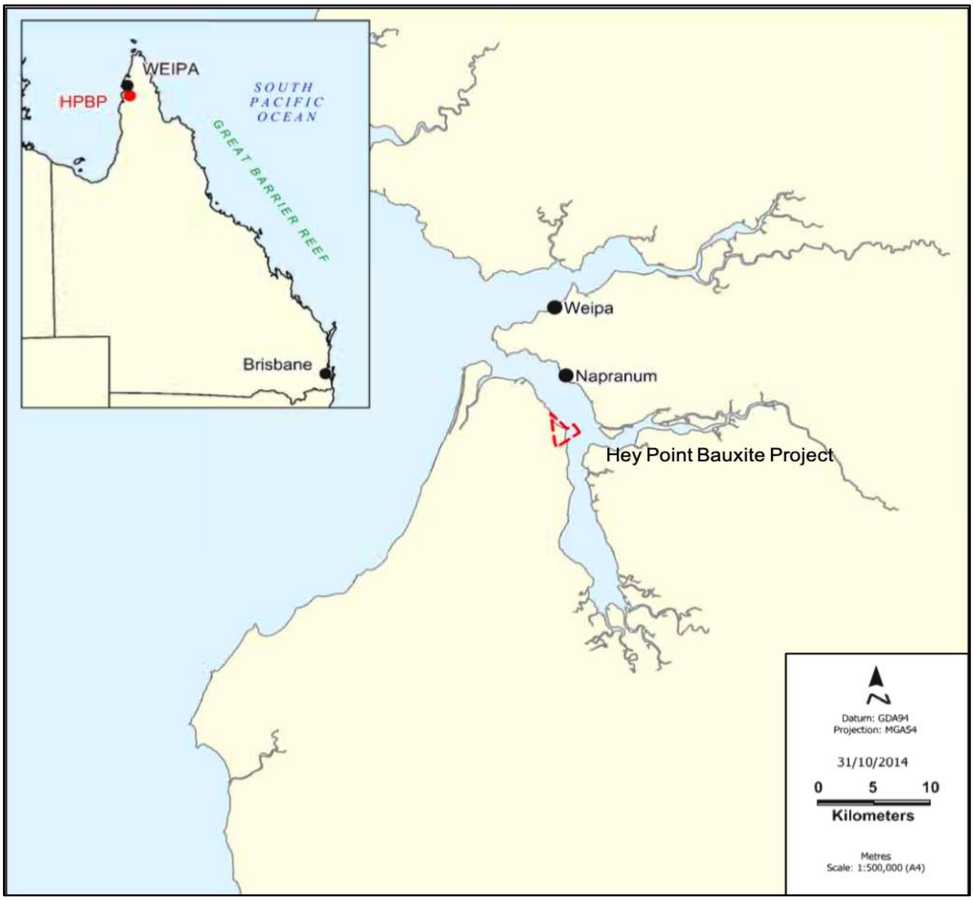


Figure 1. Location of HPBP south of Weipa
(Source: Green Coast Resources, 2014)

1.3 Aims and Objectives

This work had two general aims: the first aim was to determine the most effective method for establishing native species in the different soils of Hey Point for post-mine rehabilitation. The second aim was to investigate the effect of superphosphate application and sowing methods on germination and seedling establishment in selected species.

1.3.1 Research questions

1. Are fallow soils better for seed germination than stockpiled soils in rehabilitation?
2. How does superphosphate fertilization influence the germination success and seedling establishment of selected species?
3. Which direct seeding technique, burying verses broadcasting, has better germination for seeds of specific species?
4. What is the relationship between the seed size, sowing methods, and seedling establishment in rehabilitation for selected species?

1.3.2 Hypothesis

1. Fresh topsoil will assist germination rates more than the older stockpiled soils.
2. Phosphate fertilization will increase the germination and establishment of native species in bauxite mine rehabilitation in the wet/dry tropics of northern Australia.
3. Shallow burial of seeds is generally a more effective method of direct seeding than surface broadcasting for larger seeds.
4. Broadcast seeding is a more effective method of direct seeding than burial for small seeds.

2. Materials and Methods

2.1 Seed Collection and Storage

The native species used in this experiment were from local provenance and adapted to local climate and soil types. Those seeds from the forests near the Mine site were collected between August and September when seeds are mature. Seeds were brought to SMI and stored in the SMI Laboratory cold room to retain viability. Average seed weight for each species was calculated before storage.

2.2 Laboratory Experiment

Laboratory experiments were carried out to assess the seed quality of native species for rehabilitation and to estimate the viability of the seedlots for each species. Seeds were given the required treatments to breakdown dormancy before the germination trials. Different pre-treatments such as hot water soaking and mechanical scarification using scissor or sandpaper were used for different species based on the nature of seed coat and dormancy. The workbench, the equipment, and tools were disinfected with 70% ethanol and germination trials were prepared in a laminar flow cabinet. Seeds were also disinfected with 1% sodium hypochlorite (bleach) solution and rinsed carefully with ultrapure water before being placed in Petri dishes. The seeds were placed and distributed evenly in agar solution in Petri dishes, which were then sealed with parafilm after the placement of seeds. Petri dishes were relocated in a growth cabinet with a setting at 24°C and a 12-hour light cycle. Seed was considered to have germinated when the radicle was at least 2mm long and germination was recorded every 3-4 days.

