Final report

Livestock Productivity Partnership – Increasing livestock production by integrating tropical pastures into farming systems

Project code: P.PSH.1029

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NSW Department of Primary Industries

Date published: 7 December 2022

PUBLISHED BY
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NORTH SYDNEY NSW 2059

This is an MLA Donor Company funded project.

Meat & Livestock Australia acknowledges the matching funds provided by the Australian Government to support the research and development detailed in this publication.

Abstract

The projected climate change for southern Australia is predicted to shorten the growing season of temperate species with likely increases to the summer-autumn feed gap. Tropical perennial grasses are summer growing, drought tolerant, and offer the potential to contribute to summer and autumn forage in both current and future climate scenarios. This multidisciplinary project used a combination of modelling, field studies and social research to (i) investigate the potential of tropical pastures in Southeast (SE) Australia, and (ii) improve tropical pasture productivity and sustainability in northern NSW by better understanding the dynamics of tropical grass-legumes mixes and strategies for more effective pasture utilisation.

The project demonstrated tropical perennial pastures have potential benefits in SE Australia both under current and projected climates. Species evaluation confirmed that they can persist in environments previously considered marginal. Modelling indicated tropical pastures can increase profitability of current temperate-based grazing systems in most locations tested, although the result was variable, especially where lucerne is productively grown. Some keys to successful establishment were quantified and producer enablers and constraints to trialling these pastures were identified. The opportunity and management of temperate annual, lucerne, desmanthus and leucaena as companion legumes in tropical grass pastures were refined. Tropical pastures were also successfully ensiled.

Our project has shown the potential of tropical pastures in SE Australia (and specifically NSW). We have provided much needed evidence for red meat producers that these grasses can be part of a practical solution to provide green feed for livestock during summer-autumn in current and projected climates. Maintaining a productive persistent legume can reduce N input costs, increase the quality and quantity of pasture grown and therefore livestock production.

1. Executive summary

Background

Climate modelling has projected increased temperatures and reduced winter-spring rainfall in southern Australia by 2050. Under these environmental conditions, grazing systems based on temperate species are predicted to have a shortened growing season, prolonging the summer-autumn feed gap. Tropical perennial grasses are summer growing, drought tolerant, responsive to summer rainfall, and offer the potential to contribute to summer and autumn forage in both current and future climate scenarios.

Tropical perennial pastures have become an important component of the feedbase in northern NSW due to targeted RD&E over the last ~15 years. This project (*a*) investigated the potential for tropical pastures in central and southern NSW and (*b*) addressed issues associated with compatible legumes and forage conservation in northern NSW.

Objectives

The project had five objectives.

1. *Define the area suitable for tropical grass species and the fit in the farming system under current and future climate scenarios*. Achieved
   Modelling was used to identify the areas suitable for tropical perennial pasture species in current and future climates. These results were field tested by assessing tropical species at eight locations across NSW. Modelling was also used to investigate the effect of replacing temperate pastures with tropical species in grazing systems. Under conditions with increasing temperatures and more variable rainfall, the role of tropical pastures is likely to increase.
2. *Determine the requirements for successful establishment*. Achieved.
   Modelling was used to test the likelihood of establishment success under different management scenarios at 5 locations across NSW. Studies were also conducted to determine the 'sowing window' for eight tropical pastures. In Central West NSW studies were conducted to quantify sowing time on establishment and seeding survival and the role of cover to protect the soil surface and emerging seedlings.
3. *Develop regionally relevant agronomy packages (e.g., weed control and maintaining high feed quality)*. Achieved.
   Experiments resulted in new knowledge to support producers grow and utilise tropical pastures. For example, herbicides have been identified that are suitable for use to control broadleaf weeds in desmanthus (*Desmanthus* spp.) pastures. Tropical perennial grasses were successfully ensiled.
4. *Enhance companion legumes and refine their management*. Achieved.
   Studies quantified competition between tropical grasses and tropical legumes in mixes during establishment. Field studies investigated methods to incorporate temperate and tropical legumes into sown tropical and native pastures and determine the herbage and water productivity of mixed and pure swards of tropical species. Hardseed breakdown patterns were determined for 18 legumes. Grazing studies investigated pasture production, nutritive value and animal production.
5. *Determine the whole-farm and system benefits from introducing these species*. Achieved.
   Modelling indicated that incorporating tropical pastures increased profitability in most locations studied. Profitability declined and gross margin variability increased with a

warming and drying climate (most sites). Social research defined the benefits and challenges of tropical pastures identified by producers.

Methodology

This multidisciplinary project involved over 35 experiments/activities located across NSW. Methodology included:

- Modelling – CLIMEX (species distribution modelling); Ausfarm (farming systems modelling, establishment)
- Replicated field experiments to address specific agronomic questions with sites located from Glen Innes in northern NSW, to Trangie, Condobolin and Goolgowi in western NSW and Wagga Wagga in southern NSW.
- Social research – workshops and surveys with producers (‘experienced’ and ‘inexperienced’ with regards to establishing and managing tropical pastures) and their advisors to identify the benefits and challenges to establishing and managing tropical pastures and constraints to adoption/better utilisation of these pastures.

Results/key findings

- Potential distribution of tropical perennial grasses accounting for climate, soil type and land use is larger than that currently sown and will generally increase with projected climate scenarios in SE Australia.
- Modelling indicated tropical perennial grass pastures could provide feed during the late summer-early autumn period when the traditional temperate-based pastures are inactive. Incorporating tropical pastures increased profitability in most locations but this was less likely to occur in areas with milder conditions where lucerne (*Medicago sativa*) was productive. Profitability declined and gross margin variability increased in recent years, suggesting that while incorporating a tropical pasture can improve profitability, further adaptations will be required if climate trends continue.
- Under conditions with increasing temperatures and more variable rainfall, the role of tropical pastures is likely to increase.
- Tropical grasses that performed well at sites in central and southern NSW after 3–4 years were digit grass (*Digitaria eriantha*) cv. Premier and Makarikari grass (*Panicum coloratum* var. *makarikariense*; Bambatsi panic) cv. Bambatsi. Other grasses that performed well at some sites were Rhodes grass (*Chloris gayana*), kikuyu (*Cenchrus clandestinus* syn. *Pennisetum clandestinum*) and panic grass (*Megathyrsus maximus* var. *maximus*).
- Recommended minimum temperatures for sowing tropical species have been determined. Minimum spring temperatures for sowing range from 17°C (Rhodes grass) to 22°C (paspalum; *Paspalum dilatatum*).
- In central west NSW, seedling emergence was highest in spring and autumn. Plant survival (9–14 months after sowing) was highest for grasses sown in spring with high stored soil moisture levels. The effect of high soil moisture was still evident 18 months after spring sowing.
- Enablers and constraints to trialling tropical perennial grasses have been identified. This information is important for development of an effective extension program to achieve adoption.
- Tropical perennial grasses can be successfully ensiled, and commercially available bacterial inoculants assist fermentation and silage quality.

- Leucaena (*Leucaena leucocephala* ssp. *glabrata*) is persistent in northern NSW. An additional benefit of this legume is that it can maintain green leaf during drought. Good establishment is essential for plant productivity.
- Application for a minor use permit will be submitted to APVMP for use of a range of herbicides to control weeds in desmanthus pastures. This permit will be for Queensland and NSW.

Benefits to industry

Our research has shown that tropical pastures have potential in SE Australia (and specifically NSW), providing a practical solution for producers to maintain green feed during summer-autumn in current and projected climates. Maintaining a productive persistent companion legume can reduce input costs also increase pasture growth and quality, and therefore livestock production. The reported antimethanogenic properties of desmanthus and leucaena is an additional benefit for red meat producers.

