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Flora Restorer: sowing a diverse ecosystem

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Abstract

Seed for restoring natural ecosystems is an expensive and finite resource. Yet seedling emergence is notoriously low in mining rehabilitation and restoration projects more generally. Unlocking this potential in broadcast seed has been critical to restoring a diverse kwongan ecosystem at Iluka's Eneabba mineral sands mine, in the mid-west of Western Australia.

Using an innovative combination of rehabilitation practices in the sandy soils of Eneabba—seed burial, land imprinting, and an artificial soil crust—two-fold more seedlings emerged from broadcast seed in 2017 than from standard rehabilitation practice of ripping and seed broadcast. To combine and automate these practices in a single pass, we designed, built, and commissioned tractor-drawn equipment named 'Flora Restorer'. Flora Restorer spreads fertiliser, scarifies the uneven soil, air-seeds a diverse size and shape seed mix, land imprints and thereby buries the seed, and sprays the soil surface with dilute bitumen emulsion forming an artificial soil crust to stop wind and water erosion.

Over the last four years of use, consistently two- to three-fold more seedlings have emerged from broadcast seed using Flora Restorer than from previous rehabilitation practice. Independently, long-term botanical monitoring has also demonstrated revegetation improvement using Flora Restorer, with species richness more than 50% higher and native plant cover more than double compared to rehabilitation at Eneabba over the previous 20 years. Flora Restorer demonstrates that large improvements in revegetation outcomes are possible in mining rehabilitation by automating seed sowing in combination with land imprinting and application of an artificial soil crust.

Keywords: *mining rehabilitation, revegetation, ecosystem restoration*

1 Introduction

Seed for restoring natural ecosystems is an expensive and finite resource. Yet seedling emergence is notoriously low in mining rehabilitation and restoration projects more generally. At Iluka Resources' Eneabba mineral sands mine in the mid-west of Western Australia (Figure 1a), eight-fold more seedlings emerged under ideal nursery conditions than from seed broadcast in the field in a 2015 field trial (Dobrowolski 2019). Unlocking this potential in broadcast seed has been critical to restoring the plant density and species diversity of kwongan shrubland vegetation required after mining.

A unique combination of rehabilitation practices (seed burial, land imprinting, and an artificial soil crust) increased seedling emergence more than two-fold over standard ripping and seed broadcast in a 2017 field trial (Dobrowolski 2019). This combination of practices was trialled over a number of years (2013–2018) to overcome the factors limiting the establishment of kwongan vegetation – a hyper-diverse, low, sclerophyllous shrubland – at Eneabba in mining rehabilitation. These limiting factors are:

- Wind erosion of the sandy topsoil, which displaces seeds before they can germinate and sand-blasts emerging seedlings during the hot, windy, dry summers experienced at Eneabba (Figure 1b).
- Water erosion of the sandy topsoil, due to high intensity showers from frontal rain predominating in Eneabba during the cool, wet winters (Figure 1b), which also displaces seeds and seedlings.
- The uneven infiltration of rainfall into the soil profile, due to high intensity showers predominating in the Mediterranean-type climate experienced at Eneabba, which also has hot, dry summers and

six months drought (Figure 1b). This uneven infiltration of water prevents establishment of seedlings that emerge as they cannot grow their taproot to sufficient depth in the first winter/spring to survive the annual summer drought.

- Reliance on broadcast seed, in the absence of topsoil with a substantial seed bank and with much of the seed bank held in the vegetation canopy (serotiny) of kwongan.
- The high diversity of species required to restore kwongan vegetation (120 species are regularly collected) and therefore the large variety of seed size and shape that must be broadcast.