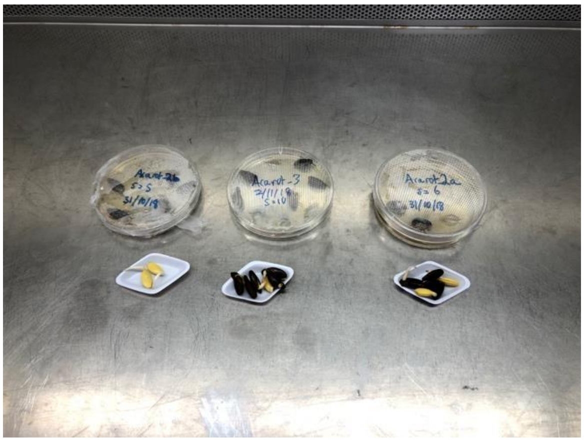


Figure 2. Seeds were placed in petri dishes and the germination was counted when the radicle emerged

2.3 Glasshouse Experiment

Glasshouse pot experiments were designed to investigate the germination of selected species with and without fertilization in different types of soils with two different seeding methods. Three different types of soils were collected from study site and used in the glasshouse experiments. These include (1) fallow (in August 2018), (2) new soil (stockpiled in August 2017) and (3) old soil (stockpiled in Feb 2016). Figure 4. Locations of stockpiled soils and fallow used in the experimentsdepicts the time of soil stockpiling and location of the soils collected at the open pit bauxite mine from Weipa. Superphosphate (P_2O_5) was applied at a rate of 200kg/ha to the soils to match application rates used by other rehabilitation operations in the region (Rio Tinto). The pots used in the glasshouse experiment were 121 cm^2 (11cm x 11 cm) in size and this measurement was used to calculate the proportion of super phosphate applied to each pot. The two different direct seeding techniques of burying and broadcasting seeds were used for each treatment. The buried seed were sown at a depth of 1-3 cm under the soil depending on seed sizes, as larger seeds need more cover soil. This gave twelve different treatments based on different combinations of different soil types, fertilization and sowing methods (

Table 1).

Table 1 Experimental design for glasshouse trials

Explanation	Old	New	Fallow
Buried without fertilizer	-POB	-PNB	-PFB
Surface without fertilizer	-POS	-PNS	-PFS
Buried with superphosphate	+POB	+PNB	+PFB
Surface with superphosphate	+POS	+PNS	+PFS

(the first letter +P and -P represents with and without superphosphate fertilization, the middle letter represents for soil types as O for old soil, N for New soil and F for fallow soil respectively and the third letter represents sowing methods as B for Buried and S for surface)

Five seeds were sown in each pot for each treatment and three replications were carried out for each species and treatment. The pots were placed on the bench randomly in a randomised block experimental design. Then the pots are watered twice a day to keep the required moisture for germination, as it the soils rapidly dried in the glasshouse.

The germination patterns, seedling survival and height growth of selected species were assessed for each treatment of seeding methods and phosphate fertilization on three different types of soils. The effect of phosphate fertilization on germination and seedling establishment was monitored and evaluated, compared with non-treated soil in the other pots.

Figure 3. Pot experiments in the glasshouse

2.4 Studied Species

Five native species of northern Australia were used for glasshouse trials. The germination rate of the selected species showed at least 70% viability and germination occurred in the first week for most of the species in the laboratory tests. The five species used in these experiments were *Acacia rothii F.M.Bailey*, *Adenanthera pavonina* L., *Corymbia ferruginea* (Schauer) K.D.Hill & L.A.S.Johnson, *Erythrophleum chlorostachys* (F.Muell.) Baill. and *Eucalyptus tetrodonta* F.Muell. Proper dormancy treatments were given for each species to shorten the germination period (see Table 2).

Table 2. Lists of species tested at glasshouse trials

Species	Family	Common name	Seed size (g)	Seed length(mm)	Treatment
Acacia rothii F.M. Bailey	Fabaceae	Roth’s Wattle	0.22	14±1	Mechanical
Adenanthera pavonina L.	Fabaceae	Red Bead Tree	0.243	8±0.6	Mechanical/hot water
Corymbia ferruginea (Schauer) K.D.Hill & L.A.S.Johnson	Myrtaceae	Rusty Bloodwood	0.13	8±1.7	None
Erythrophleum chlorostachys	Fabaceae	Cooktown Ironwood	0.535	12±2	Mechanical

(F.Muell.) Baill.					
Eucalyptus tetrodonta F.Muell.	Myrtaceae	Darwin Stingybark	0.00553	5±1.2	None

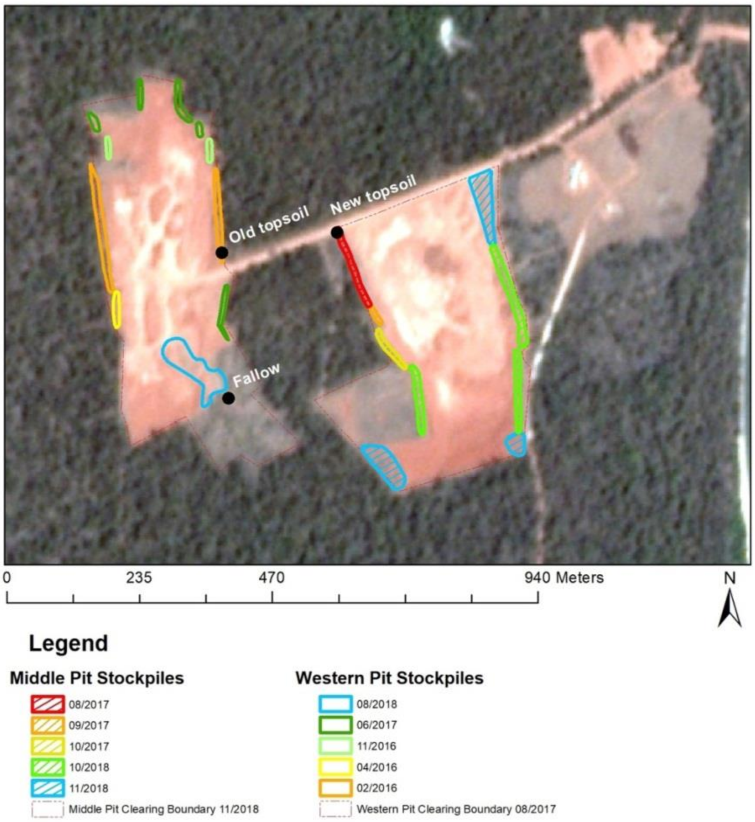


Figure 4. Locations of stockpiled soils and fallow used in the experiments (Source: Natasha Ufer, unpublished data)

2.5 Data Collection and Analysis

The mean weights for each species were calculated and recorded before storage. Seeds weights were used as a surrogate measure of seed size (see Table 1). The germination rate over eight weeks was recorded after seeds were applied to the pots.

Germination was deemed successful once a radicle emerged of at least 2 mm long from the seed surface or when the seedlings emerged above the soil for buried seeds. The germination results were recorded twice a week on every Monday and Thursday. The overall seedling survival was measured after two months.