Future research and recommendations

Based on our findings and industry feedback, the following areas of future research, development and extension (RD&E) have been identified:

1. *Increasing livestock production by integrating tropical pastures into farming systems II*. There is increasing interest in tropical pastures in central and southern NSW. A phase II of our current project would be a collaborative RD&E program. It would capitalised on the momentum we have gained in this project to support producers successfully adopt this new suite of species. This project would be largely D&E with a small research component to address priority issues identified by producers. This project would simultaneously upskill advisors, support producers, and address current and emerging issues.
2. *Sequestering carbon and reducing methane emissions with tropical legumes at southern latitudes*. Red meat producers are looking for species which offer multiple benefits for their production systems; pastures that maintain or improve animal performance, reduce methane emissions, and maximise long-term carbon (C) sequestration in a highly variable and changing climate. This project will quantify these characteristics for new and existing tropical legumes and grasses suited or potentially suited to the frost-prone summer dominant rainfall zone of northern NSW and Southern Queensland. Additionally, the project will conduct component research to address gaps in our knowledge (e.g., nitrogen fixation potential of tropical grass-legume mixes), and extension to support producers trialling and adopting tropical pasture mixes in their grazing systems. This project links with other projects in the MLA CN30 program.

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2. Background

Increasing climate variability and changing weather patterns are real issues facing the red meat industry, because of the negative impact they will have on feed availability and livestock production without adaptations. Climate change predictions vary with the scenario and models used, but in general they indicate that in southern Australia (e.g., CSIRO and BoM 2015, 2018; Cullen et al. 2009). Modelling has indicated that despite higher growth rates of temperate species due to increased CO_2, seasonal growing windows will shorten substantially (Cullen et al. 2009; Moore and Ghahramani 2013). Impacts to grazing industries include less herbage production, increased potential of erosion over summer (due to low ground cover) and an increase in the summer-autumn feedgap resulting in a reduction in the sustainable stocking rate and profitability (Cullen et al. 2009; Moore and Ghahramani 2013). In many grazing systems currently used in southern Australia, this gap is filled by carry-over forage from temperate species, lucerne, specialist pastures and forages (e.g., chicory and forage brassicas), native pastures, crop residues and/or supplementation. These forages are unlikely to be able to cover the extended feedgap anticipated under future climate scenarios. Without adaptation the operating profits of red meat producers in southern Australia is predicted to be reduced by 32% on average by 2050 (Moore and Ghahramani 2013).

Tropical pastures have gained interest from red meat producers in northern parts of southern Australia with over 450,000 ha of tropical perennial grasses sown in northern NSW over the last 15 years. These pastures have traditionally been the predominant forage source for cattle in northern Australia, but a range of species have been found to be widely adapted and are productive and persistent in northern inland NSW (e.g., McCormick et al. 1998; Boschma et al. 2009, 2014, 2017); a frost prone region once considered marginal for this suite of species. As grazing systems in southern Australia are largely based on winter growing species, it is expected that tropical species could be integrated into farming systems, particularly under future climate scenarios. Large areas of southern Australia were previously dominated by C4 perennials (e.g., kangaroo grass) prior to European settlement (Groves 1965). Furthermore, previous evaluations at locations such as Cowra, Scone and Condobolin demonstrated the potential of tropical grasses in more southern environments (Cameron 1959; Bryant 1966; Green 1978). A specific farming system that requires investigation for southern Australia is the integration of tropical grasses with hard seeded annual legumes such as biserrula (*Biserrula pelecinus*), bladder clover (*Trifolium spumosum*), gland clover (*T. glanduliferum*) and serradella (*Ornithopus* spp.), which could potentially provide year-round feed and a sustainable source of nitrogen to maintain production and quality of a tropical grass pasture. The integration of tropical grasses into farming systems using approaches like this requires investigation to quantify their potential benefits to whole-farm profit.

While there is potential for tropical species in southern Australia, these are a new suite of species and there are many management issues to understand and overcome. For example, risk of establishment of tropical species was identified as a major limitation to their widespread uptake in the Mallee regions of SA and Victoria (Smith and Llewellyn 2015) and while some producers have successfully established tropical grass pastures in central NSW, the appropriate management strategy requires systematic investigation to improve reliability. It has been demonstrated that tropical pastures can produce double the summer-autumn herbage mass compared to summer active native pastures (Murphy et al. 2010), but management to utilise the pasture and maintain high feed quality has been an issue. There are many other agronomy questions to answer including, fertilisation strategies for different climate and soil types, and management of weeds.

Both the nutritional value, in particular digestible energy of tropical grass pastures can be a major constraint to achieving high growth rates of grazing livestock. In northern Australia and northern NSW, these pastures often lack a productive and persistent legume component, and in addition, often receive little or no nitrogen fertiliser. To maintain productivity, tropical grass pastures need 50-100 kg N/ha/yr (Harris et al. 2014a; Boschma et al. 2014, 2016). Legumes are recognised as a sustainable, cost effective and significant driver for pasture production, and the subsequent red meat production and farm profitability that follows. Greater use of improved pasture systems, especially through establishment of pasture legumes into both native and sown grass pastures, represents the most widely applicable and cost-effective means of improving red meat enterprise productivity and profitability.

Research in northern inland NSW has identified three legume groups that have potential as companion legumes in tropical grass pastures: tropical legumes, temperate perennial lucerne, and hard seeded temperate annual legumes. Compatible legumes also warrant testing in southern environments. Each of these legume groups offer both opportunities and challenges as companion legumes in a tropical grass pasture including: time of year that the pasture accumulates and uses soil water; time of year that forage is available; sowing time and ease of establishment; and grazing management for reliable regeneration of annual and short lived perennial species.

There is little doubt that tropical grasses will provide multiple advantages for livestock producers throughout south-eastern Australia, should management issues overcome local adaptation barriers. The C4 photosynthesis pathway provides the mechanism for improved heat tolerance along with greater water-use and nitrogen-use efficiency (Long 1999). The summer-active growth pattern enables the tropical grasses to respond to episodic rain and utilise soil water that can be lost over summer, improving production efficiencies and reducing soil degradation attributable to excess water, such as soil salinisation and acidification. The experience in northern NSW that has seen significant areas sown to tropical grass pasture over the last 15 years is a model of the landscape-scale transformation that could be emulated in southern eastern Australia for the mutual benefit of livestock industries and the agricultural environment.

3. Objectives

3.1 Contracted objectives

The project objectives, using design led thinking methodology were:

1. Define the area suitable for tropical grass species and the fit in the farming system under current and future climate scenarios
2. Determine the requirements for successful establishment
3. Develop regionally relevant agronomy packages (e.g., weed control and maintaining high feed quality)
4. Enhance companion legumes and refine their management
5. Determine the whole-farm and system benefits from introducing these species.

A series of outcomes were developed for each objective. The activities conducted and success associated with each outcome are summarised in Table 1. Details of each component are provided in this report with full details provided in appendices. The appendix related to each activity is also provided in Table 1.

Table 1. Contracted outcomes of P.PSH.1029, success achieving them and appendix which outlines the component studies addressing the outcome.

Outcomes	Activity	Appendix
1. Defining the boundaries of tropical species	**Achieved**	
a. The potential distribution and monthly growth patterns of six key tropical pasture species (Rhodes grass (*Chloris gayana*), digit grass (*Digitaria eriantha*), panic grass (*Megathursus maximus*), kikuyu (*Cenchrus clandestinus* syn. *Pennisteum clandestinum*), *Brachiaria* spp. and *Setaria* spp.) will be estimated for current and future climate scenarios using the CLIMEX modelling software. Spatial distribution results will be further refined using soil type and land use factors which will influence the potential distribution.	Maps and areas of potential distribution determined for kikuyu, Rhodes grass, digit grass, panic grass, Makarikari grass (*Panicum maximum*) and desmanthus (*D. virgatus*) for each state/territory in Australia in baseline (1981–2010), future climate centred on 2030 (2016–2045) and 2050 (2035–2065). Growth patterns of a tropical grass pasture (compared to temperate pastures) were modelled using AusFarm in far (1960-1990) and near past (1990-2020) climate at 5 locations in NSW. Growth patterns the summer and winter growing species have changed in recent decades and give an indication of the likely changes to occur in the projected future climate (increasing temperature and decreasing cool season rainfall)	1 and 2
b. Determine the area of different pasture types needed in a farming system to produce consistent feed over a range of seasonal conditions under current and future climate scenarios using the AusFarm model.	AusFarm was used to model three pasture comparisons at 5 locations in NSW to determine effect of replacing a temperate pasture with a tropical pasture. The modelling was conducted using historic data divided into far (1960-1990) and near past (1990-2020) climate. These data showed the effectiveness and variability of temperate and tropical grass pastures to increasing temperatures and decreasing and variable rainfall. The potential to increase/maintain gross margins with tropical pastures were: 1. Tamworth – the highest gross margins occurred when ≥75% of paddocks were sown to tropical grasses. 2. Cowra and Wagga Wagga – there was benefit in replacing annual pastures with 25-50% or 75% tropical pastures at Cowra and Wagga respectively, but little difference by replacing lucerne. 3. Condobolin and Leeton – including a winter component with the tropical pasture was important. Replacing pure lucerne with a tropical grass-clover pasture improved gross margin. We used a reference site approach to determine the potential impact of future climate using the data from the existing sites. For example, the Cowra site in 2050 (under the RCP 4.5 emissions scenario) would be represented by the Tamworth results. This approach highlighted the continuing trend in declining profitability and increasing value of tropical grasses mixes with a productive winter annual species in the production system.	2
c. Assess the capacity of farming systems with and without tropical pastures to cope with stress associated with the increasing frequency of extreme events (heat and moisture stress) predicted with future climate scenarios.		
d. Field test the suitability of tropical species for different soil types and climatic zones in southern Australia, with locations based on modelling outcomes.	A range of tropical and temperate species were sown at 8 locations across NSW. Production and persistence were assessed. Sites were chosen based on modelling and ranged from Glen Innes and Guyra in northern NSW to Yanco and Wagga in southern NSW. Tropical grasses outperformed temperate grasses in warmer/drier environments (e.g., Condobolin, Goolgowi, Yanco). In cooler/wetter environments (e.g., Orange and Yanco), several tropical species were persistent and productive, but they were outperformed by the temperate species.	3
2. Understanding successful establishment of tropical species	**Achieved**	

