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Emergence and Early Growth of Four *Desmanthus* Species in Three Alkaline Clay Soils

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Abstract: Tropical pasture legumes such as *Desmanthus* are expected to improve pasture productivity in the extensive grazing systems of Northern Australia. However, the soils in these areas are often hostile (e.g., hard-setting and nutrient-deficient), which reduces legume emergence and establishment. Furthermore, these soils are often not ameliorated with amendments such as gypsum or starter fertilisers before planting. A pot trial was conducted to investigate differences in the emergence and early growth of four *Desmanthus* species. The legumes were grown in three alkaline clay soils that were unamended or amended with either gypsum (1 t $CaSO_4.2H_2O$ ha^{-1} equivalent), a starter MAP fertiliser (12 kg P ha^{-1} equivalent), or both gypsum and the starter fertiliser. Seedling emergence was recorded daily and shoot yield was determined after six weeks' growth. Final seedling emergence (as a percentage of viable seeds) varied among the *Desmanthus* species (c.f. *D. leptophyllus* = 63%, *D. pernambucanus* = 68%, *D. bicornutus* = 85%, and *D. virgatus* = 86%). On average, across the treatments, gypsum increased seedling emergence by 15%, whereas the starter fertiliser had no effect. The shoot yields and shoot phosphorus content of the *Desmanthus* species generally increased in response to the starter fertiliser. The collective results demonstrated that there were differences in emergence and early growth among the four *Desmanthus* species, which indicates that *Desmanthus* cultivar selection may be important in the relatively hostile soils of Northern Australia. Gypsum was an effective amendment for seedling emergence, whereas the starter fertiliser was an effective amendment to increase legume productivity.

Keywords: *Desmanthus virgatus*; gypsum; legume establishment; phosphorus; starter fertiliser; tropical pasture legume

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1. Introduction

Pasture productivity in Northern Australia has gradually declined due to the depletion of soil nitrogen (N) reserves [1–3]. It is therefore expected that adding tropical pasture legumes into these grazing systems will improve productivity through atmospheric N fixation [4,5], while also improving forage quality [6]. However, the soils on which these grazing systems are based are often hostile. For example, many soils are low in available phosphorus (P) and organic matter and so are nutrient-deficient [7], while some soils also have high levels of exchangeable sodium, which means that they are prone to surface crusting [8]. Under these conditions, it is likely that desirable species, such as small-seeded legumes, will be slow to emerge and establish and will eventually be outcompeted by native grasses or weeds that are more adapted and/or competitive. Furthermore, many extensive grazing systems are low-input, so these problems are often not ameliorated before planting [7]. This means that the aforementioned benefits of incorporating legumes into these grazing systems may not be fully realised. Legumes that are adapted to, or can at least tolerate, these hostile soil conditions are therefore required for successful establishment and persistence.

Desmanthus is a genus of legume that has become naturalised in Northern Australia [9,10]. It is expected to increase the productivity of tropical pastures, particularly in medium to heavy clay soils that have a neutral to alkaline pH to which the legume is adapted [11,12]. However, recent research has demonstrated that there are significant differences in yield potential and P acquisition efficiency among cultivars of *Desmanthus* [13]. The development of the root length largely explains these differences, particularly in low to moderate soil P conditions. Differences in root length and P efficiency may therefore influence the early growth and success of *Desmanthus* establishment, particularly in soils of low fertility, which are common where this legume is currently sown. In addition, fast emergence and good seedling vigour are important traits for pasture establishment [14,15], particularly in clay soils, which can form a surface crust and dry quickly. Compared to other tropical pasture legumes, *Desmanthus* germinates relatively rapidly and produces a relatively high proportion of readily germinable seed [14]. However, little is known about differences in the emergence and early vigour of commercially available *Desmanthus* species. Considering the hostility of many soils in Northern Australia, an understanding of varietal differences in seedling emergence and early plant growth, in conjunction with an assessment of the benefit of amendments at planting, would be useful to potentially improve the success of legume establishment in extensive grazing systems. The objectives of this experiment were therefore to determine (i) varietal differences in the emergence and early growth of four *Desmanthus* species, and (ii) the effect of gypsum and/or a starter fertiliser on the emergence and early growth of these species. It was hypothesised that there would be differences in emergence, early growth, and response to amendments among the four *Desmanthus* species.

