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RESEARCH ARTICLE

Waterproofing Topsoil Stockpiles Minimizes Viability Decline in the Soil Seed Bank in an Arid Environment

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Abstract

Topsoil is a valuable resource for revegetation of mine sites as it contains seeds of plant species indigenous to the local environment. As mine site restoration is undertaken after the completion of mining, it is a common practice to stockpile topsoil in preparation for restoration activities. While many studies have found a decrease in seedling emergence with increasing stockpile age in temperate regions around the world, a few examine the effect of stockpile age on topsoil seed bank and seedling recruitment in arid environments. Seed longevity is promoted under dry conditions whereas viability loss is increased under warm and moist conditions. Here in a study in Australia's Great Sandy Desert, the effect of topsoil storage age and method of storing topsoil (under-cover and exposed) on seedling recruitment was examined for a major gold mining site. There was a trend for lower seedling emergence (68% lower) and species richness (30% lower) from topsoil stored for 2 years than from topsoil direct returned and topsoil stored for 1 year. Seedling emergence from topsoil stockpiled for 2 years was more than 3.5-fold higher from covered topsoil stockpiles than uncovered topsoil stockpiles. For two ecologically dominant species, after 2 years of storage, seedling emergence of the grass *Triodia basedowii* was 13% of direct returned topsoil and seedling emergence of the shrub *Acacia stellaticeps* was 68% of direct returned topsoil. The implication of the decline in seedling emergence from topsoil stockpiling on mine site revegetation in a biodiverse arid region is discussed.

Key words: **arid ecosystem, mine site, restoration ecology, seed bank persistence, Telfer, *Triodia*.**

Introduction

The seed bank contained in topsoil provides an important source of seed for vegetation restoration of post-mine sites (Carrick & Kruger 2007; Koch 2007; Rokich & Dixon 2007; Scoles-Sciulla & DeFalco 2009; Hall et al. 2010; Golos 2013). As well as providing seed, topsoil also contains fungal and bacterial symbionts that facilitate the establishment of plant species indigenous to the local environment (Bell et al. 2003; Jasper 2007). Due to mining logistics, it is common for many mine sites to stockpile topsoil for subsequent restoration programs.

For many plant species, seed persistence (longevity) in the soil is important for recruitment (Stocklin & Fischer 1999). The selection for species with a persistent seed bank would be greater in ecosystems with unpredictable catastrophic disturbances particularly where there is a high risk of seedling failure (Cohen 1966; Fenner & Thompson 2005). For example, in arid Australia, *Triodia* hummock grasslands are widespread and common with regeneration from the soil seed bank in response to episodic wild fires and rainfall events that are also highly variable in quantity and frequency (Morton et al. 2011). Thus, a high selection pressure for species with a persistent soil seed bank in arid environments is expected.

Even though seed persistence is a seed trait (Fenner & Thompson 2005), once seed enters the soil seed bank edaphic factors influence the longevity of seeds with longer seed survival in soils with higher pH, lower moisture content and lower soil carbon to nitrogen ratio (Pakeman et al. 2012). Biological, chemical, and physical changes occur in stockpiled topsoil, mainly as a result of anaerobic conditions within topsoil stockpiles caused by elevated soil moisture content and decomposing vegetation (Abdul-Kareem & McRae 1984; Harris et al. 1989). Anaerobic conditions within the stockpile may also result in the decomposition of seeds (Ryckeboer et al. 2002). Seed longevity is promoted under either extremely cold or dry conditions, and viability loss is increased under warm and moist conditions (Murdoch & Ellis 1992; Pakeman et al. 2012) with excessive moisture also leading to seed germination or dormancy loss. Therefore, topsoil stockpiles in arid environments should have a slower decline in seed bank viability than topsoil stockpiles in mesic environments. Also, waterproofed topsoil stockpiles should retain a larger intact soil seed bank than topsoil stockpiles exposed to rain.