a. Quantify the soil moisture and temperature requirements for successful germination, establishment and persistence of tropical grasses	Ausfarm was used to model the likelihood of establishment success under different management scenarios at 5 locations across NSW. Establishment opportunities were reduced in more southern latitudes but improving ground cover will generally assist establishment and establishment windows were longer in southern NSW. Establishment success was increased on soils with higher water holding capacity in southern NSW.	4
b. Determine appropriate management practices that will deliver successful establishment and persistence for different soil types and climatic zones	Three studies were conducted: 1. A sowing time study conducted at 5 locations determined the 'sowing window' for 8 tropical pastures. Minimum temperatures for sowing each species were identified. 2. Central west NSW, 6 tropical grasses were sown in 3 seasons (spring, summer, autumn) and seedling survival monitored to determine the optimum time to sow. Establishment was highest in spring and autumn. A high level of stored soil moisture was important for seedling survival, especially in spring and summer. 3. Different levels of cover provided by forage oat on establishment of a tropical grass were investigated at Trangie. Above average rainfall resulted in good establishment in all treatments indicating that cover is not important in years with adequate rainfall.	 5 6 7
3. Developing regionally relevant agronomy packages	**Achieved**	
a. Develop recommendations for managing key weeds in tropical pastures.	Experiments were conducted to determine the effect of herbicides on desmanthus pastures: (i) pre-emergent (ii) seedling and (iii) established (>12-month old). These findings plus other data/publications will be used for an application to APVMA for a minor use permit to control broadleaf weeds in desmanthus pastures in NSW and Queensland	8
b. Determine the optimum grazing and forage conservation strategy to maximise animal production, without impacting on the persistence of tropical grass-based pastures.	Two studies showed that tropical perennial grasses can be successfully ensiled if they are well managed. For successful fermentation the pasture must be vegetative/early stem elongation and a rapid wilt essential. Applying an inoculant improved fermentation	9
c. Determine fertiliser management for tropical grass or grass-legume pastures across different soil and climatic zones	Production and persistence and soil nitrogen (N) and carbon (C) levels of digit grass fertilised with different rates of nitrogen were monitored over a 10-year period. We are still waiting for soil analysis results to compete this study.	10
Tropical pasture water use and production in Central West NSW (added with DLT)	Herbage and water productivity of 3 tropical perennial grasses, annual forage sorghum and lucerne were compared at Trangie. The perennial grasses (i) can grow for ~7 months of the year, longer than the annual forage, (ii) are productive and (iii) high WUE compared with lucerne when they have adequate nutrition. Productivity declines significantly without adequate nutrition.	11
4. Enhancing legume options for tropical pastures	**Achieved**	
a. Establishing legumes into new and existed pastures	A replacement series experiment was conducted to test the competitiveness of *Desmanthus* and *Stylosanthes* species/cultivars in mixes with a range of tropical perennial grasses during the establishment phase. All of the grasses tested were competitive	12

	against the tropical legumes, desmanthus to a slightly lesser extent than stylo. Soil water accumulation treatments were imposed in bands in sown tropical perennial and native pastures in the Tamworth district. A range of temperate and tropical legumes were sown into the strips and establishment monitored. The treatments were effective at accumulating soil water although the effect they had on ground cover varied which affected emergence. Timing of the treatments also affected the competitive effect of the perennial pasture on the establishing legumes. We successfully established temperate legumes (autumn sowing), but not tropical legumes (spring sowing). A subsequent study as conducted the refine timings and reduce competition of the perennial pasture with greater success establishing desmanthus	 13
b. Quantify seed bank dynamics (size, seed softening) and recruitment of temperate annual and tropical perennial legumes	Hardseed breakdown patterns were determined for 10 temperate and 8 tropical legumes. Legumes ranged from desmanthus and barrel medic which had high initial levels of hardseed and a slow breakdown pattern, to siratro and fine stem stylo with high initial level and rapid breakdown.	14
c. Determine grazing management tactics to ensure regeneration of desmanthus in a tropical grass pasture	Desmanthus failed to persist into the second year of the grazing experiment (unrelated to the treatments imposed) so the experiment was adjusted in the second year to determine the effect of N fertility and grazing system on the production, persistence, nutritive value of digit grass during the growing season. Animal production was also monitored. Although we were unable to achieve the planned objective, there were multiple other leanings about desmanthus persistence, digit grass productivity, and animal production that this was still a worthwhile study.	15
d. Quantify soil water dynamics of tropical grass-tropical legume mixes to understand the impacts on pasture growth and companion legume dynamics	We compared the herbage and water productivity of desmanthus, leucaena and lucerne in pure and mixed swards with digit grass. The lucerne-digit grass mix was equally as productive and water use efficient as fertilised digit grass, although lucerne dominated productivity. Leucaena generally underperformed compared to both lucerne and desmanthus.	16
e. Assess temperate legume-tropical grass systems for southern NSW.	Seven temperate legumes were summer sown in mixes with 2-3 tropical grasses at 3 sites in central and southern NSW. Two of the studies failed and ceased, but there were multiple learnings including establishing grass first and tropical grasses do not persist when smothered for extended periods.	17
f. Continue to evaluate leucaena lines for southern Australia	Leucaena cultivars were established in 3 locations in 2013 and productivity and persistence monitored. Leucaena has shown high persistence (once established) and a sustainable production potential over variable rainfall conditions year to year.	18
Quantify the ratio of digit grass and lucerne in a mixed pastures that provides optimal dry matter production and efficient use of soil water	Digit grass and lucerne were sown in a replacement series style experiment in the field. During hot/dry climatic conditions mixes with ≤50% lucerne were the most productive, while during mild/wet conditions, mixes with ≥50% lucerne were more productive. Over the 4 years of the study, mixes with 50% lucerne had the most consistent annual herbage production and the highest overall water productivity. Nitrogen fixation was assessed during one season. This study found that lucerne in lucerne-digit grass mixes fixed a similar amount of	19 and 20