2. Materials and Methods

2.1. Plant Growth Conditions

Four *Desmanthus* species were grown in three alkaline clay soils to determine differences in emergence and early growth in response to gypsum and a starter fertiliser. The four species were *D. virgatus* (cv. JCU 2), *D. bicornutus* (cv. JCU 4), *D. leptophyllus* (cv. JCU 7), and *D. pernambucanus* (cv. JCU 9). These cultivars are commercially available and can be combined into enviro-specific blends of Progardes® Desmanthus. The seed of each cultivar was bare and was individually heat-treated by submersion in 85 °C water for 10 s to break seed dormancy prior to sowing [16]. The seed of the four *Desmanthus* species was not inoculated with rhizobia prior to sowing.

Three alkaline clay soils were collected from across Queensland, Australia: Armraynald Station, Burketown (17°57′57.1″ S 139°42′51.5″ E), Gregory Downs Station, Gregory (18°38′51.5″ S 139°9′6.4″ E), and Cungelella Station, Mantuan Downs (24°40′13.5″ S 147°9′23.8″ E). The basic properties of each soil are shown in Table 1. The soils were dried, crushed, and homogenised before 1.3 kg (oven-dry equivalent) of each was weighed into PVC pots (87 mm internal diameter, 200 mm height). A +/−gypsum ($CaSO_4.2H_2O$) treatment was prepared by applying the equivalent of either 0 or 1 t ha^{-1} to the surfaces of the pots. The pots were then moved to a glasshouse (natural daylight, ~1800 mmol m^{-2} s^{-1} peak intensity; 30/25 °C, day/night) in Armidale, New South Wales, Australia. Following this, a wetting and drying cycle was simulated by watering the soil to 80% field capacity and then drying for seven days. A +/−starter fertiliser treatment was then prepared by applying mono-ammonium phosphate (MAP, $NH_4H_2PO_4$) to the pots at rates equivalent to either 0 or 12 kg P ha^{-1} immediately prior to sowing. This resulted in four soil treatments: soil that was unamended or amended with either gypsum, the starter fertiliser, or gypsum and the starter fertiliser. The soils were not amended with any other basal nutrients.

Micro-swards of each *Desmanthus* species were established by sowing 25 viable seeds per pot. Seed viability was based on the germination percentages of the four *Desmanthus* species determined prior to planting. The seeds were placed on the soil surface to mimic a broadcast application, which is common in extensive grazing systems, and then pressed lightly to achieve some seed–soil contact, as would occur following trampling by livestock.

Four replicate pots of each species in each soil treatment were prepared. For the duration of the experiment, plants were watered from the surface every second day to reach 80% field capacity (estimated by saturating the three soils and measuring water content after the excess water had drained). This meant that the soil surface was periodically dry. Plants were grown between March and April 2022. Pots were arranged in a randomised complete block design (blocks comprised the different replicates), which was generated using DiGGer Version 1.0.4 [17].

Table 1. The organic carbon, pH ($CaCl_2$), nitrogen content (nitrate N), phosphorus content (Colwell P), phosphorus buffering index (PBI), potassium content (Colwell K), and sulphur content (KCl40-S) of three Northern Australian soils used in the experiment.

Soil	Organic Carbon (%)	pH ($CaCl_2$)	Nitrate N (mg kg^{-1})	Colwell P (mg kg^{-1})	PBI	Colwell K (mg kg^{-1})	KCl40-S (mg kg^{-1})
Burketown	0.5	7.3	12	3	78	123	4
Gregory	0.4	7.4	15	3	68	78	3
Mantuan Downs	1.1	7.2	4	13	90	274	5