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The stockpiling of topsoil for restoration often results in lower seedling emergence in comparison to freshly spread (direct return) topsoil (Koch et al. 1996; Rokich et al. 2000; Tozer et al. 2012). Both Rokich et al. (2000) and Koch et al. (1996) found approximately 50% less seedling emergence from topsoil stockpiled for no more than 1 year. A seed burial trial in topsoil stockpiles by Rivera et al. (2012) found a 40% reduction in seed viability after 6 months of storage. In other studies, Dickie et al. (1988) reported significantly lower viable seed count with 4-year-old topsoil stockpiles compared with 3-month-old stockpiles, while Johnson and West (1989) found an increase in viable seed count with older stockpiles. The variation in the outcomes between Johnson and West (1989) and the other studies may have resulted from confounding factors such as differences in topsoil stripping depths, season of stripping and vegetation cover leading to variation in the initial size of the topsoil seed bank at time of topsoil removal and storage. To avoid these confounding factors, it is ideal to investigate changes in topsoil seed bank of a single-sourced stockpile over time rather than investigating differences in topsoil seed bank of different aged stockpiles at one point in time.

This study undertook an investigation into the temporal changes in seed viability in recently stripped and stored topsoil. The study was undertaken at the Telfer mine site on the western edge of Australia's Great Sandy Desert where 3 million m^3 (June 2010) of topsoil have been stored awaiting restoration at a later date. The aims of the study were to investigate the effect of topsoil stockpile age and waterproofing on seedling emergence and species richness over a 3-year period. We hypothesize there will be a decline in seed bank viability in topsoil stockpiles during storage and water proofing topsoil stockpiles will reduce the decline in the soil seed bank viability.

Methods

Study Site

This study site is in the Great Sandy Desert, Western Australia (21°43′S, 122°13′E). The climate is arid, subtropical with a mean annual precipitation of 369 mm (74% falling in the summer wet season from December to March), and mean maximum/minimum temperature of 40.6/26.1°C in January and 25.3/10.6°C in July (Bureau of Meteorology 2011). During the 3-year period of the study, mean annual rainfall was only 205 mm. The natural vegetation is dominated by three major landforms, sandplain, sand dune, and stony hills, with associated vegetation types (Goble-Garratt 1987, Golos 2013). At Telfer, the most extensive vegetation type is associated with sandplains (dune swales and flats) dominated by *Triodia basedowii* hummock grasslands with scattered shrubs grading to shrublands of *Acacia* species (Goble-Garratt 1987; Golos 2013). Other species of shrubs, herbs, and grasses are found and the species composition is dependent on local conditions such as soil texture, gravel/rock content, landscape position and time since fire. Overall, the study ecosystem though arid, is biodiverse with over 270 plant species recorded (Goble-Garratt 1987; Golos 2013).

Analysis for Effect of Topsoil Age

Topsoil was sourced from a 1.2 ha sandplain site at the foot of the southern waste rock dump at the Telfer mine site during October before the start of the summer wet season (December to March). The sandplain site was intact vegetation typical of the majority of the vegetation at the mine site. Immediately following clearing of vegetation with a bulldozer, topsoil was stripped to approximately 10 cm depth and formed into three stockpiles approximately 1.5 m high and containing 60 m^3 of topsoil. Topsoil was spread, before the summer wet season (December to March), into three replicate plots (14 × 13 m) for direct return (stripped and replaced immediately), 1- and 2-year-old storage age treatments. Within each treatment plot, a 12 × 11 m plot was marked for counting of seedling emergence in each of the 3 years of the study. Only newly emergent seedlings were counted in each year. Due to plant size differences it was relatively easy to discern newly emergent seedlings from previous year's seedlings.

Analysis for Effect of Topsoil Stockpile Age and Cover

Topsoil was formed into six topsoil stockpiles (6 m long × 1.5 m wide by 1 m high containing approximately 9 m^3 of topsoil) with three stockpiles covered with waterproof tarpaulins (8 × 4 m, 680 gsm ripstop PVC, Bee Jays Canvas, Perth, Australia) with the remaining three stockpiles not covered. From each stockpile, topsoil was spread, before the summer wet season (December to March) into a plot (7 × 8 m) using a compact loader, at 10 cm depth in November 2007 (direct return), October 2008 (1 year old) and October 2009 (2 years old). Within each plot a 6 × 7 m plot was marked for counting of seedling emergence in June/July the year after spreading.