	N from the atmosphere as lucerne grown in a pure sward. There were also indications of N transfer from the legume to the grass suggesting mixtures can be productive without the addition of fertiliser N when lucerne was >25% of the mix.	
5. Whole-farm economics and systems analyses (including barriers, risks and perception)	**Achieved**	
a. Post-experimental modelling will be used to refine management of farming systems including tropical grasses	Farms modelled in 5 locations outlined in Outcome 1b and c above were used to determine gross margins for the different pasture systems in far and near past climate. Incorporating tropical pastures increased profitability in most locations although the result was variable in areas with milder conditions where lucerne was productive (e.g., Cowra). Profitability declined and gross margin variability increased from far to near climate, suggesting that while incorporating a tropical pasture can improve profitability, further adaptations will be required if climate trends continue.	2
b. Whole-farm economics used to determine the most appropriate farming systems based on pre- and post-experimental modelling		
c. Understanding of the barriers to adoption of tropical pasture species	Workshops, a surveys and semi-formal interviews were used to determine the benefits and challenges of tropical pastures identified by producers who were experienced and inexperienced with establishing and managing tropical perennial grasses. Priority areas of research were identified and suggestions for means/strategies to engage with producers/advisors provided.	21
6. Communication and adoption using design led thinking methodology	**Achieved**	
a. Extending previous tropical grass information to continue uptake of previous research	• 110 extension activities engaging with >5700 people, predominantly red meat producers and their advisors. • YouTube clip of producer relating his first experience trialling tropical perennial grasses (https://www.youtube.com/watch?v=jdViPDqW-uw) • 2 scientific publications in refereed journals • 5 conference papers	–
b. Extending project results and information in relevant regions		
c. Monitoring and evaluation with producers, researchers and development staff to determine the impacts and benefits of the research		

4. Methodology

4.1 Modelling the potential distribution of tropical species in current and future climates

This study aimed to identify the potential suitability of a range of tropical pastures species to Southeast (SE) Australia, and how projected climate scenarios may influence this suitability in the future. For the purpose of this study SE Australia is defined as New South Wales (NSW), Australian Capital Territory (ACT), Victoria and Tasmania.

This study combined the (1) potential climatic suitability with (2) soil pH_{CaCl2} and (3) land use suitability (Lawson *et al.* 2004) for six tropical pasture species: kikuyu (*Cenchrus clandestinus*), Rhodes grass (*Chloris gayana*), digit grass (*Digitaria eriantha*), panic grass (*Megathursus maximus*), Makarikari grass (*Panicum coloratum* var. *makarikariense*) and desmanthus (*Desmanthus virgatus*). Distributions were modelled using climate data for 1981–2010 (baseline) also future climate for periods 2016–2045 (2030) and 2035–2065 (2050).

4.1.1 CLIMEX

Firstly, for each species a climate model was developed using the CLIMEX software version 4.0.2 (Hearne Scientific Software Pty Ltd) (Kriticos *et al.* 2015). CLIMEX is a species distribution model that uses species specific parameters to define their potential geographical distribution in relation to climate. A series of temperature and moisture parameters describe the species growth response. Outside these settings growth does not occur, and negative growth accumulates. These are described by stress indices and their interactions. Together these growth and stress parameters determine the geographical distribution. The parameters to model the distribution of each species are presented in Table 2.

Table 2. CLIMEX model parameter values for each species.

Index	CLIMEX parameter	Kikuyu[1]	Rhodes grass[2]	Digit grass	Panic[3]	Makarikari grass	Desmanthus
Temperature	DV0 (°C, lower threshold)	8	8	8	10	10	10
	DV1 (°C, lower optimum temperature)	14	19	16	19	16	22
	DV2 (°C, upper optimum temperature)	25	35	35	35	32	37
	DV3 (°C, upper threshold)	32	40	40	40	38	40
Moisture	SM0 (lower soil moisture threshold)	0.1	0.1	0.1	0.1	0.1	0.1
	SM1 (lower optimum soil moisture)	0.4	0.35	0.3	0.35	0.35	0.19
	SM2 (upper optimum soil moisture)	2.5	2.5	2.5	2.5	2.5	2.5
	SM3 (upper soil moisture threshold	10	7	5	7	10	7
Heat stress[4]	TTHS (°C, temperature threshold)	35	45	45	42	40	43
	THHS (stress accumulation rate)	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005
Cold stress[4]	TTCS (°C, temperature threshold)	0	2	2	3	2	3.4
	THCS (stress accumulation rate)	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01
Dry stress[4]	SMDS (threshold soil moisture)	0.02	0.01	0.02	0.02	0.02	0.02
	HDS (stress accumulation rate)	-0.0003	-0.0003	-0.0003	-0.0003	-0.0003	-0.0003
Hot-Wet stress[4]	TTHW (°C, temperature threshold)	30	37	37	37	37	35
	MTHW (soil moisture threshold)	0.8	0.8	0.8	0.8	0.8	0.8
	PHW (stress accumulation rate)	0.075	0.075	0.075	0.075	0.075	0.075

[1] Kikuyu is a highly diverse species (Morris 2009). Parameters were based on cv. Whittet.

[2] Parameters were based on diploid type Rhodes grass cultivars.

[3] Parameters were based on the short type (Cook et al. 2020), primarily cv. Gatton.

[4] Each stress consists of a threshold value and an accumulation rate.

4.1.2 Climatic data, soil pH and land use

A climatic data set from 1981–2010 (Kriticos *et al.* 2012), was used to model the baseline climate. CliMond climate data were also used for future climate projections for 2030 (2016–2045) and 2050 (2035–2065). The future projections were generated using the A1B and A2 emission scenarios for future global emissions of greenhouse gases and sulphate aerosols (SRES scenarios) and two Global Climate Models (GCMs): CSIRO-MK 3.0 and MIROC-H (Kriticos *et al.* 2012). The A1B emission scenario used represents a middle range scenario while the A2 scenario represent a high emissions scenario (Harris *et al.* 2014b). The CSIRO-MK 3.0 and MIROC-H models project temperature increases by the end of this century of 2.11 and 4.31°C respectively (Kriticos *et al.* 2012). Annual average rainfall is projected to decrease 14% under the CSIRO-MK 3.0 model and 1% under the MIROC-H model (Chiew *et al.* 2009). The four future climate scenarios are herein referred to as MIROC-H A1B, MIROC-H A2, CSIRO-MK 3.0 A1B and CSIRO-MK 3.0 A2.

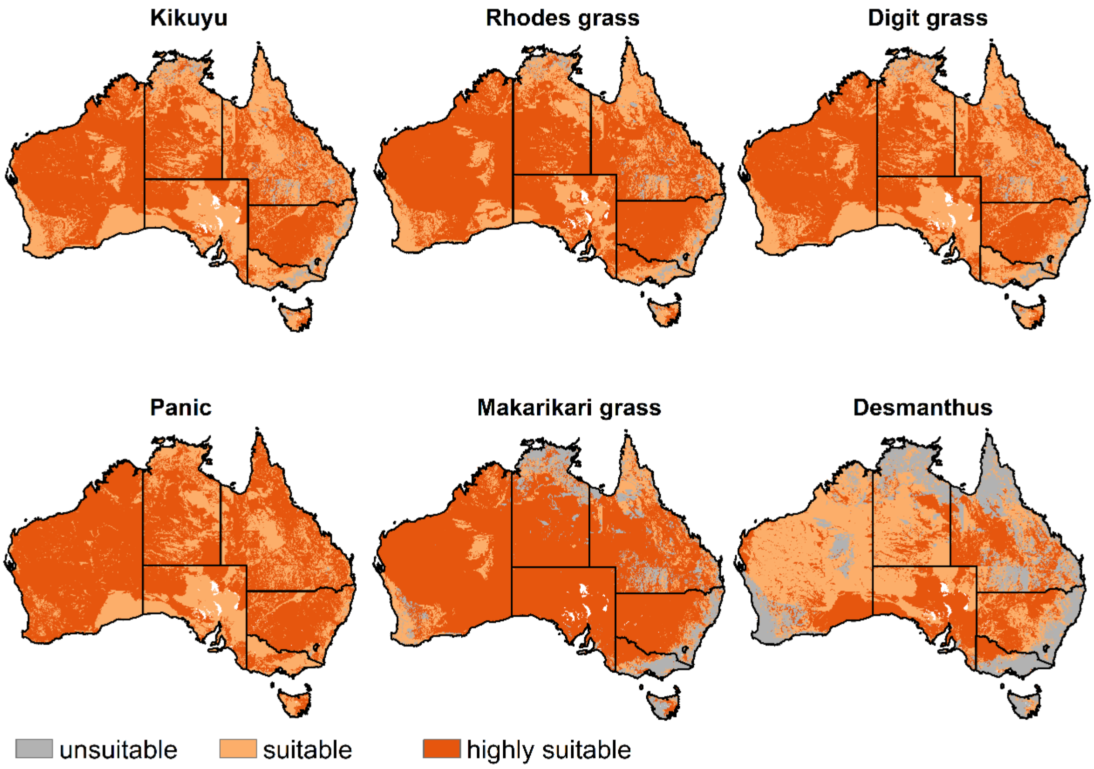
In the second step we developed soil pH_{CaCl2} suitabilities using reported sensitivities and tolerances (Table 3). Based on soil pH_{CaCl2} 0–30 cm (ASRIS 2001), the majority of Australia was suitable for the species in our study (Fig. 1). Thirdly, forestry and nature conservation land use were delineated as unsuitable (Fig. 2).