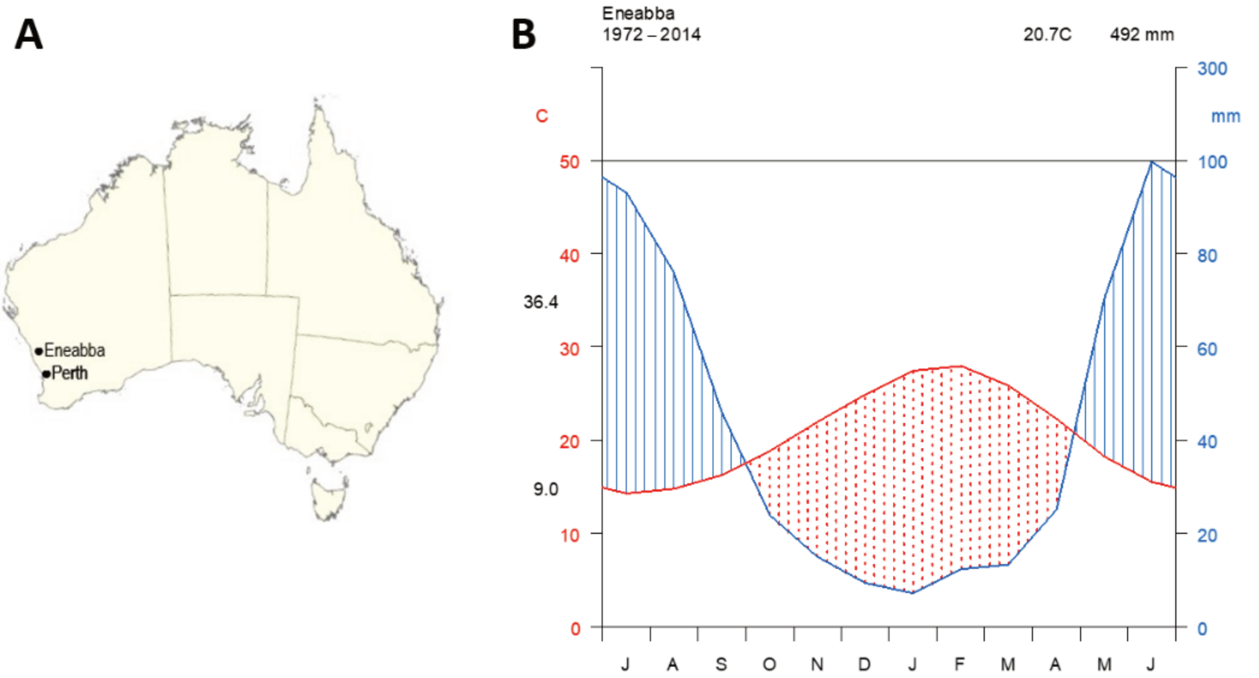

Figure 1 (a) Map showing the location of Iluka's Eneabba mine in the mid-west of Western Australia; (b) Walter-Leith diagram of the monthly rainfall and daily average temperature of Eneabba

Wind erosion is overcome by spraying an artificial soil crust, with the long-established practice of using dilute bitumen emulsion (van der Westhuizen et al. 2011) in current use at Eneabba. Water erosion is reduced by the combination of the artificial soil crust and land imprinting, and the micro-catchments created by land imprinting increase infiltration of rainfall (Dixon 1995), even high intensity rainfall. The variety of seed and reliance on its broadcast meant a simple and flexible method was required to achieve seed burial at appropriate depth in the soil. Scarification of the soil surface by straight tines, air-seeding onto that scarified soil surface from a rotating drum with different compartments, followed by land imprinting and spraying dilute bitumen emulsion, achieved seed burial and placement for germination.

These rehabilitation practices were combined in the tractor-drawn equipment named Flora Restorer (Figure 2). Designed and constructed in 2018 and commissioned in 2019, Flora Restorer has since been used to rehabilitate over 250 ha of kwongan, an annual area twice that of previous rehabilitation practice. This paper will report on the design and commissioning of Flora Restorer, results of seedling emergence in the first year of establishment from its use 2019 to 2021, and also present longer-term botanical monitoring data of the vegetation established from these improved rehabilitation practices and equipment, showing the improvement possible by automating seed sowing in mine rehabilitation.