2.6 Statistical Analysis

The effect of sowing methods on germination in different types of soils was analysed by using analysis of variance (ANOVA) and compared by treatment groups, with no fertilizer and superphosphate fertilization. Seeding methods were assumed to have the same effects in all soil types with and without treatment. Tukey HSD tests were undertaken after ANOVA to analyse all post-hoc comparisons of means. The differences were assumed to be significant when the probability was 5% or less. Pearson correlation was used to analyse the relationships between germination, seedling survival, and seed size.

3. Results

3.1 Laboratory Experiments for Viability Tests

The laboratory trials for viability tests were carried out before the glasshouse pot experiment. Germination mostly occurred in the first week for all species after seeds are placed in the agar medium in the petri dishes. The results of laboratory viability tests for selected species were described in the Table 3. The mechanical scarification with scissor and sandpaper was shown to be the most effective for *A. rothii and A. pavonina*, resulting in high germination rates, 76% and 95% respectively, which were higher than hot water soaking. Whereas *E. chlorostachys* indicated a higher rate with hot water treatment but a considerably in longer time for germination. *E. tetrodonta* and *C. ferruginea* do not require any pre-treatment with germination rates of 79% and 92% respectively.

Table 3. Laboratory viability test results, pre-treatment, and storage information for different tree species

Species	Germination (%)	Treatment	Germination time(weeks)	Storage
Acacia rothii	40	Hot water	8	Air-conditioned
	67	Sandpaper	1	
	82	Sandpaper	1	
Adenanthera pavonina	90	Sandpaper	1	Air-conditioned
	100	Scissors	1	
Corymbia ferruginea	92	None	1	Air-conditioned
Erythrophleum chlorostachys	100	Hot water	11	Air-conditioned
	64	Sandpaper	1	
Eucalyptus tetrodonta	79	None	1	Air-conditioned

3.2 Glasshouse Pot Experiments

Overall germination by species under different conditions

Table 4 illustrates the germination rate of each species under different conditions of soil types, seeding methods and fertilization. Germination occurred in the first and second week after seeding for most of the species. Among the different species under different conditions, *C. ferruginea* was generally shown to have the highest germination rate whereas the lowest germination rate was found in *E. tetrodonta* and *Adenanthera pavonina* without superphosphate fertilization. *E. chlorostachys* had the best germination rate in new soil with 73% in -PNB and 53% in PNB. The surface seeds germinated the least in -PFS, POS, and PFS with 13% respectively. Generally, the higher emergence was observed in buried seeds than surface seeds in all different soils. Germination and seedlings emergence of *E. chlorostachys* was relatively low in soils with superphosphate fertilization compared to the non-fertilized soils. The fallow soil provided relatively better germination for *C. ferruginea* with 93% in -PFS and PFB.

The lowest germination was found with the surface seeds from the old soil without fertilization -POB. The most germinated condition for *A. rothii* was new soil with superphosphate application however in buried seeds, it was 93% in PNB. Generally, the fallow soil with buried seeding provided a higher emergence for this species.

The germination of *E. tetrodonta* was found to be the best in the old soil with superphosphate when the seeds were broadcasted on the surface with germination rates of 53% in POS. However, there was an inconsistent trend in germination success and better results were seen when seeds were buried in non-fertilized soils while the surface seeds germinated relatively better in phosphate soils. *A. pavonina* had a better germination in superphosphate applied soils compared to non-phosphate soils. The best germination was observed in fertilized new soil when the seeds were buried, having 93% rate in PNS.

Table 4. Overall germination rate of targeted native species for different combination of soil types, treatments, and conditions

	No Fertilizer(-P)						Phosphate					
Species	-POB	-POS	-PNB	-PNS	-PFB	-PFS	POB	POS	PNB	PNS	PFB	PFS
Erythrophleum chlorostachys	47±6.7	20±20	73±26.7	20±20	67±13.3	13±6.7	47±6.7	13±6.7	53±24	20±0	47±26.7	13±6.7
Corymbia ferruginea	47±29	87±13.3	73±26.7	73±6.7	67±6.7	93±6.7	80±11.5	73±6.7	73±13.3	80±11.5	93±6.7	67±6.7
Acacia rothii	60±23.1	13±13.3	60±0	20±11.5	67±24	53±13.3	33±33.3	67±24	93±6.7	40±11.5	73±6.7	67±24
Eucalyptus tetrodonta	27±6.7	7±6.7	20±11.5	13.3±6.7	33±6.7	13±6.7	7±6.7	53±13.3	27±6.7	20±0	20±11.5	33±6.7
Adenanthera pavonina	7±6.7	27±6.7	13±13.3	13±6.7	0±0	13±6.7	60±30.5	47±24	93±6.7	20±11.5	80±11.5	87±13.3

Values are replicate block means ± S.E. (n=3). Note: *Adenanthera pavonina* seed treatment was mechanical for Phosphate treatment and hot water for non-Phosphate treatment

3.3 Germination Difference in relation with Soil Types

There was no significant difference in germination between all three types of soils for all species. The best germination rate was observed in new soil for *E. chlorostachys* in both treatment with and without superphosphate fertilization. *C. ferruginea* and *A. rothii* had the highest germination rate in fallow soil while showing relatively lower germination results in old and new stockpiled soils (See Table 5). The lowest germination was found in old soils for these species whether fertilization was applied or not. *E. tetrodonta* tended to follow the same results to *C. ferruginea* and *A. rothii* having the highest germination in fallow soil but the old soil was found to be the best for treatment with phosphate fertilization with more standard error. *A. pavonina* also indicated the best germination rate with phosphate fertilization however the old soil was observed to give the highest rate with no fertilization. The old stockpiled soil provided the lowest germination for all species with the exception of *E. tetrodonta* with superphosphate fertilization and *A. pavonina* with no fertilization showing the optimum germination rate compared to other soil types.

Table 5. The germination in three different types of soils: Old, new and fallow

Species	No Fertilizer(-P)			Phosphate		
	Old	New	Fallow	Old	New	Fallow
Erythrophleum chlorostachys	33±11.2	43±14.1	40±13.7	30 ±8.6	37±13.1	30±14.4
Corymbia ferruginea	67±16.9	73±12.3	80±7.3	77±6.2	77±8.0	80±7.3
Acacia rothii	36±15.8	40±10.3	60±12.6	50±19.8	67±13.3	70±11.3
Eucalyptus tetrodonta	17±6.2	17±6.2	23±6.2	30±12.4	23±3.3	27±6.7
Adenanthera pavonina	17±6.2	13±6.7	7±4.2	53±17.6	57±17.5	83±8.0

Values are replicate block means ± S.E. (n=6). Note: *Adenanthera pavonina* seed treatment was mechanical for Phosphate treatment and hot water for non-Phosphate treatment.