Soil Temperature. To analyze differences in soil temperature between covered and uncovered topsoil stockpiles during storage, we used soil temperature loggers (Tinytag Plus 2, Gemini Data Loggers [UK] Ltd, Chichester, U.K.). Loggers were maintained for 1 year at 5 mm depth recording temperature every half hour in the covered and uncovered topsoil stockpile.

Statistical Analysis

To avoid counting seedlings that may have been derived from wind blown seed, all species found growing on the southern waste rock dump were excluded from all counts (Table 1). After 1 year of storage, seedlings had emerged on topsoil stockpiles during storage and a small number of plants, annuals, and short lived perennials, were observed to have flowered and seeded, although the number was considered too low (<10 plants per stockpile) to have added in any significant way to the seed bank of 2-year-old topsoil stockpiles.

Table 1. Mean seedling emergence (±SE) of species not included in statistical analysis due to their presence on the southern waste rock dump before spreading of topsoil and with the potential to have seed migrate onto spread topsoil.

Species	*Direct Return*	*1 yr Storage*	*2 yr Storage*
Salsola tragus	44.3 (22.1)	49.3 (18.5)	15.3 (3.3)
Ptilotus nobilis	15.3 (6.2)	5.7 (3.2)	3.7 (0.9)
*Aerva javanica**	1.7 (0.9)	0.7 (0.7)	0.0 (0.0)
Dysphania kalpari	0.3 (0.3)	3.3 (2.0)	0.0 (0.0)
Dysphania rhadinostachya	3.7 (3.7)	6.7 (3.8)	6.7 (4.8)

*Weed species.

Multiple pairwise comparisons, adjusted using Fisher's protected least significant difference (LSD) after analysis of variance (ANOVA), were used for comparing the means. Residual plots were examined for any severe deviation from ANOVA assumptions of normality and homogeneity of variances. To conform data to ANOVA assumptions of normality and homogeneity of variances all seedling emergence counts were square root transformed prior to statistical analysis (Zar 2010). The differences were assumed to be significant when the probability was 5% or less. GenStat Release 12.1 (VSN International Ltd., Hemel Hempstead, U.K.) was used for all statistical analysis.

Results

Analysis for Effects of Topsoil Age

There was high variability in seedling emergence from direct return topsoil plots. However, there was a trend ($F_{[2,6]} = 4.46$, $p = 0.065$) for lower total seedling emergence from 2-year-old topsoil than from direct return and 1-year-old topsoils (Fig. 1a). There was also a trend ($F_{[2,6]} = 4.90$, $p = 0.055$) for decreasing mean species richness of emergent seedlings with increasing topsoil storage age with 17 species emerging from topsoil direct returned, 15 species from topsoil stored for 1 year and 11 species from topsoil stored for 2 years (Fig. 1b).

Though rainfall was lower in 2008 than 2010 (142 vs. 220 mm), seedling emergence was highest in 2009 and the lowest in 2010 for both the direct return topsoil and 1-year-old topsoil treatments (Fig. 2). Seedling emergence in the first year from 2-year-old topsoil (2010) was similar to the first year seedling emergence from direct returned topsoil (2008) but only a third of first year seedling emergence from 1-year-old topsoil (2009).