Areas modelled climatically or with a soil pH_{CaCl2} as unsuitable and occupied by forestry/nature conservation remained unsuitable in the combined model. Climate and soil pH_{CaCl2} had an equal influence as we considered both factors to be equally important. The three outputs were merged on a common scale and assigned the categories of highly suitable, suitable, marginal and unsuitable to produce a potential distribution based on climate, soil pH and land use across Australia. Each layer was resampled to a resolution of 0.1 degree. The area of all categories for the climate only and combined models was calculated to estimate the potential distribution for Australia.

Table 3. Soil pH ($CaCl_2$) ranges for suitability categories for each species.

Species	Unsuitable	Suitable	Highly suitable
Kikuyu[1]	<4.5, >8.0	4.5–<5.5, >7.0–8.0	5.5–7.0
Rhodes grass	<4.5, >9.0	4.5–<5.5, >7.5–9.0	5.5–7.5
Digit grass	<4.4, >8.5	4.5–<5.5, >7.0–8.5	5.5–7.0
Panic	<3.5, >8.4	3.5–<5.0, >7.0–8.4	5.0–7.0
Makarikari grass	<5.0, >8.0	5.0–<5.5	5.5–8.0
Desmanthus	<5.5, >9.0	5.5–<6.5, >8.0–9.0	6.5–8.0

[1] The common acceptable soil pH range for cv. Whittet was used. This had a higher minimum soil pH range than observed in WA (P. Sanford, pers. comm.)


Kikuyu

Rhodes grass

Digit grass

Panic

Makarikari grass

Desmanthus

Fig. 1. Map of soil $\mathrm{pH_{CaCl2}}$ suitability based on ranges provided in Table 2 for kikuyu, Rhodes grass, digit grass, panic, Makarikari grass and desmanthus.

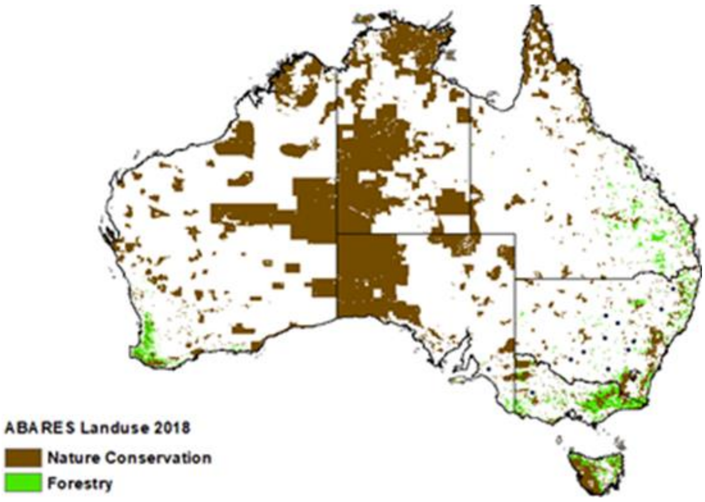


Fig. 2. Map of areas of nature Conservation and Forestry land use across Australia delineated from the ABARES land use dataset (ABARES 2022).

The climate and combined climate-soil pH-land use models were validated against herbarium records, experimental field sites and other data such as publications and technical expert knowledge. Herbarium records for the period 1981–2010 were intersected with the four suitability categories and are presented in Table 4. The total number of herbarium records for each species was variable, ranging from 21 for desmanthus to 3779 for kikuyu. Based on herbarium records, the climate models were generally a good fit. The number of herbarium records in areas modelled as climatically unsuitable ranged from <1% (kikuyu) to 22% (Rhodes grass). The climate suitability model was a better fit for the herbarium records than the combined climate-soil pH-land use model. This is likely due to plants often collected and sent to the herbarium when they are growing in an uncommon location which would include forested or conservation areas. The proportion of herbarium records collected from areas considered unsuitable by the combined model ranged from 13% for kikuyu to 46% for digit grass.

Table 4. Occurrence of Australian herbarium records for each species for the period 1981–2010 intersected with the four suitability categories for the climate and combined climate-soil pH-land use model (Combined).

Species	Model	Unsuitable	Marginal	Suitable	Highly suitable
Kikuyu	Climate	22	27	106	3556
	Combined	497	278	1902	1034
Rhodes grass	Climate	313	19	40	1023
	Combined	448	65	302	580
Digit grass	Climate	11	0	4	49
	Combined	30	1	18	15
Panic	Climate	37	40	66	467
	Combined	96	26	161	327
Makarikari grass	Climate	22	26	53	70
	Combined	29	22	60	60
Desmanthus	Climate	2	0	0	19
	Combined	7	2	3	9

4.2 The potential fit of tropical perennial grasses in farming systems in southern NSW

4.2.1 Sites and climate data

Five sites in NSW were selected for the study; Tamworth, Cowra, Condobolin, Wagga Wagga and Leeton (Table 5). Historical weather data were generated from the Silo Patched Point Data base Datadrill (Jeffery et al. 2001), while soil characteristics were obtained from the ApSoil database (Dalgliesh et al. 2012).

For each site the historical weather data were split into two thirty-year groupings: Far Climate from June 1960 to May 1990, Near Climate from June 1990 to May 2020. (Note that the start and end months were selected to fit in with the livestock production system described below). Mean monthly rainfall, and maximum and minimum temperatures were determined for each site for both groupings. The Far Climate grouping was selected as the base climate data for the project.

Table 5. Site location, latitude and longitude, weather data source and soil type for sites used for modelling.

Location	Latitude (decimal degrees)	Longitude (decimal degrees)	Weather data source	Soil type
Tamworth	-31.0867	150.8467	Tamworth Airport, Station 55054	Loam over clay (Apsoil: Narrabri No. 615-Y)*
Cowra	-33.8087	148.7071	Cowra Research Centre (Evans St), Station 63023	Sandy loam over a sandy clay and heavy clay (ApSoil: Greenethorpe No. 691)
Condobolin	-33.0664	147.2283	Condobolin Ag Research Station, Station 50052	Sandy loam over sandy to light clay (ApSoil: Condobolin No. 690)
Wagga Wagga	-35.1583	147.4575	Wagga Wagga AMO, Station 72150	Red Chromosol (ApSoil: Coolamon No. 175)
Leeton	-34.6222	146.4326	Yanco Agricultural Institute, Station 74037	Red Chromosol (ApSoil: Coolamon No. 175)

*Adjusted based on Murphy et al. (2017).

4.2.2 Model description

CSIRO’s AusFarm™ model (version No 1.5.3) (Moore et al. 2007) was used to model the potential of a tropical perennial grass at the five locations across NSW. The model was run from 1 January 1955 to 26 May 2021, with results collected for the Far Climate (June 1960 to May 1990) and Near Climate (June 1990 to May 2020).

The model farm was setup with four 100 ha pasture paddocks. Pasture composition for the permanent pastures consisted of a combination of lucerne, annual ryegrass, subterranean clover, and/or a generic tropical perennial grass. Three comparisons were undertaken to explore which pasture composition can provide the highest benefit from the introduction of a tropical pasture (Table 6). For each comparison five levels of tropical based pasture inclusion were analysed (0%, 25%, 50%, 75% and 100%).

Table 6. Pasture compositions used for the comparative analysis to assess farming system performance.