Figure 2 Flora Restorer being drawn by tractor: seeding, land imprinting, and applying bitumen emulsion

2 Methods

The trials and implementation of the different rehabilitation practices occurred from 2015 to 2018, and rehabilitation using Flora Restorer from 2019 to 2021. This native rehabilitation occurred in different areas of Iluka's Eneabba mine. In all years, standard Iluka practice was to re-contour the mine pits and tailings dams to blend with the surrounding topography and reduce all slopes to less than 1 in 10. Mineral sands tailings is produced from a wet separation process and can be coarse sand tailings or fine-textured, clayey material or a mixture of the two. Overburden or subsoil, when available, was also used in re-contouring. Soil profiles were therefore highly variable across the rehabilitation areas. Upon this surface 100–200 mm of topsoil was spread using tractor pulled carry-graders. Topsoil was of poor quality, sandy textured with little or no clay-sized particles and stockpiled for ten or more years. It was also taken from areas previously rehabilitated, hence contained few germinable seed apart from hard seedcoat species such as *Acacia blakelyi* and *Acacia pulchella*, both species that are readily identified at the seedling stage. The different rehabilitation practices trialled are described in the Results and Discussion section.

The seed mix broadcast each year consisted mostly (approximately 80%) of species from Proteaceae, Myrtaceae, Fabaceae and Ericaeae plant families but many other families were also included. A core of species were broadcast each year although their abundance may have differed, and 10–25% of the species differed between years, both differences depending on seasonal availability of seed for collection. On average approximately 120 different species were broadcast each year (minimum of 116 in 2016 and maximum of 146 in 2018). Application rates of seed were approximately 3.5–4.5 kg/ha in all years.

Assessment of broadcast seed emergence used randomly placed 4 m wide variable area transects (VATs), given VATs' superiority (both accuracy and efficiency) in estimating plant density (Engeman et al. 2005). Monitoring was done in late spring (November) following seeding of the rehabilitation area in the autumn (April/May). Seedlings were identified to genus or family level; species level identification is impossible at the seedling stage for many species in kwongan, even for expert botanists. In VATs seven individuals of each plant group were counted before recording the transect length, the plant groups being: Myrtaceae; Proteaceae; topsoil-derived species (*A. blakelyi* and *A. pulchella*); other native perennial species; native annuals, and; weeds (all being annuals). Early assessment (within the first 6–8 months of seed broadcast) of revegetation has been the critical method for measuring success of the rehabilitation practices, ensuring information is available to adjust the practices in the following year. The biological reason for early assessment is that seed germination and emergence is a key limiting step in plant recruitment (Lamichhane et al. 2018) and therefore a critical first hurdle to restore vegetation. Early assessment also removes the added year-to-year variability of the first summer's mortality of seedlings.

Long-term, permanent plots were monitored in the second year (18 months in after establishment) and fourth year during spring (August/September) by qualified botanists according to established protocols. In summary, each monitoring unit is a 40 m long transect with 20 permanent 1 m^2 quadrats placed in pairs every

4 m along the transect, with these transects distributed across the rehabilitated areas every 5 ha. Every plant within quadrats was identified to species level and plant cover estimated. Species found around the quadrats, but not rooted in them, were also recorded (to assess total species richness). Plant cover and species richness were calculated for each transect by consolidating all quadrat-level observations. This long-term monitoring, which has occurred in a consistent manner for the last 21 years at Eneabba, is more accurate for species identity and plant growth attributes although less accurate for plant establishment density given its far lower sampling intensity. However, given VAT monitoring only began in 2016, the transect monitoring is very useful for comparing revegetation performance of Flora Restorer to historical practice, which included spreading of native mulch that previously provided about 90% of viable seed in rehabilitation (Bellairs & Bell 1993) and stabilised the soil surface (Bell et al. 1986).

Robust statistics were used for estimation: all comparisons were between 20% trimmed means using the percentile bootstrap method (Wilcox 2012) using R software (R Core Team 2013).