A total of 28 species emerged from all topsoil treatments with only 17 species having a mean seedling emergence greater than one seedling per plot (Fig. 3). Seedling emergence was dominated by three species, *Triodia basedowii* (47% of all seedlings), *Acacia stellaticeps* (19%) and *Eriachne aristidea* (17%). Only six species had differences ($p < 0.05$) in seedling emergence between years with *E. aristidea* more than doubling seedling emergence from direct return topsoil compared with other the ages. *Heliotropium pachyphyllum* also had lower seedling emergence with increasing age of topsoil

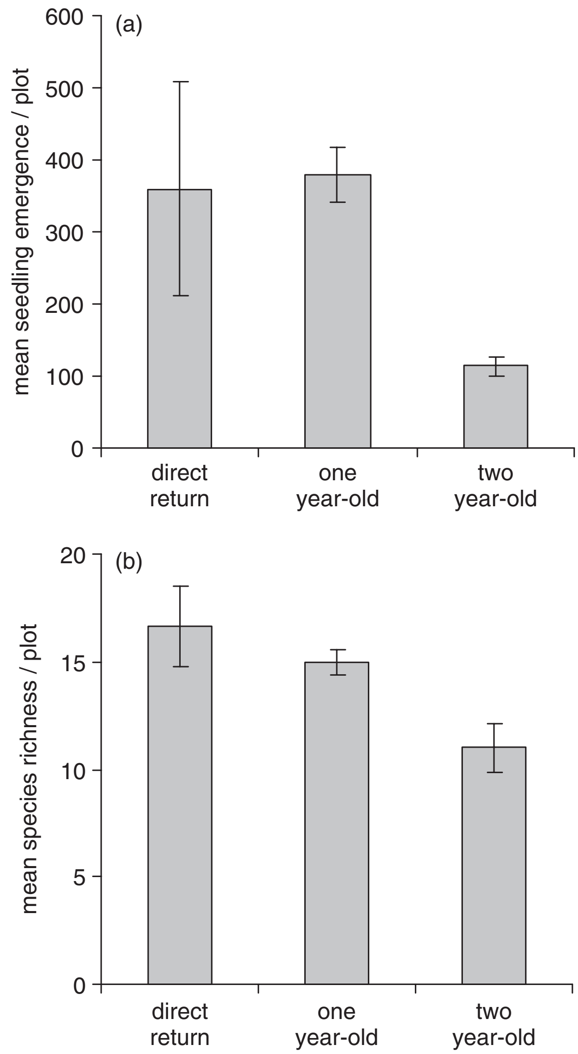

Figure 1. (a) Mean seedling emergence and (b) mean species richness from direct returned topsoil and topsoil stored for 1 and 2 years and spread into 12 × 11 m plots ($n = 3$). Bars indicate standard errors of the mean. There were no significant differences between means ($p > 0.05$).

age. *Tribulus hirsutus* and *T. macrocarpus* had lower seedling emergence from topsoil stored for 2 years than topsoil direct returned or stored for 1 year. *Dampiera candicans* had 10-fold higher seedling emergence from topsoil stored for 1 year than topsoil stored for 2 years but no different to topsoil direct returned. There was also a trend ($F_{[2,6]} = 4.83$, $p = 0.056$) for lower mean seedling emergence of *T. basedowii* seedlings from topsoil stored for 2 years than from direct returned topsoil and topsoil stored for 1 year. *Senna notabilis* was the only species that had greater seedling emergence from 2-year-old topsoil than from direct returned topsoil and 1-year-old topsoil.

Analysis for Effects of Covering Topsoil Stockpile

Soil Temperature. There was little difference (0.3°C) in the surface temperature range between covered topsoil stockpile