3.4 The Effect of Superphosphate Fertilization to Germination

The effect of superphosphate fertilization on germination was analysed for the four species. *A. pavonina* was excluded from this test as the pre-treatments used were different in phosphate and without phosphate treatment. There was no significant difference in germination of *A. rothii, C. ferruginea, E. chlorostachys and E. tetrodonta* between phosphate and no fertilizer application. The average germination percentages of the four different species are presented in Table 6. The phosphate fertilization gave a considerably higher germination rate compared to non-fertilized soils for the three other species, except *E. tetrodonta* in which seed germination occurred more in non-fertilized media.

Table 6. germination rate of four selected tree species with and without superphosphate fertilization

Species	No Fertilizer(-P)	Phosphate(P)
Erythrophleum chlorostachys	39±7.1	32±6.7
Corymbia ferruginea	73±7.1	78±3.9
Acacia rothii	46±7.6	62±8.5
Eucalyptus tetrodonta	19±3.4	27±4.6

Values are replicate block means ± S.E. (n=18)
Note: *Adenanthera pavonina* was excluded due to different pre-treatment given for -P and P.

3.5 Effect of Seeding Techniques on Germination

The effects of seeding methods were compared between groups of phosphate and non-phosphate treatments. The Table *7* depicts the result of ANOVA tests comparing mean germination rates between treatments for the different species. The effects of sowing methods varied between species. There was a significant difference in germination success between buried and surface seeding for *E. chlorostachys* in both fertilized and non-fertilized trials. The greater germination rate was recorded for buried seeds of *E. chlorostachys* (with 49±10.6 %, $p < 0.05$ and 60±5.8%, $p < 0.01$ respectively) in both treatments with and without superphosphate fertilization. The effect of seeding methods was not significant in *C.*

ferruginea and *A. pavonina* when the seeds were sown by either being buried or broadcasted on the surface. The germination of *A. rothii* significantly increased when the seeds were buried in the soil for non-phosphate treatment (62±9.7%, p <0.05), but no significant difference was found in seeds with superphosphate fertilization. The result of *E. tetrodonta* was contrary between superphosphate and non-fertilized soils showing the higher germination in surface for phosphate treatment, while the later had the better germination in buried seeds. The significant increase in seedling emergence of *E. tetrodonta* was recorded when the seeds were buried in the soil with non-fertilized treatment (27±4.7%, p<0.05). The better performance was found in the surface seeds of *A. pavonina* in untreated soils (with 18±4.0, p<0.05), but the seedling emergence was relatively very low compared to other species.

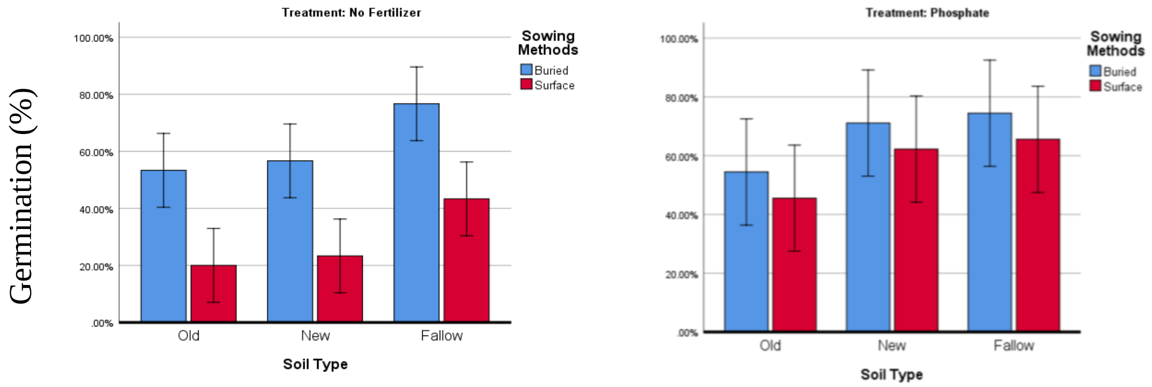
Table 7. The effect of seeding methods on germination by species

Species	No Fertilizer(-P)			Phosphate		
	Buried	Surface	P value	Buried	Surface	P value
Erythrophleum chlorostachys	60±5.8	18±8.5	<0.01	49±10.6	16±2.9	<0.05
Corymbia ferruginea	62±12.2	84±5.6	NS	82±6.2	73±4.7	NS
Acacia rothii	62±9.7	29±8.9	<0.05	67±13.3	58±11.3	NS
Eucalyptus tetrodonta	27±4.7	11±3.5	<0.05	18±5.2	36±6.5	NS
Adenanthera pavonina	7±4.7	18±4.0	<0.05	78±10.8	51±12.9	NS

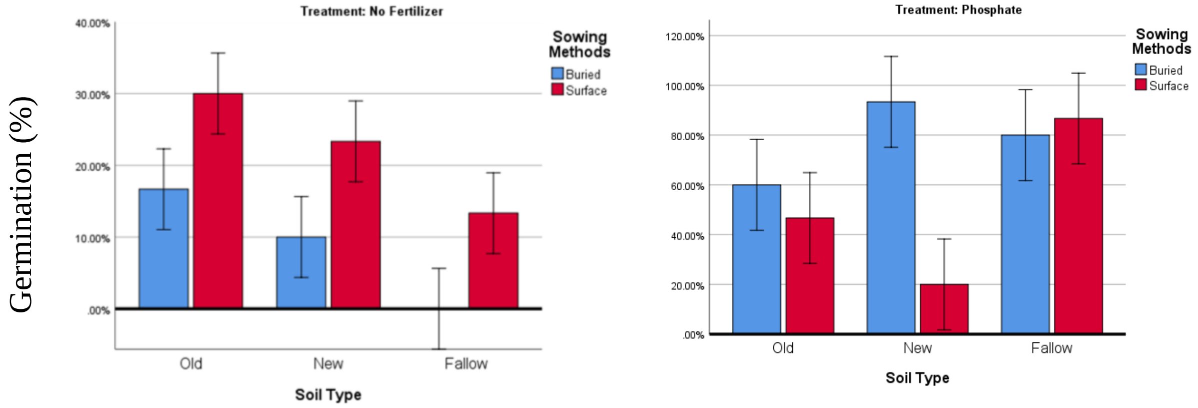
Values are replicate block means ± S.E. (n=9)