3 Results and discussion

3.1 Vegetation performance monitoring

Flora Restorer was commissioned in 2019, although the rehabilitation practices it employs were combined and used in 2018. The evolution of these practices over the years including commissioning and use of Flora Restorer is described in Figure 3 and in Dobrowolski (2019) and shows that the emergence from native perennial broadcast seed had tripled because of those rehabilitation practices (Figure 3). Only native perennial seedlings derived from broadcast seed are compared here as they represent the most stable year-to-year comparison for rehabilitation areas undergoing different rehabilitation practices: annuals are far more weather dependent and topsoil-derived species (mainly *A. blakelyi* and *A. pulchella*) vary many-fold depending on the topsoil stockpile used for a particular rehabilitated area. While 2019 was the driest year at Eneabba for nearly two decades, commissioning problems with the equipment meant that dilute bitumen emulsion was applied at less than half the required rate. This led to rapid breakdown of the crust and immediate wind and water erosion in much of the 2019 rehabilitation area. However, in areas of 2019 rehabilitation that received the appropriate crust application or were sheltered (wind fetch less than 100 m or so) broadcast seedling emergence was 3.4 plants/m^2 and equivalent to other years of Flora Restorer use (2020, 2021) or practices (2018). Even in dry years such as 2020 (> 100 mm below average annual rainfall) the broadcast seedling emergence from Flora Restorer was double that of 2016 practice (Figure 3).

Vegetation performance over the longer-term also indicates that the practices employed by Flora Restorer have a marked improvement on species richness and native plant cover. Species richness is 60–80% higher in 2-year-old rehabilitation of the three years (2018, 2019 and 2020) using Flora Restorer practices (44 taxonomically confirmed species on average) than in 2-year-old rehabilitation when native mulch was used (24 species; rehabilitation years 2000–2009) or when no mulch was used (28 species; rehabilitation years 2011–2017; Figure 4, top left). This improvement is maintained or increased in 4-year-old rehabilitation being 50–120% higher (Figure 4, bottom left), although only one year's observations are available as yet for Flora Restorer practices (only 2018 rehabilitation is old enough). Native plant cover in 2-year-old rehabilitation using Flora Restorer practices (22% native plant cover) is 80–210% higher than rehabilitation using mulch (12% native plant cover) or no mulch (7% native plant cover; Figure 4, top right). Similarly, this improvement is maintained in 4-year-old rehabilitation being 90–160% higher (Figure 4, bottom right).