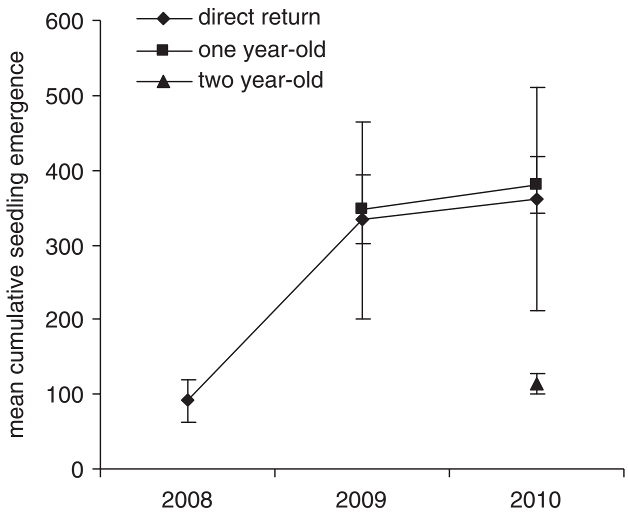

Figure 2. Mean cumulative seedling emergence for the period 2008–2010 from direct returned topsoil and topsoil stored for 1 and 2 years and spread into 12 × 11 m plots ($n = 3$). Sandplain topsoil was harvested from a site cleared in October 2007 and stockpiled on the SWD plateau then spread in October 2007 (direct returned), 2008 (1-year-old topsoil) and 2009 (2-year-old topsoil) on the SWD plateau, Telfer mine site. Bars indicate standard errors of the mean. SWD, southern waste dump.

(8.5–54.0°C) and uncovered topsoil stockpile (8.5–53.7°C). Temperature differences tended to be greatest during the day with surface temperature being cooler on the covered topsoil stockpile between 6 am and 2 pm and warmer on the covered topsoil stockpile from 2 pm to 5 pm. Surface temperature of the covered stockpile ranged from 4.8°C cooler than uncovered topsoil stockpile at 9 am to 3.3°C warmer than uncovered topsoil stockpile at 4 pm.

Seedling Emergence. Covering topsoil stockpiles increased seedling emergence 3.5-fold ($F_{[1,4]} = 9.76$, $p = 0.035$) after 2 years storage (Fig. 4a). Although there was no significant difference in mean species richness of emergent seedlings between covered and uncovered topsoil stockpiles there was a trend ($F_{[1,4]} = 5.78$, $p = 0.074$) for higher mean species richness from covered topsoil stockpiles than uncovered topsoil stockpiles (Fig. 4b).

Ten species emerged from all topsoil storage treatments (Fig. 5). Only five species recorded mean seedling emergence of greater than one seedling per plot, including the dominant grasses *T. basedowii* and *E. aristidea*, and the shrubs *A. stellaticeps* (woody shrub), *D. candicans* (sub-shrub) and *Ptilotus calostachyus* (annual to sub-shrub). For the grasses, mean seedling emergence of *T. basedowii* was nearly 16-fold greater ($F_{[1,4]} = 20.15$, $p = 0.011$) from covered topsoil stockpiles than uncovered topsoil stockpiles while there was no difference ($F_{[1,4]} = 4.25$, $p = 0.108$) in mean seedling emergence for *E. aristidea*. For non-grasses there was no difference in mean seedling emergence of *A. stellaticeps* ($F_{[1,4]} = 0.01$, $p = 0.927$) while *D. candicans* seedlings were only found emerging from covered topsoil.