Comparison	Existing temperate base pasture	Tropical species replacement pasture
LRC v TRC	lucerne/annual grass/subterranean clover (LRC)	tropical grass/annual grass/subterranean clover (TRC)
L v TC	lucerne (L)	tropical grass/subterranean clover (TC)
RC v TC	annual grass/subterranean clover (RC)	tropical grass/subterranean clover (TC)

The livestock production system was a terminal lamb system based on medium Merino ewes (60 kg standard reference body weight) joined to Border Leicester rams to sell lambs at a target liveweight of 55 kg. Key periods in the production system are shown in Fig. 3. Ewes were joined in April and lambed in September to align with maximum spring pasture growth. Lambs were weaned in December and sold to a target liveweight of 55 kg, or by the beginning of May. Cast for age (CFA) ewes older than 6 years were sold after weaning in early January, with new ewes bought in February, in preparation for the next joining in April.

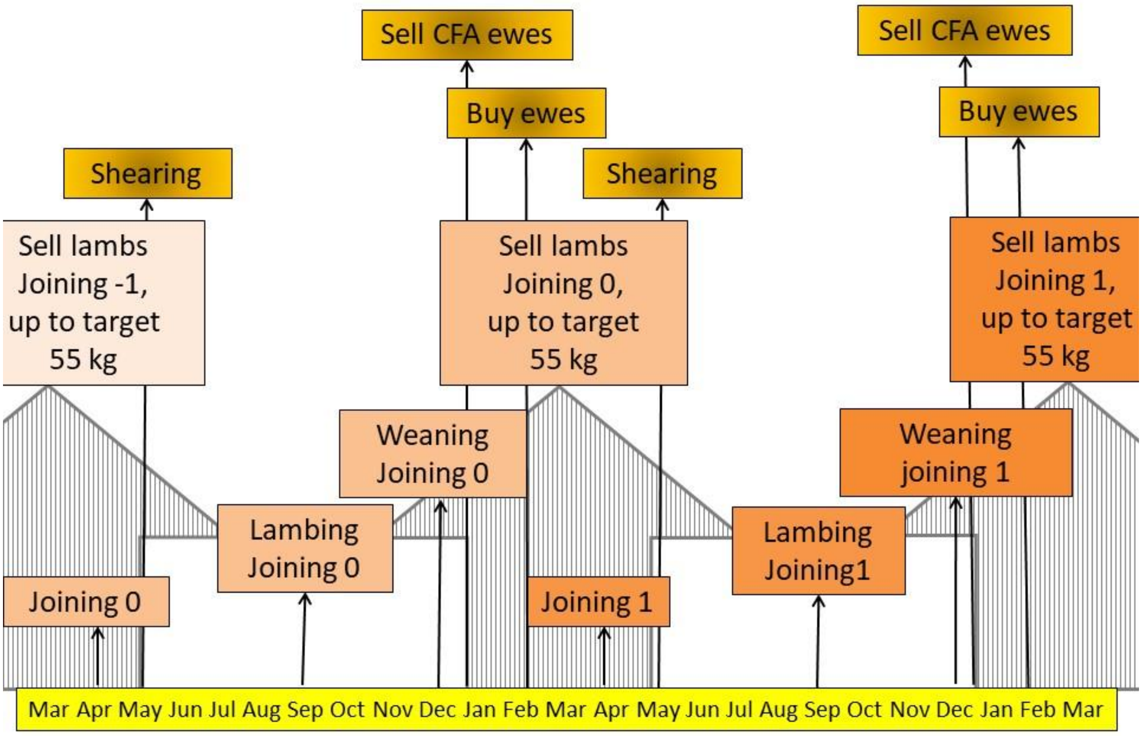


Fig. 3. Timeline of livestock activities for successive joining. Ewes were joined in April, lambing commenced in September. Lambs were weaned in December. Lambs that had not reached 55 kg liveweight were sold by May. Cast for age ewes were sold in January, with replacement ewes bought in February. Shearing occurred in May.

Triggers for the movement of stock between paddocks were determined by ranking paddocks with the best green feed available, and the production stage of the livestock. Barley was used as supplementary feed. In this study the livestock production year ran from 1 June to 31 May. This coincided with the final sale of lambs, and all results are based on this time frame.

Each pasture used AusFarm derived parameter sets; lucerne was a semi winter dormant variety (obtained from the parameter file *pasture-307.prm*), subterranean clover was cv. Seaton Park (default pasture parameter set compiled in *PASTURE.DLL*), annual grass was annual ryegrass (default pasture parameter set compiled in *PASTURE.DLL*), and the tropical perennial grass was *Megathyrsus maximus* (syn. *Panicum* maximum) cv. Gatton (obtained from parameter file *eta_pastures_tpp.prm*). While the AusFarm pasture parameters for lucerne, subterranean clover and annual ryegrass are well established, the parameter set for the tropical grass (based on the data from Descheemaker et al. 2014) did not produce growth rates comparable to experimental data for Tamworth (Boschma unpublished, Fig. 2). After consultation with Neville Herrmann (CSIRO Canberra), the Monteith water uptake (kl) sub-model in the parameter set was modified. The revised values improved growth rate over the original parameters, but it was still well below that recorded in experimental data (Fig. 4). Because of the modification of the Monteith water uptake sub-model for the tropical grass, lucerne, the other perennial species in the pasture mix had to be modified to obtain growth rates recorded prior to the tropical grass adjustment.

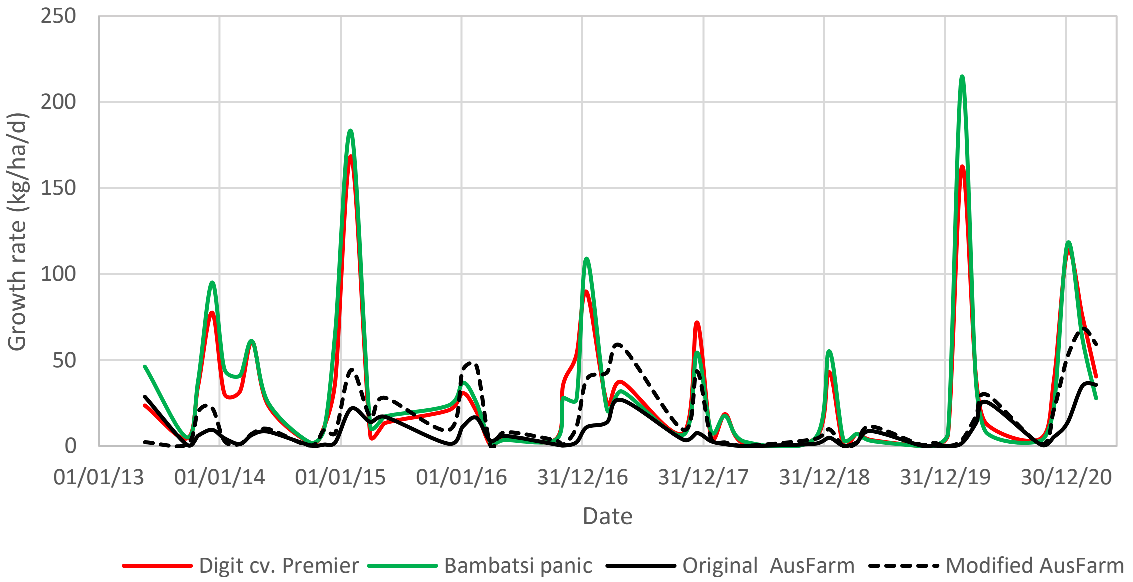


Fig. 4. Mean daily growth rates for digit grass cv. Premier, Bambasti panic, the original AusFarm modelled Gatton panic, and modified AusFarm modelled tropical grass at Tamworth.

The fertility scalars in AusFarm for the pasture species were set at 1.0 (non-limiting). The exception was the annual grass/subterranean clover pasture (RC, Table 6) which was set at 0.7 to represent a poor annual pasture.

An important factor in pasture utilisation is feed quality. Changing the pasture growth parameters reduced available dry matter digestibility (%DMD), with the original tropical grass AusFarm parameters having an average available %DMD of 56.2 compared to modified parameters at 53.8 for Tamworth. Comparing AusFarm with data from an experiment conducted at Tamworth (Boschma et al., unpublished), AusFarm greatly underestimated %DMD (data not shown).

While the modifications to the AusFarm parameters for a tropical grass have improved growth rates, they do not approach maximum growth rates or digestibility recorded in experiments. The development of parameter sets for tropical grasses is beyond the scope of this project, and so it must be emphasised that the parameters chosen for the tropical perennial grass are a compromise and both pasture and livestock productivity will be underestimated in the TC and TRC comparisons (Table 6).