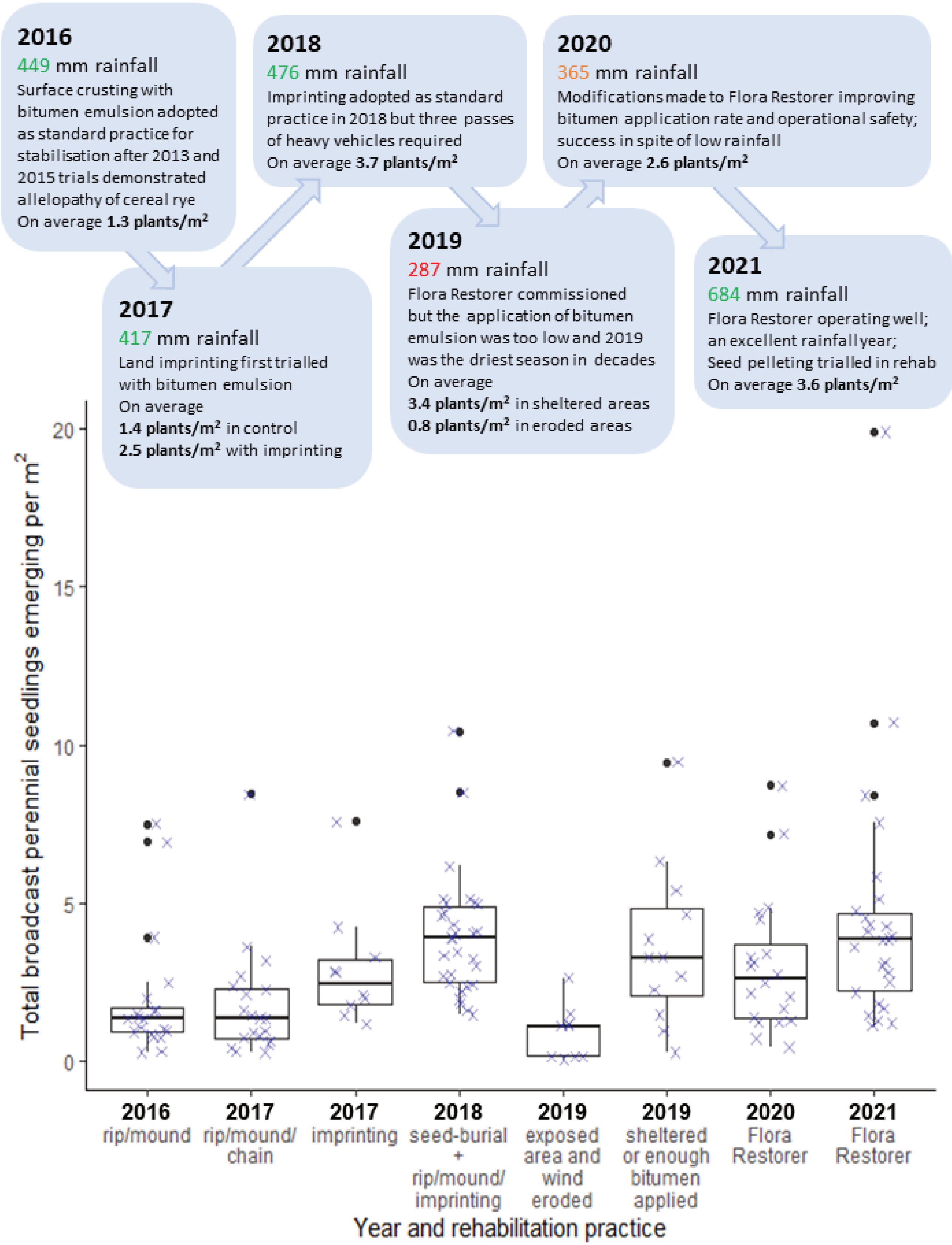

Figure 3 **Total native perennial seedlings emerging per m² derived from broadcast seed, observed in late spring (November) in the year of establishment from rehabilitation areas of years 2016–2021, which underwent different rehabilitation practices indicated in the timeline above the boxplot graph. Individual VAT observations are indicated by blue ×**