2.2. Harvest and Measurements

Seedling emergence was recorded daily for two weeks following planting. The final emergence percentage was calculated as the proportion of the number of emerged seedlings divided by the number of viable seeds that were sown (i.e., 25 seeds per pot). After the first two weeks, the plants were thinned to achieve a consistent population of 5 plants per pot across the treatments. The average canopy height was then recorded weekly until the end of the experiment. After six weeks' growth, plants were harvested to determine the shoot yield and tissue P concentration. Shoots were cut at the soil surface, oven-dried at 70 °C for 72 h, and weighed. Shoot samples were then ground to <2 mm before a ~0.5 g subsample was pre-digested in a glass tube with 1 mL deionised water and 4 mL 70% (*v*/*v*) nitric acid for at least 4 h. Samples were then digested using a Milestone UltraWAVE 640 (Milestone Srl, Sorisole, Italy). The P concentration of the digested samples was determined colourimetrically at 630 nm using the malachite green method [18]. Shoot P content was calculated by multiplying the shoot P concentration and shoot dry mass.

2.3. Statistical Analyses

Measured parameters were analysed in R Version 4.3.1 [19] by fitting linear models and using an analysis of variance with 'soil', 'gypsum', 'starter', and 'species' as predictor variables. When appropriate, the effect of 'replicate' was included in the most parsimonious model. The linear models were simplified when the predictor variables were not significant. Means and standard errors were calculated from the fitted linear models (R package: emmeans) [20] and means were compared using Tukey's honest significant differences (HSD). The time to emergence was determined by fitting a self-starting Weibull growth function ($y = a - b * \exp(-\exp(c) * x^d)$, where x is days and y is emergence), as described by Crawley [21]. Time to 90% emergence was calculated as the days taken to achieve 90% of maximum emergence based on the fitted Weibull growth functions. The 95% confidence intervals of the time to 90% emergence were determined by bootstrapping residuals as described by Crawley [21]. Normal quantile–quantile plots and Shapiro–Wilk tests were used to test the normality of the residuals for all fitted models. When required, these models were log-transformed to meet the assumptions of normality. A 5% level of significance was applied for all statistical tests.

3. Results and Discussion

Final emergence was not influenced by the soil in which the legumes were sown ($p = 0.460$), so the emergence results (i.e., time to 90% emergence and the final emergence percentage) were summarised according to *Desmanthus* species, gypsum application, and starter fertiliser application (Table 2). Across the treatments, the time to 90% emergence ranged between 7 and 11 days after sowing. On average, *D. leptophyllus* took the longest time to reach 90% emergence, while *D. bicornutus* took the shortest time. The final emergence percentage also varied among the *Desmanthus* species ($p < 0.001$), with species *D. virgatus* and *D. bicornutus* (avg. 86%) achieving higher levels of emergence than species *D. leptophyllus* and *D. pernambucanus* (avg. 65%). These final emergence percentages are similar to previously reported levels for *Desmanthus* [15]. Differences in final emergence indicate that species selection may be important when *Desmanthus* is sown into some alkaline clay soils—for example, soils that are hard-setting and dry quickly. Alternatively, sowing rates could be adjusted to account for these differences. However, if several species are sown as a blend, which is the case for the Progardes® Desmanthus cultivars [12,13], then it is possible that the more adapted species will emerge more quickly and dominate establishment.

Table 2. Time in days to 90% emergence (T90) and the final emergence percentage (%) 16 days after planting four *Desmanthus* species, which were grown in response to soil that was unamended or amended with either gypsum (1 t $CaSO_4.2H_2O$ ha^{-1} equivalent), a starter MAP fertiliser (12 kg P ha^{-1} equivalent), or both gypsum and the starter fertiliser. The T90 values were calculated as the days taken to achieve 90% of maximum emergence based on the fitted Weibull growth functions, with the value range in parentheses showing the 95% confidence intervals determined using bootstrap analysis [21]. The final emergence percentages were calculated as the proportion of seedlings emerged divided by the total number of viable seeds that were sown (i.e., 25 seeds per pot). Values show the mean ± standard error ($n = 4$). Different letters denote significant differences at $p = 0.05$; lowercase letters for species*treatment and uppercase letters for the species average. ANOVA results for the main effects were: species $p < 0.001$, gypsum $p = 0.001$, starter $p = 0.947$.