The gross margin calculator within AusFarm was used to record and value expense or income events that occur during a year. The cost allocations were developed using NSW DPI gross margin budgets for Merino ewes (20 micron) – Terminal rams (NSW Department of Primary Industries 2020). A full listing of prices used in the model is provided in Supplementary information Table 1.

An annual pasture maintenance cost of $38/ha was used for all pastures except the annual grass/subterranean clover pasture (RC) which was unfertilised. This cost was determined by application of 90 kg/ha of single superphosphate at $350/t plus an application cost of $6.50/ha. As the RC pastures were low fertility, this resulted in a pasture maintenance cost for the RC v TC comparison (Table 2) that increased with increasing tropical grass (i.e $0/ha for RC100TC00, $9.50/ha for RC75TC25, $19/ha for RC50TC50, $28.80/ha for RC25TC75, and $38/ha for RC00TC100). All gross margins were recorded on a per hectare basis.

Determining optimal stocking rate is difficult when modelling as sheep stocking rate influences farm profit significantly (Young et al. 2022). The stocking rate (number of ewes per hectare) was determined for the Far climate scenario, as this was the base climate for this project. Amongst the temperate based pastures modelled, the LRC pastures were the most productive therefore requiring the highest stocking rates. The NSW DPI gross margin included supplementary feeding at ~$117/ha (costed at $320/t and representing 10 weeks supplementary feeding ewes and 12 weeks supplementary feeding lambs), so the model was run for each pasture at each of the 5 sites adjusting the ewe stocking rates to reach ~$117/ha supplementary feeding. This ewe stocking rate was set for all subsequent model runs at each site (Table 7).

Within each 30 year climate grouping (i.e., Near and Far climate), means for each parameter were calculated. Standard errors were also determined.

Table 7. Site and stocking rate (ewes/ha)

Site	Stocking rate (ewes/ha)
Tamworth	2.80
Cowra	3.35
Condobolin	2.05
Wagga Wagga	3.10
Leeton	1.90

4.3 Confirming potential production and persistence of tropical species in southern NSW

The CLIMEX and Ausfarm modelling showed that tropical species have potential in areas south of where they are currently grown. To test the modelling results, a range of temperate and tropical pasture species were sown at 8 contrasting sites across NSW representing areas identified as potentially suitable in our species distribution modelling, but commonly considered marginal or unsuitable for these species (Table 8).

4.3.1 Species selection and site management

Ten tropical grasses and two cultivars of the tropical legume desmanthus (*Desmanthus* spp.) were sown at each site. Several temperate species commonly grown in the area were also sown for comparison (Table 9). All experiments in the study were arranged in spatially adjusted randomised complete block designs with partial neighbour balance with three replicates.

A composite soil sample (0–0.1 m) was taken at each site prior to sowing and analysed for pH (1:5 soil/0.01 M $CaCl_2$), EC1:5 soil/water extraction, P (Colwell), sulphur (KCL_{40}), exchangeable cations, total nitrogen, electrical conductivity (Rayment and Lyons 2011) and organic carbon (Walkley and Black 1934) (Table 10). Lime was applied at approximately 3 t/ha and incorporated prior to sowing at some sites. Rainfall and temperature were recorded at each site or at a nearby weather station.

Five sites were sown in 2018: Condobolin, Cowra, Yanco (November), Glen Innes and Orange (December). Subsequent sites were sown at Goolgowi (October 2019), Guyra (November 2020) and Wagga Wagga (October 2020) (Table 8). All experiments were sown with a cone seeder with ~0.18 m row spacings into plots which were ~2 x 8 m. Starter fertiliser (100 kg/ha; 14%N, 12%P, 10%S) was applied at sowing.

Table 8. location, long-term average annual rainfall (LTAA) soil classification and sowing dates for field evaluation sites

NSW Region	Location	Coordinates	LTAA (mm)	Soil Classification[#]	Tropical species sow date	Temperate species sow date
Central West Plains	Condobolin	S33°39.786’ E147°15.625’	461.8	Red Chromosol	2-Nov-18	7-May-19
Central Slopes	Cowra	S33°48.372’ E148°42.625’	624.5	Red Chromosol	19-Nov-18	13-May-20*
Northern Tablelands	Glen Innes	S29°41.430’ E151°41.598’	841.5	Brown Chromosol	19-Dec-18	17-May-19
Western Riverina	Goolgowi	S33°59.464’ E145°51.397’	380.0	Red Chromosol	30-Oct-19	22-May-19
Northern Tablelands	Guyra	S30°18.262’ E151°54.042’	875.4	Grey/yellow chromosol	10-Nov-20	-$
Central Tablelands	Orange	S33°19.565’ E149°4.818’	919.6	Brown Ferrosol	6-Dec-18	3-Apr-19
Central Riverina	Yanco	S34°38.074’ E148°25.579’	426.9	Red/Brown Chromosol	7-Nov-18	15-May-19*
Eastern Riverina	Wagga Wagga	S33°39.786’ E147°15.625’	504.0	Kandosol	10-Oct-20$	-$

[#] Australian Soil Classification (Isbell 1996)
* Sowing attempt in May 2019 failed
$ No temperate species sown at this site

Due to dry conditions, irrigation was applied over 3-4 months at Condobolin, Cowra, Orange and Yanco to assist establishment. The temperate species were sown at each site the following autumn. Due to the dry conditions, the temperate grasses at the Cowra and Yanco sites failed. The grasses were resown at Cowra in autumn 2020 while the Yano site continued with tropical species only. At the Goolgowi site, temperate species were sown in May 2019 and the tropical species in October 2019.

Table 9. Tropical and temperate species sown at field evaluation sites. Cultivars included at each site are indicated by an enclosed circle (●)

Common name	Botanical name	Cultivar /line	Condobolin	Cowra	Glen Innes	Goolgowi	Guyra	Orange	Yanco	Wagga Wagga
			Tropical grasses							
Bahia grass	*Paspalum notatum*	Pensacola	●	●	●	●		●	●	●
Digit grass	*Digitaria eriantha*	Premier	●	●	●	●	●	●	●	●
Kikuyu	*Cenchrus clandestinus*	Whittet	●	●	●	●	●	●	●	●
Makarikari grass	*Panicum coloratum* var. *makarikariense*	Bambatsi	●	●	●	●	●	●	●	●
Panic grass	*Megathyrsus maximus* var. *maximus*	Megamax 059	●	●	●	●	●	●	●	●
		Gatton	●	●	●	●	●	●	●	●
Paspalum	*Paspalum dilatatum*		●	●	●	●	●	●	●	●
Rhodes grass	*Chloris gayana*	Reclaimer	●	●	●	●		●	●	●
		Katambora	●	●	●	●	●	●	●	●
		Callide	●	●	●	●	●	●	●	●
			Tropical Legumes							
Desmanthus	*Desmanthus virgatus*	JCU Blend	●	●	●	●		●	●	●
		Marc	●	●	●	●		●	●	●
			Temperate grasses							
Cocksfoot	*Dactylis glomerata*	Currie		●				●		●
		Kasbah	●			●			●	
		Porto						●		
Phalaris	*Phalaris aquatica*	Holdfast		●	●			●		●
		Horizon				●			●	
Tall fescue	*Festuca arundinacea*	Hummer		●	●					
		Temora		●						
Veldt Grass	*Ehrhata calycina*	Mission				●				
			Temperate legumes							
Lucerne	*Medicago sativa*	SARDI Grazer	●	●	●	●			●	
		Pegasus						●		
		Aurora								●
Tedera	*Bituminaria bituminosa*	Lanza	●						●	

Table 10. Soil test results describing the average pH (in $CaCl_2$), available phosphorus (Colwell P), total nitrogen (N), effective cation exchange capacity (ECEC), organic carbon and electrical conductivity (EC) in the 0–0.1 m depth of soil at each of the experimental sites before sowing.