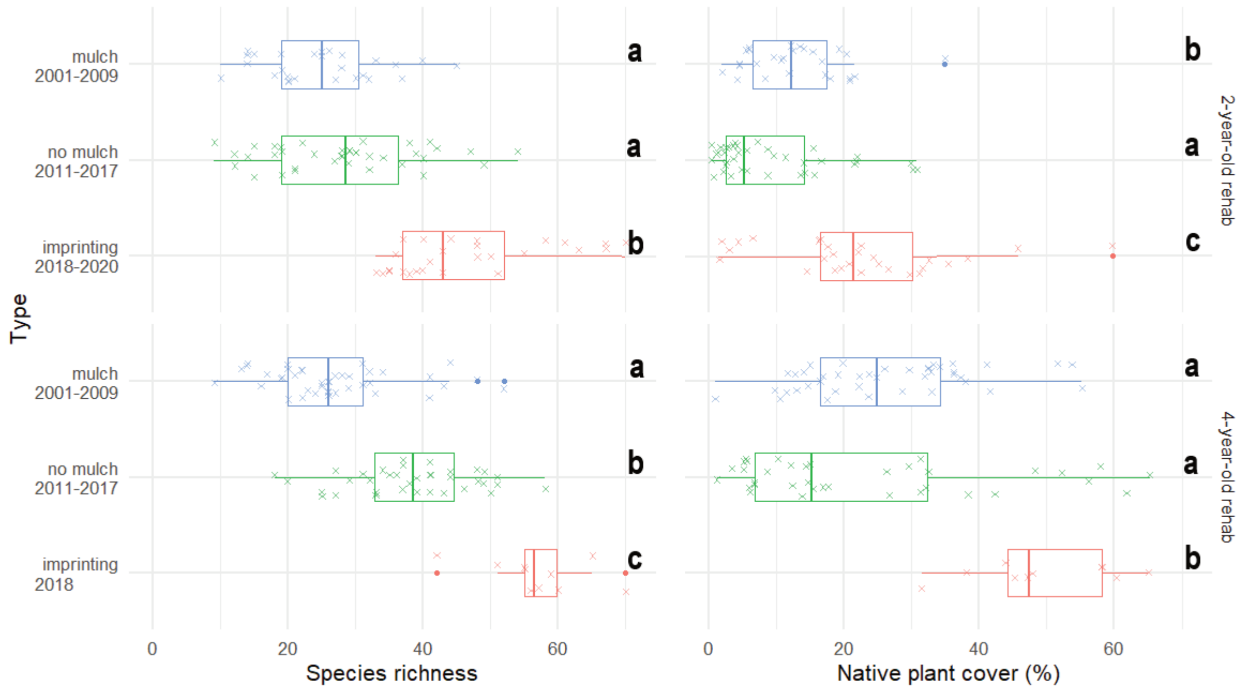

Figure 4 Native species richness (left) and native plant cover (right) of 2-year-old (top) and 4-year-old (bottom) rehabilitation areas from years 2000–2020 using mulch, no mulch, or imprinting and bitumen emulsion (Flora Restorer rehabilitation practices). Boxplots indicate median, IQR, and range with crosses indicated individual (transect) observations. Common letters (to the right) indicate groups that are not significantly different at 0.05 level (comparisons among three types of same age)

In addition to native plant performance, there were fewer weed species and less weed cover in areas of rehabilitation employing Flora Restorer practices. On average five weed species were observed in Flora Restorer rehabilitation in 2-year-old rehabilitation, whereas five were observed in mulched areas and nine in no mulch rehabilitation (Figure 5, top left). In 4-year-old rehabilitation the number of weed species were on average three, five, and nine in Flora Restorer, mulch, and no mulch areas respectively (Figure 5, bottom left). On average, weed cover was 0.2% in Flora Restorer rehabilitation in 2-year-old rehabilitation, whereas weed cover was 0.9% in mulched areas and 2.8% in no mulch rehabilitation (Figure 5, top right). In 4-year-old rehabilitation the weed cover was 0.03%, 0.8%, and 1.2% in in Flora Restorer, mulch, and no mulch areas respectively (Figure 5, bottom right). The improved native plant performance in Flora Restorer rehabilitation appears to exclude weed establishment in the second and fourth years, reducing the ecological niches available for weeds, given almost all weeds at Eneabba are annual species.

These comparisons are made between rehabilitation areas established in different years, hence different seasonal conditions could be responsible for some the observations. However, given the multiple years of rehabilitation activity that are being compared, the marked size of the improvements observed, and that these improvements mirror the completely separate VAT monitoring of seedling emergence (Figure 3), it is more likely that Flora Restorer practices are the key factor driving the improvements in revegetation performance.