The main effects of seeding methods were compared between groups of phosphate and non-phosphate treatment

Acacia rothii



Adenanthera pavonina



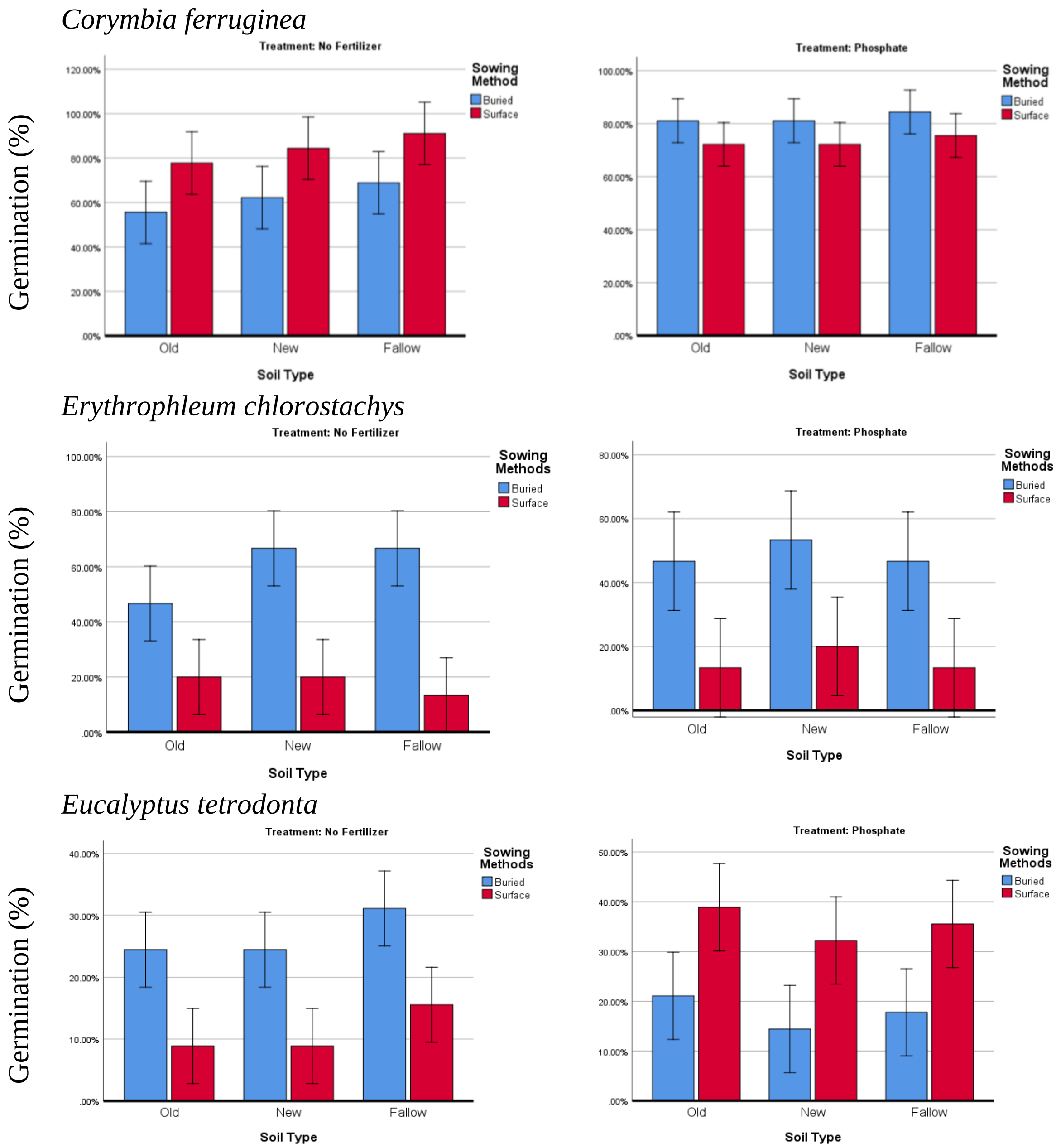


Figure 5. Germination of selected species on different types of soils with buried and surface broadcast seeding

3.6 The Effect of Seeding Methods on Seedling Establishment Rate (Survival %)

The overall survival of the seedlings was recorded at the end of experiment after two months. Some of seeds were found to have germinated during the trial but did not grow and died because of being dried and the roots could not penetrate the soil. This led the survival rate of some species remarkably low even though successful germination was recorded. Seeding techniques had a significant effect on the survival rate of *E. chlorostachys* and *A. rothii* with the superphosphate treatment. The survival rate appeared to be reduced when seeds were placed on the surface although it might have germinated at a time. The survival rate of *E. chlorostachys* declined to 15±11.2 % for surface seeds and 36±16.7% for those of

A. rothii. No significant difference in survival was found between two different seeding methods for other species. *E. tetrodonta* seeds experienced greater survival rates with a seed burial technique rather than surface broadcasting.

Table 8. Survival rate by species explained by different treatments

Species	Phosphate			No Fertilizer(-P)		
	Buried	**Surface**	**P value**	**Buried**	**Surface**	**P value**
Erythrophleum chlorostachys	51±14.1	33±16.7	NS	83±9.3	15±11.2	<0.001
Corymbia ferruginea	97±2.8	94±4.34	NS	66±13.5	76±7.3	NS
Acacia rothii	76±14.4	71±12.4	NS	79±8.2	36±13.9	<0.05
Eucalyptus tetrodonta	56±17.6	36±6.5	NS	78±14.7	44±17.6	NS
Adenanthera pavonina	89±11.1	55±14.8	NS	22±14.7	78±22.2	NS

The main effects of seeding methods were compared between groups of phosphate and non-phosphate treatment.