Species and Treatment	T90 Emergence (Days)	Final Emergence (%)
D. virgatus		
unamended	8.9 (7.5–10.6)	92 ± 6 bc
gypsum	8.5 (7.5–9.5)	95 ± 6 bc
starter	9.5 (8.0–10.9)	76 ± 6 abc
gypsum/starter	8.1 (7.2–9.2)	84 ± 6 abc
Average	8.7 (8.1–9.5)	86 ± 3 B
D. bicornutus		
unamended	8.3 (6.7–9.8)	77 ± 6 abc
gypsum	8.0 (6.7–9.8)	86 ± 6 abc
starter	8.4 (7.0–9.9)	77 ± 6 abc
gypsum/starter	7.3 (6.4–8.6)	99 ± 6 c
Average	7.9 (7.1–8.8)	85 ± 3 B
D. leptophyllus		
unamended	8.9 (7.5–10.1)	60 ± 6 a
gypsum	8.0 (6.7–9.6)	68 ± 6 abc
starter	10.9 (9.1–13.4)	57 ± 6 a
gypsum/starter	9.2 (7.9–10.4)	66 ± 6 ab
Average	9.3 (8.4–10.1)	63 ± 3 A
D. pernambucanus		
unamended	8.6 (6.7–10.4)	55 ± 6 a
gypsum	8.5 (7.0–9.8)	70 ± 6 abc
starter	8.9 (7.5–10.2)	66 ± 6 ab
gypsum/starter	7.3 (6.4–8.2)	79 ± 6 abc
Average	8.3 (7.5–9.2)	68 ± 3 A

The application of gypsum increased the final emergence percentages of the four *Desmanthus* species by an average of 15% across the treatment combinations ($p = 0.001$, Table 2). Benefits due to gypsum may have arisen either through improved soil surface conditions and reduced hard setting with the wetting/drying cycles [22] or through the dissolution of gypsum to release calcium and subsequent osmo-priming as the seeds imbibed water [23]. Gypsum may therefore be a useful amendment to increase the emergence of *Desmanthus*, particularly if it is to be planted in a soil that is known to be hard-setting. However, the benefit of gypsum was greater for species *D. bicornutus* and *D. pernambucanus* compared to species *D. leptophyllus* and *D. virgatus*. Considering that *D. virgatus* had relatively high final emergence that was not benefited by gypsum application, it may be an appropriate species to use when soil amelioration is not feasible at planting. In contrast to the application of gypsum, the starter fertiliser did not influence seedling emergence across the species (p = 0.947). However, the starter fertiliser reduced the final emergence of *D. virgatus* both in the presence and absence of gypsum (species*starter interaction; p = 0.038).

Shoot yields were influenced by the soil in which the plants were grown (p < 0.001). On average, across the different treatment combinations, the highest yields were achieved in the Mantuan Downs soil, followed by the Gregory soil and then the Burketown soil. In each soil, the addition of gypsum did not influence the shoot yield (p > 0.050). Because of this, the shoot yield results are summarised in Figure 1 according to the *Desmanthus* species and starter fertiliser application (although the results were also summarised according to *Desmanthus* species and gypsum application, available in the Supplementary Material Figure S1). On average, the addition of the starter fertiliser increased the shoot yields of the *Desmanthus* species in the Burketown and Gregory soils, but not in the Mantuan Downs soil. This result most likely reflects the difference in native soil fertility between the soils (Table 1), as the Mantuan Downs soil had a Colwell P concentration of 13 mg kg^{-1} compared to the Burketown and Gregory soils, which had Colwell P concentrations of 3 mg kg^{-1}. Based on these results, and recently published findings by Macor et al. [24], it is expected that the addition of a starter fertiliser will benefit legume establishment in low-P soils (e.g., Colwell p < 10 mg kg^{-1}), as it will encourage seedling vigour and root growth for further nutrient acquisition. In contrast, starter fertiliser application in soils with moderate P (e.g., Colwell p > 15 mg kg^{-1}) may provide a limited benefit for legume establishment. Rather, a starter fertiliser that contains both N and P is likely to encourage the growth of existing or fast-establishing grasses and weeds, which could quickly outcompete small-seeded legumes such as *Desmanthus* that are slow to establish.