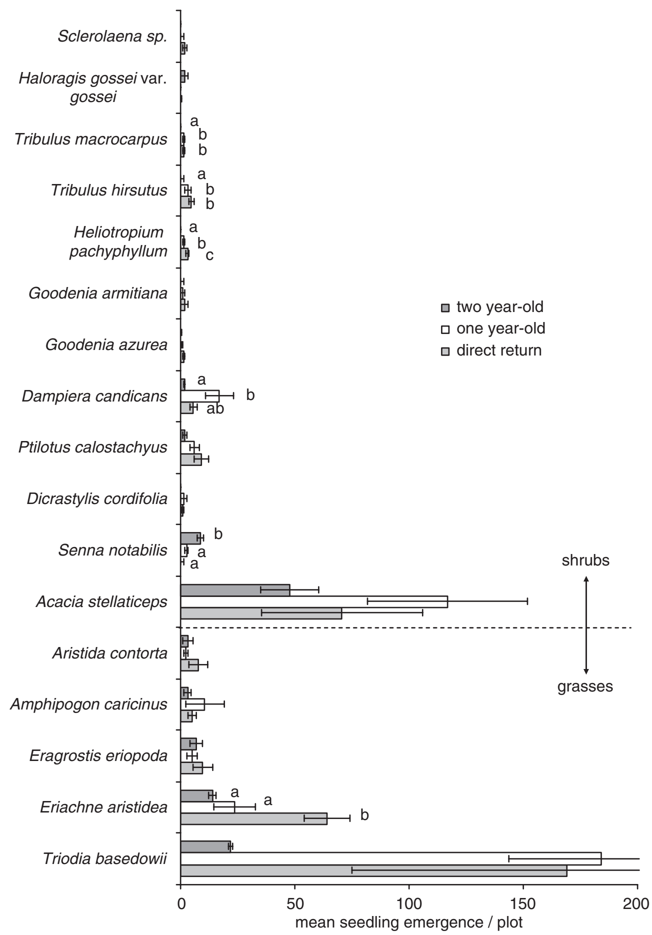

Figure 3. Mean total seedling emergence by species from direct returned topsoil and topsoil stored for 1 and 2 years and spread into 12 × 11 m plots ($n = 3$). Only species with greater than one seedling/plot are shown. Bars indicate standard errors of the mean. Different letters indicate significant differences according to Fisher's protected LSD ($p < 0.05$).

During the 2 years of storage, seedlings emerged on uncovered topsoil stockpiles while no seedlings emerged on the covered topsoil stockpile. Topsoil from covered stockpiles was dry with no compaction making it easier to spread than topsoil from uncovered stockpiles that was covered by a hard consolidated layer and, at depth, was observably moist. Fewer than 10 emergent seedlings were counted from all plots for topsoil spread in 2008 (stored for 1 year) that did not allow meaningful statistical comparisons of means to be made.

Discussion

This study found no significant decline in topsoil seed bank viability after stockpiling for 1 year, however, there was a 68% decline in seed bank viability after 2 years of storage. In contrast, a decline in seed bank viability has been found to be more rapid in studies conducted in more mesic environments. In a mediterranean woodland, there was 46% less seedling emergence from topsoil stored for 1 year (Rokich et al. 2000)

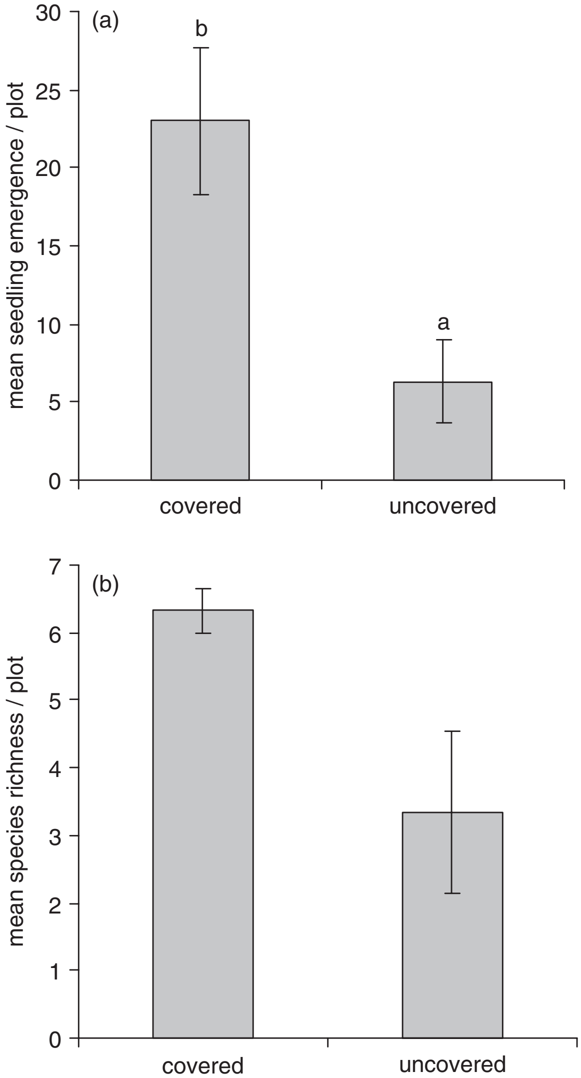

Figure 4. (a) Mean seedling emergence and (b) mean species richness from 2-year-old covered and uncovered topsoil stockpiles and spread into 7×6 m plots ($n = 3$). Bars indicate standard errors of the mean. Different letters indicate significant differences according to Fisher's protected LSD ($p < 0.05$).