3.7 The Relationship between Seed Size and Germination

The results of correlation tests between germination and seed size are presented in Table 9. The correlation of these two variables were tested according to two different seeding methods used in the experiments. Figure 6 shows the correlation between seed size and germination success depending on seeding methods. The germination rates did not vary between different seed size in all buried seeds in both treatments. A significant negative correlation was found between seed size and germination for surface broadcasting of seeds. Germination of smaller seeds tended to decrease when they were sown on the surface. The seed size did not have significant effect on germination for buried seeds.

Table 9. Correlation test between seed size and Germination (%) in relation to seeding methods

		Phosphate Buried	**Phosphate Surface**	**No Fertilizer (-P) Buried**	**No Fertilizer (-P) Surface**
Germination (%)	Pearson Correlation	.127	-.377*	.222	-.283
	Sig (2-tailed)	.407	.011	.142	0.60

* Correlation is significant at the 0.05 level (2-tailed)

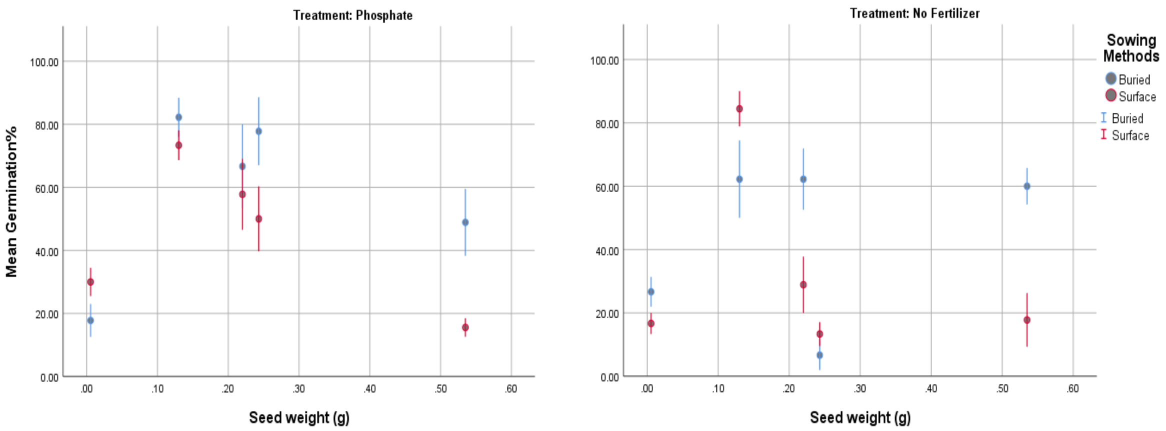


Figure 6. Correlation between germination and seed size

3.8 The Influence of Seed Size on Survival in Sowing Methods

The correlation tests were conducted to test the relation between seed size and survival rate based on different seeding methods and treatments (results shown in Table 10). Buried seeds did not indicate a significant correlation between seed size and survival rate. The survival rate of surface seeds showed a negative correlation to seed size for both treatments. Smaller seeded species tended to have higher survival rates when seeds were broadcasted on surface. The larger the seed size, the more the survival rate decreased when the surface broadcasting method was used.

Table 10. Correlation test between seed size and survival (%) in relation to seeding methods

		Phosphate Buried	**Phosphate Surface**	**No Fertilizer Buried**	**No Fertilizer Surface**
Survival (%)	Pearson Correlation	-.139	-.462**	.054	-.380*
	Sig (2-tailed)	.363	.001	.723	.010

** Correlation is significant at the 0.01 level (2-tailed)
* Correlation is significant at the 0.05 level (2-tailed)

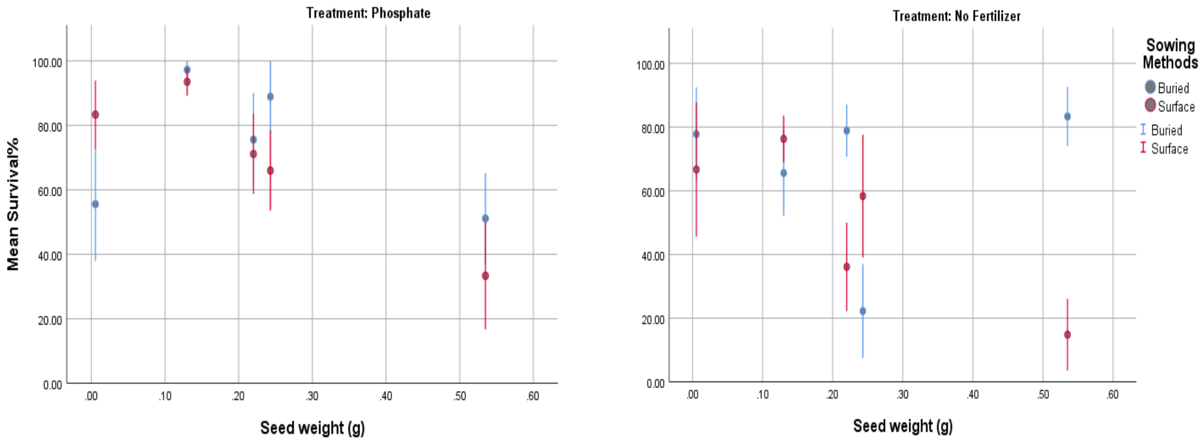


Figure 7. Correlation between germination and seed size

4. Discussion

4.1 Effect of Different Soil Types on Germination

Comparing the mean germination rates between different soils, most of the species showed the best performance in the fallow soils. *E. chlorostachys* performed the best in the new soil compared to other soils having the highest seedling emergence in both treatment with, and without, fertilization. The old soil generally had the lowest germination rates for *E. chlorostachys*, *A. rothii*, *C. ferruginea* and *A. pavonina.* The occurrence of lower establishment rates of these species in old soil could be due to the effects of stockpiling on the soil. The stockpiling of topsoil, even for a short period, caused soil damage and deficiency in soil physical and chemical properties (Rokich et al., 2000, Tacey and Glossop, 1980). The decline of seed viability and natural seedling recruitment from topsoil seedbanks has been long reported in the literature as a result of the stockpiling effect in rehabilitation of degraded post-mine sites (Dickie et al., 1988, Golos et al., 2016, Koch et al., 1996, Tacey and Glossop, 1980). Likewise, topsoil stockpiling significantly reduced the viability and germinability of the directly seeded species in woodland restoration undertaken in Western Australia (Rokich et al., 2000).