Shoot yields differed among the *Desmanthus* species. For example, *Desmanthus* species *D. leptophyllus* and *D. pernambucanus* were more productive in the Mantuan Downs soil than species *D. virgatus* and *D. bicornutus*. This indicates that there are differences in yield potential among the species, as has been observed in previous experimentation [13], even in moderately fertile soil, in which the starter fertiliser did not increase the shoot yields. Where the starter fertiliser did increase the shoot yields (i.e., the Burketown and Gregory soils), the application of N and P affected the species differently. For example, the starter fertiliser increased the shoot yields of *Desmanthus* species *D. virgatus*, *D. leptophyllus*, and *D. pernambucanus* by ~2.1-fold in the Burketown soil and by ~1.9-fold in the Gregory soil, but did not influence the shoot yield of *D. bicornutus*. This suggests that *D. bicornutus* is relatively P-efficient but does not produce large shoot yields, which is consistent with the findings of McLachlan, Guppy, and Flavel [13]. Under mixed sward conditions, the application of a starter fertiliser may even reduce the productivity and persistence of *D. bicornutus*, particularly if the increased fertility benefits other components of the sward, such as grasses and weeds, but not the legume.

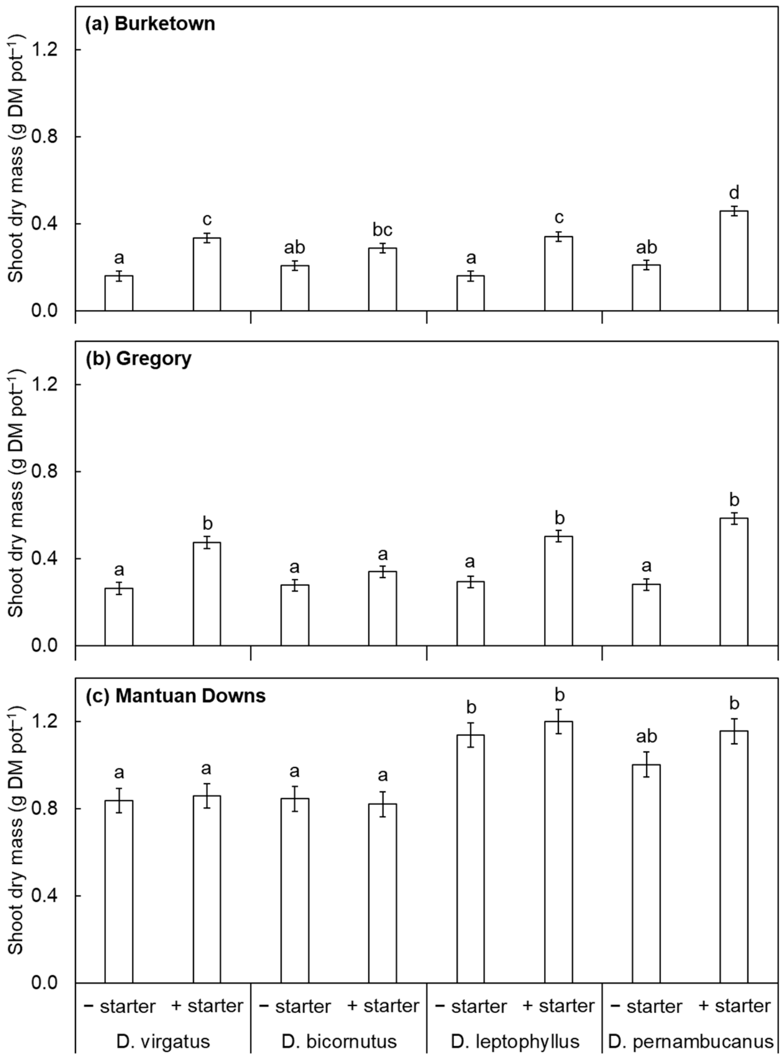

Figure 1. Shoot dry mass of four *Desmanthus* species grown in response to +/− starter fertiliser (12 kg P ha^{-1} equivalent) in three soils: Burketown (**a**), Gregory (**b**), and Mantuan Downs (**c**). Values show the mean ± standard error (n = 4). The main effect of soil was significant ($p < 0.001$), with Mantuan Downs > Gregory > Burketown. Different letters denote significant differences at $p = 0.05$ within each panel (i.e., soil).