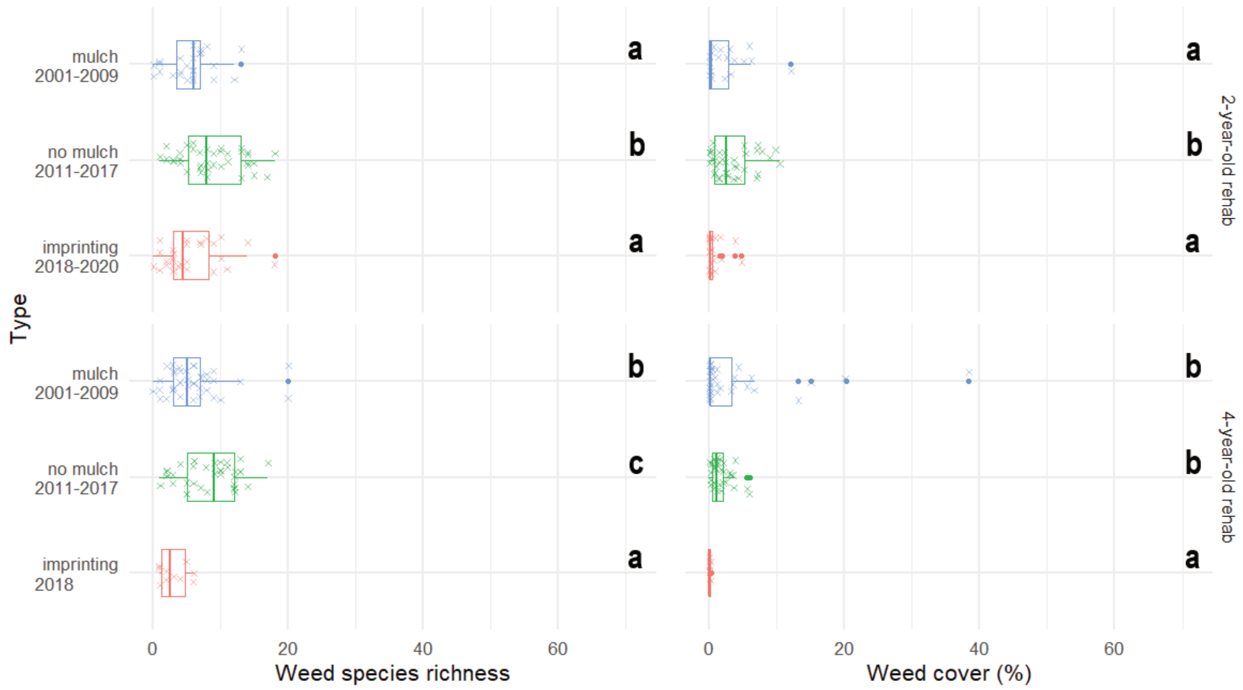

Figure 5 Weed species richness (left) and weed cover (right) of 2-year-old (top) and 4-year-old (bottom) rehabilitation areas from years 2000–2020 using mulch, no mulch, or imprinting and bitumen emulsion (Flora Restorer rehabilitation practices). Boxplots indicate median, IQR, and range with crosses indicated individual (transect) observations. Common letters (to the right) indicate groups that are not significantly different at 0.05 level (comparisons among three types of same age)

3.2 Flora Restorer rehabilitation practice implementation

The key to Flora Restorer's success has been to identify those limiting factors, both environmental and logistical, with the greatest influence on long-term vegetation performance (see list above in introduction section), combining that with a rapid but accurate method for early assessment of vegetation performance that can be done at rehabilitation scale (VATs), and testing practical methods to overcome limiting factors. Implementing practical methods that proved worthy in trials then became a solvable engineering problem, and no longer a knowledge gap.

Previous rehabilitation practice at Eneabba combined the necessary soil profile decompaction step of deep-ripping with seeding. However, it was quickly recognised that deep-ripping could be achieved in the majority of areas at Eneabba using a tractor-drawn agricultural deep ripper. This had the additional benefit of being able to access areas of rehabilitation with wet tailings beneath that may bog a dozer, whereas a tractor would pass unhindered. Hence the deep-ripping step at Eneabba is performed separately to allow for ground-strength variability, which may require dozer ripping in some areas. Seeding, imprinting and crust application, the final steps in rehabilitation, can occur at a (necessarily) constant ground-speed (Flora Restorer is the final vehicle movement over the ground surface at Eneabba; hand-planting of specialty propagated plants occurs later). Flora Restorer has successfully implemented the combination of soil surface scarification, seeding and fertilising, land imprinting, and application of an artificial soil crust, using a one-pass, tractor-drawn equipment that is hydraulically driven by an ordinary agricultural tractor (Figure 6), thereby demonstrating a marked improvement in revegetation performance (Figure 7).