The difference in germination of selected species was not statistically significant between three types of topsoils used in this experiment despite a little increase in fallow. This could be because the soils from Weipa have low nutrient availability regardless of mining disturbances (Short et al., 2000). Another possible reason could be due to soil mixing during the process of soil collection, which would impact the original structure of the stockpile and fallow soils. This finding indicates that the effect of stockpiling does not affect the seedling establishment of directly seeded species in rehabilitation. However, there were limitations to this research since it was conducted *ex situ*, under standard glasshouse conditions and used small sample sizes with limited species and different seeding methods. *In situ* field research will be necessary to investigate the different effects of stockpile and fresh soil on the early establishment of native species. There was a consistent finding that fallow soils assisted the seedling establishment of most species tested in this experiment more than the stockpiled soils. This would suggest that higher number of seeds could be used to improve the establishment of native species when the stockpiling is unavoidable in rehabilitation of these areas.

4.2 Effects of Superphosphate Fertilization on Germination

Superphosphate fertilization did not have significant effect on the establishment success of selected species. A slight increase in germination of *A. rothii, C. ferruginea* and *E. tetrodonta* occurred in fertilized soils whereas *E. chlorostachys* performed better in untreated soils. The immediate effects of phosphate fertilization were not seen in this experiment despite a little germination success in some species. However, phosphate fertilization had some beneficial effects including increase in species richness, plant cover and biomass, growth of particular plant species such as ephemeral and legumes, and assists in nutrient cycling (Daws et al., 2013, Daws et al., 2015, De Sousa et al., 2014, Soliveres et al., 2012). Alternatively, fertilization reduced the seedling survival and growth of some woody species due to increased competition with herbaceous plants and weed abundance (Holmes, 2001, Soliveres et al., 2012). The positive effects of phosphate fertilizer could be hindered by P binding properties of iron and aluminium oxide that are abundant in these soils, thus reducing the P availability for plants. The effect of P immobilization was found to have decreased re-sprouter species and understory species in the restoration of Jarrah forests (Bolan et al., 1983; Handreck 1997, cited in Daws et al., 2013). Indeed, the application of phosphorous fertilizer may have either a long-term positive or negative effect on the growth and establishment of re-established plant community, thus its long-term effects should be monitored with *in situ* research.

4.3 Effects of Seeding Methods on Seedling Establishment

Seeding methods influenced the germination and seedling establishment of the native species tested. There was a significant difference in average germination rates between two seeding methods for *E. chlorostachys, A. rothii and E. tetrodonta.* Seeding methods did not have significant effect on the seedling emergence of *A. pavonina* and *C. ferruginea.* Several studies have found that the effect of seed burial is highly species-specific. The seed burying methods increased seed germination of some pastoral species (Camargo et al., 2002, de Souza Gomes Guarino and Scariot, 2014, Sovu et al., 2010) and tropical species (Doust et al., 2006, Pellizzaro et al., 2017). The effects of seed burial were consistently found in *E. chlorostachys* in both fertilized and non-fertilized treatments increasing seedling emergence rate significantly. The surface seeds of *E. chlorostachys* were found to have poor performance compared to the buried seeds in both treatments. This poor establishment of surface seeds was probably because germination was hampered by seed mortality during the experiment. The chance of seed mortality was increased due to direct exposure of sunlight, wind, and watering effects when the seeds were placed on the soil surface.

Mechanical scarification applied prior to seeding probably benefits the seeds to germinate faster, however, it was more likely to expose direct contact of adverse environmental effects to the seed's endosperm for surface seeds. The alteration in seed-water relationships through direct exposure of atmosphere or insufficient soil contact could be an influential factor which determines the seedling recruitment from seeds (Doust et al., 2006). Another beneficial factor for buried seeds might be soil coverage which prevents seed desiccation by maintaining sufficient moisture around seed, and predation which is very important for seedling emergence in degraded habitats where seed predation is common (Silva and Vieira, 2017). A similar result was found for *A. rothii and E. tetrodonta* in non-fertilized soils with increased germination from buried seeds (see Table 7). However, the different germination rate was not significant in superphosphate treatment for the buried seeds of *A. rothii.* This may be because of dormancy treatment by scissor scarification which helped the surface seeds to initiate germination faster. Despite rapid germination, survival and establishment rate of the surface seeds was significantly lower than that of buried seeds (see in

Table *8*). Most of broadcasted seeds were dried and sometimes affected by algae during the experiment even though germination occurred at some point. Although the radicle emerged from the seed's embryo, it was unable to grow well and failed to establish successfully. Some germinated seeds survived and continued to grow until the end of experiment but most of them were found to be in an irregular shape and the roots could not penetrate into the soil layer (see Figure 8). This type of seed desiccation generally occurred in most seeds of *E. chlorostachys*, *A. rothii* and *A. pavonina* when they were unburied in the soil. The occurrence of seed burial is merely infrequent without artificial intervention after seed dispersal event under natural circumstances. The result suggests that the risk of mortality is increased for naturally dispersed seeds, especially large seeded species, by direct exposure of adverse environmental effects and extreme conditions (e.g., high temperatures) and seed desiccation at the soil surface (Zimmerman et al., 2000).

(a) *E. chlorostachys* (b) *A. rothii* (c) *A. pavonina*

Figure 8. Seedling establishment of surface broadcast seeds glasshouse pot experiment (a)*E. chlorostachys* seeds were dried and dead during trial (b) *A. rothii* seeds survived but its roots could not penetrate to the soil (c) *A. pavonina* seeds germinated but most fail to establish well

The seed burial had a significant effect on the germination of *E. tetrodonta* in non-fertilized soils. The rate of germination of buried seeds was found to be relatively higher than surface seeds. The inconsistent result was found in phosphate applied soils where the seedling emergence of buried seeds was half that of surface seeds (see in Table 7). This may be due to the planting depth which was possibly greater than optimal for the seeds of *E. tetrodonta* to emerge. The depth of seed burial is important for small seeded species and increasing depth can restrict seedling emergence. Seed burial can sometimes affect the seed dormancy by increasing the length of dormancy with an increase in burial depth (Baskin and Baskin, 1998). The buried seeds were possibly unable to acquire sufficient light for germination. In contrast, greater germination was observed in buried seeds in non-fertilized soils, which could be because the depth of seeds might have created the optimal condition required for germination. This indicates that investigation of the optimal burial depth of small seeded species, such as *E. tetrodonta*, would be necessary for better establishment in different soil characteristics.