Shoot P concentrations were influenced by the soil in which the plants were grown ($p < 0.001$), with the highest concentrations achieved in the Mantuan Downs and Gregory soils. Similar to shoot yield, there was no effect of gypsum on shoot P concentrations, so the results are summarised in Figure 2 according to the *Desmanthus* species and starter fertiliser application (although the results were also summarised according to *Desmanthus* species and gypsum application, available in the Supplementary Material Figure S2). On average, the addition of the starter fertiliser increased the shoot P concentrations of the *Desmanthus* species in each of the soils. In general, the shoot P concentrations of *Desmanthus* species *D. leptophyllus* and *D. pernambucanus* were lower than those of species *D. virgatus* and *D. bicornutus*. This was clearly seen in the Mantuan Downs soil, where species *D. leptophyllus* and *D. pernambucanus* also produced higher shoot yields. This result indicates that these species may achieve higher shoot yields through the more efficient use of acquired P. This is consistent with the findings of McLachlan, Guppy, and Flavel [13], who reported that *D. pernambucanus* cv. JCU 9 was highly productive compared to the other *Desmanthus* varieties because it had efficiently used the acquired P even when grown in soil that had been amended with high rates of P fertiliser.

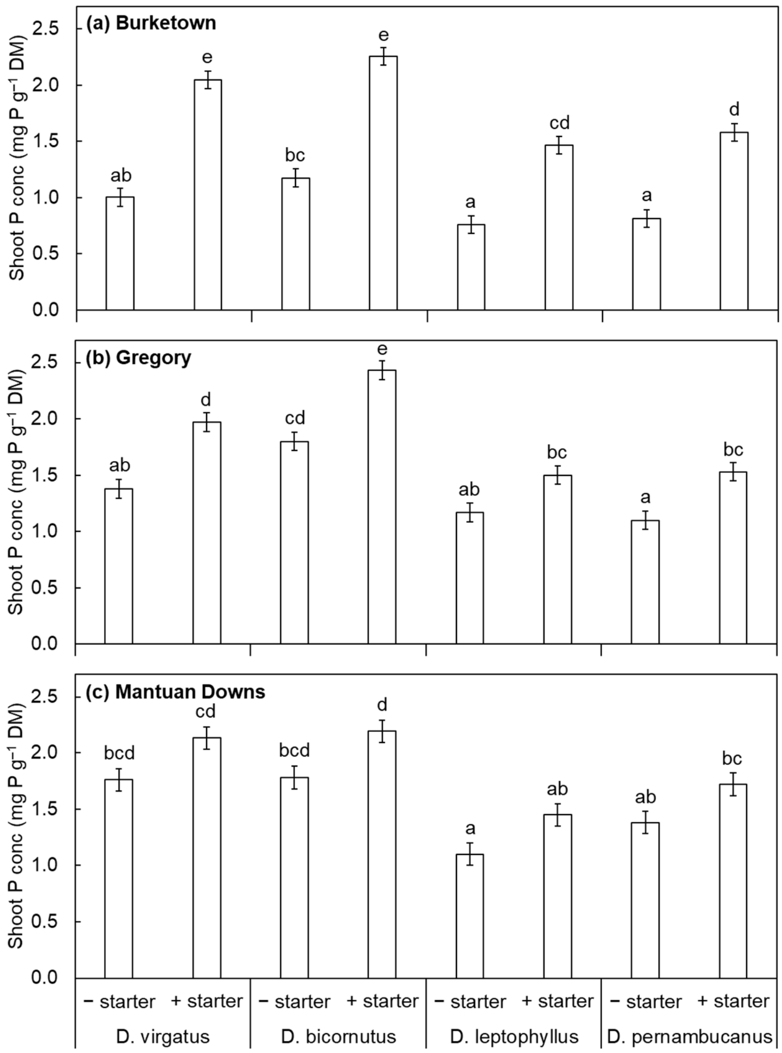

Figure 2. Shoot phosphorus concentrations of four *Desmanthus* species grown in response to +/− starter fertiliser (12 kg P ha^{-1} equivalent) in three soils: Burketown (**a**), Gregory (**b**), and Mantuan Downs (**c**). Values show the mean ± standard error (n = 4). The main effect of soil was significant ($p < 0.001$), with Mantuan Downs = Gregory > Burketown. Different letters denote significant differences at p = 0.05 within each panel (i.e., soil).