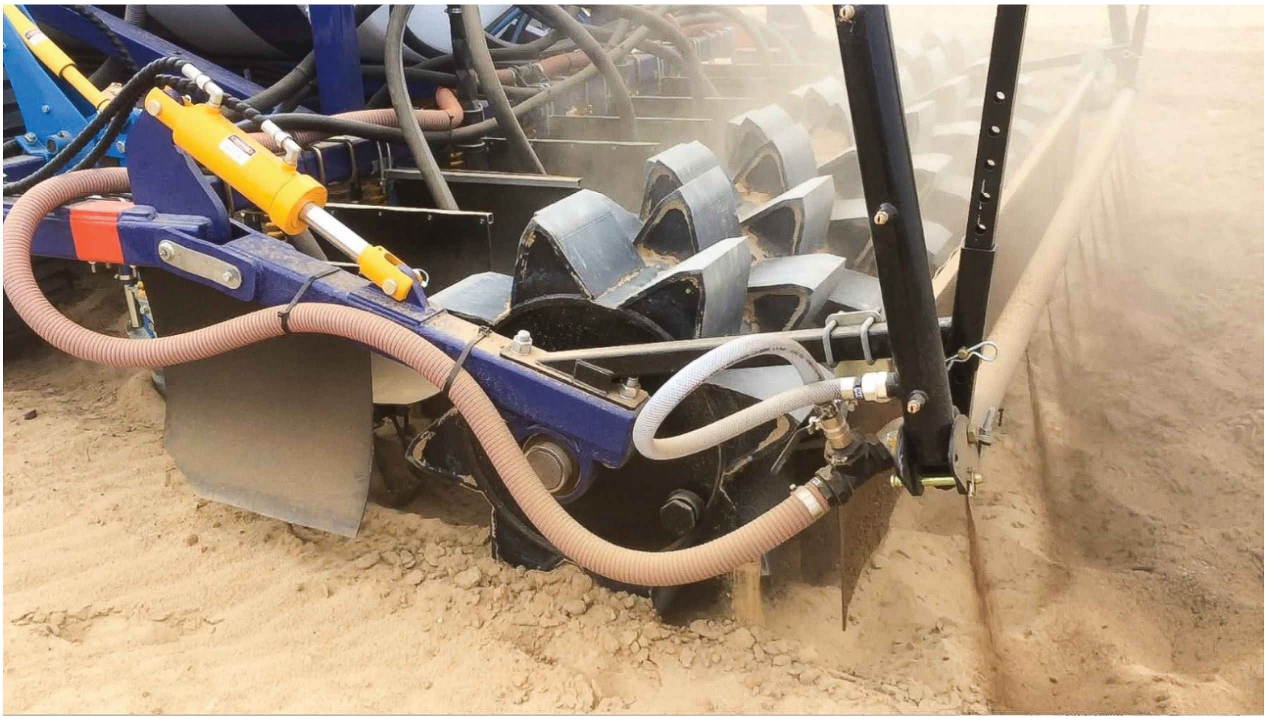

Figure 6 Close-up of the working (rear) end of Flora Restorer showing scarification tines, fertilising and seeding pipes, imprinting roller, and spray bar applying dilute bitumen emulsion

Figure 7 Diversity of seedlings emerging six months after sowing by Flora Restorer at Eneabba in 2020

3.3 Application to other mine sites and revegetation projects

The rehabilitation/revegetation practices that Flora Restorer employs are more widely applicable, particularly if similar limitations to seedling establishment are present: loose, erodible soil; reliance on broadcast seed for native plant establishment, and; a diverse seed mix. Flora Restorer was designed for use on re-contoured mineral sands mining rehabilitation with relatively gentle slopes and loose soils, hence this equipment would not cope with more severe topography of waste rock dumps common to other mineral resources. However, the principles of practically achieving seed burial with a diverse seed mix, utilising the soil infiltration enhancing practice of land imprinting, and reducing erosion by applying an artificial soil crust (in combination with land imprinting), are all applicable to mine site rehabilitation more widely. Flora Restorer is primarily a seeding machine designed to broadcast a diverse seed mix, so its immediate alternative application is to restore native ecosystems on former, marginal agricultural land.

4 Conclusion

Flora Restorer has transformed rehabilitation practice at Iluka's Eneabba mineral sands mine. Improvement in vegetation performance has been demonstrated using two separate monitoring methods: short-term showing a two- to three-fold increase in seedlings emerging from broadcast seed; long-term showing substantial increases in species richness and native plant cover, and reductions in weed species and weed cover. Flora Restorer is applicable to other restoration sites with similar limitations to seedling establishment, and the practices it employs are more widely applicable in part or in combination.

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