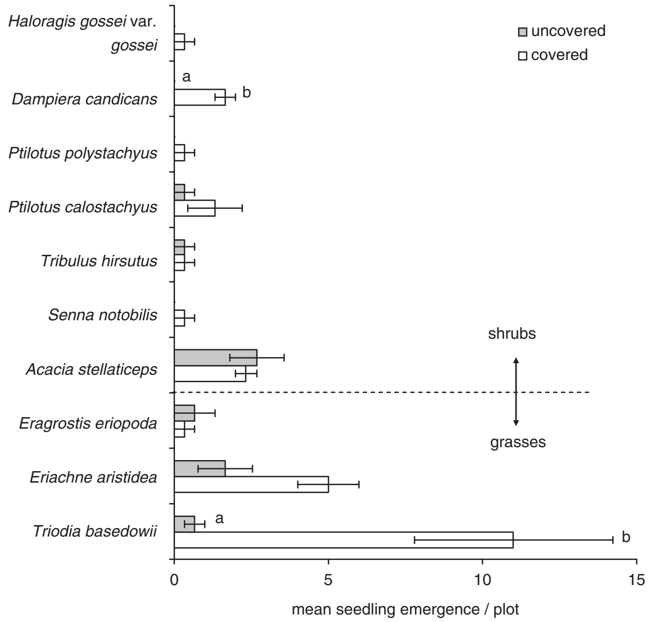

Figure 5. Mean seedling emergence from 2-year-old covered and uncovered topsoil stockpiles and spread into 7×6 m plots ($n = 3$). Bars indicate standard errors of the mean. Different letters indicate significant differences according to Fisher's protected LSD ($p < 0.05$).

and in a jarrah forest, Koch et al. (1996) found a 58% decrease in the germinable seed bank after spreading of topsoil that was stockpiled for only 10 months.

This slow decline in the size of the topsoil seed bank has been observed in other arid environments. A study in the Eastern Mojave Desert (average rainfall 100 mm/year) found negligible decline (7%) in the seed bank of topsoil stockpiled during the dry season for 4 months (Scoles-Sciulla & DeFalco 2009). Greater longevity of the soil seed bank in xeric environments is likely to be linked to the extended periods of drier soil conditions (Murdoch & Ellis 1992; Baskin & Baskin 1998; Pakeman et al. 2012) in comparison to regions with higher rainfall. With drier soil conditions there is less likelihood of germination and reduced rate of seed loss to moisture-linked aging (Long et al. 2009). Indeed, the application of a waterproof cover to topsoil stockpiles resulted in 3.5-fold greater seedling emergence than uncovered topsoil stockpiles. During the period of this study, rainfall was well below the long-term average (179 mm/year vs. 360 mm/year); consequently, during storage periods with higher rainfall, seedling emergence would likely be even lower with increasing storage time (due to higher moisture in stockpiles) and the benefit of water proofing topsoil stockpiles would be even greater. Water proofing of topsoil stockpiles would likely benefit more mesic environments where the decline in soil seed bank viability is more rapid (Dickie et al. 1988; Koch et al. 1996; Rokich et al. 2000).

Differences or lack of differences in seedling emergence between freshly stripped topsoil and stockpiled topsoil could be confounded by differences in rainfall between years. When seedling emergence was at its highest for fresh and 1-year-old topsoil, total rainfall was higher and the period between rainfall events was shorter. Whether higher seedling emergence was due to more favorable rainfall or changes to the germination of the soil seed bank is unclear.