Shoot P content reflected differences in shoot yields and shoot P concentrations, with the largest shoot P content achieved when the *Desmanthus* species were grown in the Mantuan Downs soil, followed by the Gregory soil and then the Burketown soil. Because of this, the results are again summarised in Figure 3 according to the *Desmanthus* species and starter fertiliser application (although the results were also summarised according to *Desmanthus* species and gypsum application, available in the Supplementary Material Figure S3). The application of the starter fertiliser had a positive effect on the shoot P content of the *Desmanthus* species in each of the soils. This indicates that although a starter fertiliser may not always increase the shoot yield, it is likely to increase the legume diet quality for grazing livestock. This response to the starter fertiliser by legumes would be valuable in the extensive grazing systems of Northern Australia, because these grazing systems are currently dominated by C_4 grasses, which quickly lose quality when not grazed heavily, whereas legumes are likely to maintain feed quality for longer. Nevertheless, the benefit of the starter fertiliser on shoot P content was greater in the less fertile Burketown (3.7-fold) and Gregory (2.2-fold) soils compared to the Mantuan Downs soil (1.3-fold).

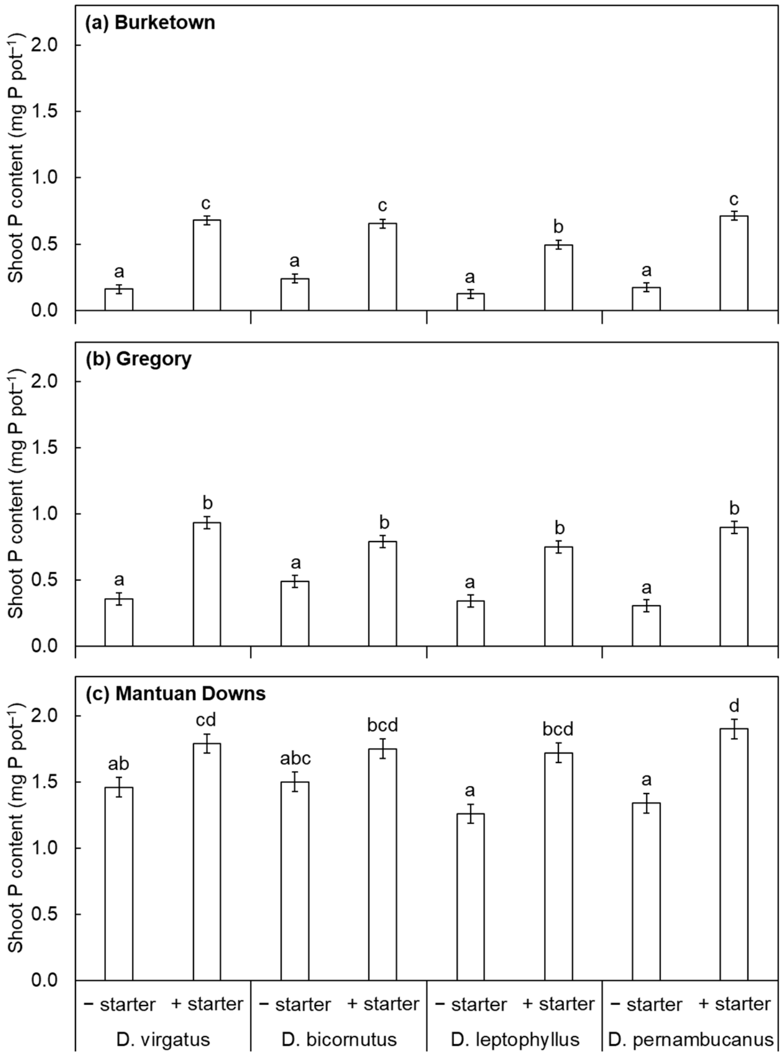

Figure 3. Shoot phosphorus content of four *Desmanthus* species grown in response to +/− starter fertiliser (12 kg P ha^{-1} equivalent) in three soils: Burketown (**a**), Gregory (**b**), and Mantuan Downs (**c**). Values show the mean ± standard error (n = 4). The main effect of soil was significant ($p < 0.001$), with Mantuan Downs > Gregory > Burketown. Different letters denote significant differences at $p = 0.05$ within each panel (i.e., soil).

The collective results indicate that a starter fertiliser will provide a benefit for legume productivity in the soils of Northern Australia once seedlings have emerged. Although the application of gypsum was generally beneficial, the lower levels of emergence when most of the *Desmanthus* species were grown without gypsum could be offset by increasing the sowing rates, as the cost of seed is lower than that of gypsum. Alternatively, species such as *D. virgatus* could be used, which have relatively high emergence regardless of gypsum application. These options may be considered more feasible than gypsum as the potential to apply large rates of gypsum in extensive grazing systems is likely to be constrained by the quantity required. A starter fertiliser could therefore be prioritised, particularly when soil testing indicates that the Colwell P levels are below the critical levels for optimal plant growth. Nevertheless, care must be taken when using a starter fertiliser as it is likely to benefit the grass component and even weeds, particularly in soils that have a moderate native Colwell P level. Further research could therefore investigate the potential for P fertiliser application to optimise legume productivity in these systems.