The dormancy treatments played a critical role in the successful germination of *A. pavonina* seeds. Mechanical scarification applied in phosphate treatment exhibited significantly greater performance of seedling emergence than hot water soaking in non-fertilized soils (see Table 7). In non-fertilized soils with hot water treatment, the surface seeds performed significantly better than the buried seeds. However, the germination success of both methods was relatively very low (with < 20%) and no germination occurred in fallow soil. In contrast, no significant difference was found between buried and surface seeds of *A. pavonina* in fertilized soils with a slight increase in burying seeds. Similarly, the seedling emergence of *C. ferruginea* was not different significantly between seed burial and broadcasting in both treatments. The buried seeds performed slightly better in fertilized soils while the surface seeds germinated more in non-treated soils. Seed desiccation was not a serious issue for the seeds of *C. ferruginea* even though seeds were broadcasted on the soil surface. This suggests that regeneration of small seeded species such as *C. ferruginea and E. tetrodonta* might probably be sufficient assisted through natural seed dispersal process and broadcasting is likely to be more effective in restoration. Many tropical species with small seeds and seeds with low water content are less susceptible to desiccation and broadcast seeding can be more effective for these species in restoration (Grossnickle and Ivetić, 2017, Statwick, 2016, Silva and Vieira, 2017).

4.4 The Relationship with Seed Size and Germination Success in Relation to Seeding Methods

The seed size was found to be an influential factor in determining seeding method to optimize seed germination and seedling establishment. In correlation tests, there was a significant association between seed size and germination success in relation to different seeding methods. The germination and establishment success had a significant negative correlation with seed size when surface broadcasting methods were applied to those seeds. With the surface broadcasting method, the rate of germination and seedling emergence is most likely to reduce with increasing seed size. Large seeded species, like *E. chlorostachys* and *A. rothii*, had significantly lower germination rates when the seeds were placed on the surface of the soils. Some of the seeds sown were found to have emerged and counted as germinated but these did not persist. The germinated seeds dried and failed to establish during the experiment and required soil coverage to avoid seed desiccation. This indicates that soil burial is necessary for large seeded species to enhance germination and seedling survival and keep the moisture around the seed within the soil (Silva and Vieira, 2017, Sovu et al., 2010). Again, the correlation between the seed size and survival rate was also significant in surface broadcasted seeds. A significant negative association was found between seed size and survival rate of species tested. The survival rates tended to reduce with increasing seed size when those seeds were applied to surface. Broadcast seeding was thus likely to decrease the rate of germination and survival of large seeded species. For instance, even though there was only a small variation in germination for *A. rothii* between the two different seeding methods, the survival rate was significantly higher for buried seeds. This may be because the mechanical scarification that had been applied to seeds prior to seeding helped them to germinate faster. The germination and early establishment of surface seeds will most likely fail under long adverse conditions such as fluctuation of temperatures, fire, and seed predation in the natural environment. In this study, the overall establishment success of broadcasted seeds was reduced during the two-month duration of experiment. This result suggests that surface broadcasting technique is not suitable for large seeded species and leads to failure to establish. Shallow burial of seeds is probably a more promising seeding method for large seeded species for better germination and establishment success. In plant ecology, surface broadcasting can be considered as the natural process of seed dispersal in many instances. This result suggests that the chance of vigorous seedling recruitment from natural dispersal is likely to be relatively low. Large seeded species especially, need to be exposed to favourable environmental conditions for seed burial to occur and accelerate re-establishment of those species in some areas. This result supports the study of Doust et al., (2006) who suggested that it was necessary to improve the availability of appropriate microsites for larges seeded species because large seeded species experienced a more restricted availability of optimal microsite conditions than the smaller seeded species.

However, no significant correlation was observed between seed size and germination of buried seeds. This lack of association may be because small seeded species such as *C. ferruginea* did not have much variation in germinability between the two seeding methods. Another reason could be a small range of seed sizes used in this study (1 species <0.1 g, four species<0.6 g which were categorized as intermediate by Doust et al., (2006)). Nonetheless, this result indicates that seeding methods did not have a significant effect on the germination of small-seeded species. Similarly, the survival rate and overall establishment success of small seeded species was not significantly affected by seeding methods. Therefore, it was recommended that seeding method wasn't a serious determinant for the establishment of small seeded species such as *C. ferruginea* and *E. tetrodonta* unless the burial depth wasn't within optimal. This finding suggests that the surface seeding method may not always be the best for the small seeded species. Overall, different seeding strategies and conditions should be taken into consideration for the establishment of seeds of different sizes and should include the creation of favourable microsites, correct timing of seeding, and appropriate seeding practices (Grossnickle and Ivetić, 2017).

5. Conclusion

The results of this study suggest that direct seeding can be an effective method for establishment of selected native species of the wet/dry tropics for the rehabilitation of post-bauxite mining in northern Australia. Proper pre-treatment was required to accelerate plant establishment and reduce the seeds exposure to adverse environmental effects. Increased seeding rates could be a possible alternative to improve the establishment of native species on the stockpiled soil. The association between seed size and establishment success, in relation to seeding methods, was clearly proven in this study. Large seeded species are mostly likely to fail when surface broadcasting is applied. This suggests that shallow burial of seeds is generally an effective method for the successful establishment of all selected species. However, planting depth is a critical issue of burial seeding method especially for small-seeded species, thus identification of an appropriate depth is necessary before seeding. Superphosphate fertilization was found to have no immediate effect on the early establishment of native plants in post-mine rehabilitation. Nevertheless, further field research is needed to investigate the long-term effect of topsoil handling, fertilization, and direct seeding in the study area. Periodic evaluation on the outcomes of native plant restoration will be necessary to examine whether they meet the restoration goal of re-establishing self-sustaining ecosystems in the post-mine degraded areas of northern Australia.

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