The decrease in seedling emergence with increasing storage time was particularly significant for some grasses. After 2 years, seedling emergence of the grasses *Triodia basedowii* was 13% and *Eriachne aristidea* 22% of that from direct returned topsoil. In comparison, there was no difference in seedling emergence of *Eragrostis eriopoda* over the same period. All three species can be found in mature vegetation and are killed by fire and regenerate from the soil seed bank. In the early stages after fire, *E. eriopoda* can be the dominant species by cover in comparison to the other two species. It is, however, unclear how differences in seed biology between the species resulted in differences in viability in response to storage within topsoil stockpiles. Rokich et al. (2000) also found a decrease in seedling emergence of grasses after topsoil storage except perennial veld grass (*Ehrharta calycina*), a weed species, that exhibited higher seedling emergence after storage that was attributed to either stockpiles catching wind blown seed or veld grass requiring a period of soil aging before germination will occur. In this study, germination of seeds was found on uncovered topsoil stockpiles and grasses such as *E. aristidea* had flowered and reseeded the stockpile. The contribution of this plant cover to replenishing the seed bank of topsoil stockpiles is unknown and over a long period of time could be significant though balanced by the decline of seed viability in stockpiles following wetting.

For non-grass species after 2 years of topsoil storage there was a significant decrease in seedling emergence for *Dampiera candicans* (30% of direct returned topsoil) while the decline in seedling emergence for physically dormant (and presumably long-lived) species, *Acacia stellaticeps* (68% of direct returned topsoil) was not significant. Although seed dormancy and seed persistence are not synonymous (Thompson et al. 2003; Honda 2008), many studies have found that seed persistence is linked to physical dormancy (Russi et al. 1992; Auld 1995; Owens et al. 1995; Tozer et al. 2012). Species with physically dormant seeds such as *Acacia* are known to have extended seed longevity (Cavanagh 1980; Daws et al. 2007) that is attributed to the highly impermeable seed coat preventing moisture uptake and germination, with *Acacia* known to be a problem weed due to its long-lived seed bank (Grant et al. 2007). Likewise, seed burial trials by Erickson et al. (2010) in the Pilbara region to the west of Telfer found that grass species lost viability more rapidly compared with *Acacia* species. There was only one species, *Senna notabilis* a physically dormant species, with significantly higher seedling emergence with increasing storage time. This could be due to loss of physical dormancy of *S. notabilis* seeds during storage within the stockpile. However, seed persistence was not limited to physically dormant species as all species germinating from direct returned topsoil showed at least short term persistence of greater than 1 year (Thompson 1993) as expected in arid environments (Cohen 1966; Fenner & Thompson 2005).

The trend for decreasing seedling emergence and species richness from topsoil with increasing age of storage has implications for mine site revegetation at the study site. Considering the bulk of stockpiled topsoil is older than 2 years it may be difficult to achieve restoration targets for vegetation indices of cover, species richness, and diversity comparable to undisturbed reference sites. Of most concern is the large decline in seedling emergence for *Triodia basedowii*, one of the key species in terms of abundance and cover that is difficult to restore from broadcast seed. Ideally, priority should be to utilize freshly stripped topsoil in mine site restoration as soon as possible to minimize loss of viability to the soil seed bank. Otherwise, to reach restoration targets it will be even more important to maximize seedling emergence by choosing appropriate topsoil handling techniques that will maximize seedling emergence and establishment from the remnant seed bank found in topsoil stockpiles. Also, supplemental seed broadcasting will be required to achieve restoration targets although technology to achieve effective seeding for this arid environment is yet to be developed.

Implications for Practice

- Stockpiling of topsoil for 2 years can result in more than 50% loss in soil seed bank viability. To reduce the loss of soil seed bank viability during topsoil storage priority should be given to returning topsoil to restoration sites as soon as possible after harvesting.
- Dry storage of topsoil can result in 3.5-fold larger germinable seed bank than in uncovered topsoil. Dry storage of topsoil should be considered to preserve topsoil seed bank for vegetation restoration.
- After 2 years of topsoil stockpiling, the ecologically important grass *Triodia basedowii* experienced an 87% reduction in seed bank viability requiring alternative strategies for plant replacement, such as seed broadcasting and greenstock planting, to enable restoration targets to be achieved.

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