4. Conclusions

There were differences in emergence and early growth among the four *Desmanthus* species. These differences may be informative when selecting cultivars to be sown in hostile soils, such as the medium to heavy, alkaline clay soils of Northern Australia. In general, the *Desmanthus* species responded to the two amendments positively. Gypsum had a positive impact on seedling emergence; however, the use of this amendment is likely to be limited in the extensive grazing systems of Northern Australia. The starter fertiliser had a positive impact on shoot yields after seedlings had emerged, and it has greater potential for adoption in Northern Australia than gypsum, particularly when new pastures are being established in low-P soil. Further experimentation is required to determine the longer-term benefit of these amendments, and how the starter fertiliser can be applied to achieve the greatest benefit for the legume component. Nevertheless, our work shows that consideration should be given to both species selection and soil amelioration when establishing *Desmanthus* species in alkaline clay soils.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy13122996/s1, Figure S1. Shoot dry mass of four *Desmanthus* species grown in response to +/− gypsum (1 t $CaSO_4.2H_2O$ ha^{-1} equivalent) in three soils: Burketown (a), Gregory (b), and Mantuan Downs (c). Values show the mean ± standard error (n = 4). The main effect of soil was significant ($p < 0.001$), with Mantuan Downs > Gregory > Burketown. Different letters denote significant differences at $p = 0.05$ within each panel (i.e., soil). Figure S2. Shoot phosphorus concentration of four *Desmanthus* species grown in response to +/− gypsum (1 t $CaSO_4.2H_2O$ ha^{-1} equivalent) in three soils: Burketown (a), Gregory (b), and Mantuan Downs (c). Values show the mean ± standard error (n = 4). The main effect of soil was significant ($p < 0.001$), with Mantuan Downs = Gregory > Burketown. Different letters denote significant differences at $p = 0.05$ within each panel (i.e., soil). Figure S3. Shoot phosphorus content of four *Desmanthus* species grown in response to +/− gypsum (1 t $CaSO_4.2H_2O$ ha^{-1} equivalent) in three soils: Burketown (a), Gregory (b), and Mantuan Downs (c). Values show the mean ± standard error (n = 4). The main effect of soil was significant ($p < 0.001$), with Mantuan Downs > Gregory > Burketown. Different letters denote significant differences at $p = 0.05$ within each panel (i.e., soil).

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Data Availability Statement: The data presented in this study are available on request from the corresponding author.

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Conflicts of Interest: The authors declare no conflict of interest.

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