Site	pH_{Ca}	Colwell P (mg/kg)	Total N (mg/kg)	ECEC (cmol(+)/kg)	Organic carbon (%)	EC (dS/m)
Condobolin	5.0	27	11	10.00	1.1	16.0
Cowra	5.0	33	18	4.26	1.1	0.06
Glen Innes	5.0	38	11	9.30	1.59	0.04
Goolgowi	5.4	26	9	8.6	0.88	0.05
Guyra	4.2	33	47	2.50	1.34	0.11
Orange	5.5	35	29	6.2	1.8	0.12
Wagga Wagga	6.2	70	30	8.65	1.08	0.60
Yanco	5	69	9	7.4	1.2	0.06

In the years after establishment, all grass plots received urea (100 kg/ha; 46%N) in a split application, generally in November and February and timed to coincide with a rainfall event. All plots also received a single application of single superphosphate (150 kg/ha; 9%P, 11%S) in spring. The exception was the Goolgowi site which received no follow-up fertiliser post-sowing.

4.3.2 Data collection

Establishment plant counts were conducted 4–6 weeks and 6–8 weeks for tropical and temperate species respectively after emergence. The number of plants along a 0.5 m length of row in two adjacent sowing rows in two locations within three strata in each plot (total 6 counts/plot) were recorded. The data were converted to plants/m^2 based on row spacing.

Plant persistence was measured through assessments of basal frequency in autumn of each year at each site (Brown 1954). Fixed quadrats (1.0 x 1.0 m) divided into 100 cells (each 0.1 x 0.1 m) were located centrally in each plot. The number of cells which contained a live plant base were recorded. For species that spread by stolons (e.g., Rhodes grass), nodes which were anchored by roots were also included as a plant base in the cell count. Change in frequency was calculated by subtracting the final frequency assessed in autumn 2022 from the initial frequency assessed in year 1. A persistent cultivar was considered to have a positive or stable change in frequency over time.

Herbage dry matter (DM) production was assessed (Lodge and Harden 2011) every 4–12 weeks. After each herbage production assessment the experiment was mown to 5-10 cm and plant material removed.

Herbage samples were collected for forage mineral content at each herbage mass assessment at three sites: Condobolin, Cowra and Orange. Grab samples of each species were collected and dried at 60°C for 48 hrs. Ground samples were analysed by Department Primary Industries AgEnviro laboratory, Wollongbar, NSW to determine N, P, S, copper, zinc, manganese, potassium (K), sodium (Na), magnesium (Mg), calcium (Ca), boron, iron and nitrate contents, through closed vessel microwave nitric acid and hydrogen peroxide digestion (SPAC 1998) and processed using ICP-OES (Agilent 5110, ICP_OES). Chloride was extracted in 1:125 water solution using the ferricyanide method (SPAC 1998) on a flow injection analyser (QuikChem 8000, Lachat). Mineral indices were calculated:

1. K:(Na+Mg) ratio was calculated from the percentage of mineral in the dry matter using the formula (K/0.039)/[(Na/0.023)+(Mg/0.012)] (Dove *et al.* 2016).
2. Ca:P ratio was calculated from the percentage of each mineral in the diet.

3. Tetany index was calculated as (K/0.039)/[(Mg/0.012)+(Ca/0.02)] (Kemp and 't Hart 1957), and
4. Dietary cation anion difference (DCAD; meq/100 g) was calculated using the formula (Na/0.023 + K/0.039)-(Cl/0.0355 +S/0.016) (Takagi and Block 1991).

4.3.3 Statistical analysis

Data were analysed using Genstat 20th Edition (VSN international, Hemel Hampstead, UK). An analysis of variance (ANOVA) was conducted for each site. For plant establishment data, 'cultivar' was set as a fixed term and replicate the random term in the model. Least significant differences (l.s.d) were calculated (P = 0.05).

Change in frequency % data were square root transformed then analysed by ANOVA as above. The relationship between plant frequency and pasture herbage production at each site were examined using x-y plots using predicted means of averages of all assessments of each attribute for each cultivar derived from ANOVA at each site (Sanford *et al.* 2005).

Data for each forage mineral component was analysed across sites using ANOVA. As above, 'cultivar' was the fixed term and replicate the random term in the model.

4.4 Modelling emergence of tropical grasses in NSW

This study evaluated emergence of tropical pasture at five locations across NSW. Our hypotheses were:

1. Emergence rates would generally be higher in northern NSW, decreasing further south as the proportion of summer rainfall decreased.
2. Management practices which increase ground cover and controlled winter weeds would increase soil moisture and provide more emergence opportunities.

To determine the influence of increasing climate change on pasture establishment of tropical grasses historic climate data were assessed over the far (1957/58 to 1987/88) and near past (1989/90 to 2019/20). Preliminary data from this study were published in 2022 (Broadfoot et al. 2022).

4.4.1 Farming System Description

CSIRO's AusFarm™ model (version No 1.4.13) (Moore *et al.* 2007) was used to model the emergence of a tropical pasture at five locations across NSW: Tamworth, Condobolin, Cowra, Leeton and Wagga Wagga. The base model represented a 1000 ha, 8-paddock mixed farming system. Each farm consisted of four paddocks of permanent pasture and four in a crop-pasture rotation (canola, wheat, 2 years tropical pasture). A generic tropical pasture based on *M. maximus* (panic grass) was used for this analysis (Moore et al. 2007). Soil characteristics for each location were obtained from the APSoil database (Dalgliesh et al. 2012):

1. Tamworth – APSoil No.615-YP adjusted based on findings from Murphy *et al.* (2017),
2. Condobolin APSoil No.690,
3. Cowra – APSoil No.691, and
4. Leeton and Wagga Wagga – APSoil No.175.

Weather data for each location were generated from Datadrill (Jeffery et al. 2001). AusFarm was run for a period of 71 years (1 February 1950 to 1 June 2020) and two time periods selected for comparison of establishment: 1957/58 to 1987/88 and 1989/90 to 2019/20.

A series of thresholds were developed in consultation with industry experts and coded into AusFarm to restrict the emergence of the tropical grass. These thresholds 'triggered' emergence if, between the period 10 September and 25 March, the extractable soil water in the top layer (0–15 cm) was >75% (S. Murphy, pers. comm.) and the minimum air temperature over the past 7 days and 'today' exceeded 10°C. Emergence success was assumed to be when these conditions were met and for the first event the growth rate of the tropical pasture was above 1 kg/ha for more than 5 days (For subsequent events tropical grasses were already present).

4.4.2 Analysis of different management techniques

To examine the influence of different management techniques on tropical grass emergence four comparisons were undertaken:

1. Baseline management. This was maintenance of a clean fallow from the end of the cropping phase of the rotation (~9 months) prior to sowing the tropical pasture.
2. Weed incursion. This analysis examined the impact of winter weeds. A 'weed' was introduced into the fallow after the cropping phase of the rotation and allowed to grow until 10 September. At this time the weeds were removed by herbicide and the tropical pasture sown. The aim was to see if emergence of the tropical pasture was reduced due to weed competition for soil moisture.
3. Ground cover. Ground cover can improve surface soil moisture (Glendening 1942; Ward 1993). Since ground cover was unable to be incorporated into AusFarm the emergence threshold for extractable soil water was adjusted to 68%. This was based on findings of Glendening (1942) and Ward (1993).
4. Soil type comparison. An additional comparison was undertaken to examine the influence of different soil characteristics on tropical grass emergence at Leeton. At this location, a brown Chromosol (APSoil: Euroley Bridge No.174) with a higher water holding capacity was compared with the red Chromosol (i.e., APSoil No.175) using the baseline farming system.

Emergence of tropical grasses often occurs over multiple events, due to incomplete germination during the first event when conditions are marginal. The number of emergence events that occurred per year was examined to understand the opportunity for multiple establishment events. Using the baseline scenario with both far and near time periods, the number of emergence events per year, the days per year where emergence was possible and the average emergence length were determined.

4.5 Quantifying seedling emergence response of tropical perennial pasture species to temperature

4.5.1 Treatment details

The experiment was conducted every month over a 12-month period from August 2019 at five sites in NSW: Tamworth, Trangie, Orange, Cowra and Wagga Wagga. Four core species were sown at all sites with additional species sown at Trangie and Tamworth (Table 11). Seedling trays (330 x 280 x

50 mm deep) were filled with a brown Chromosol soil (Isbell 1996) sourced from a single location at the Trangie Agricultural Research Institute, Trangie NSW. The filled trays were wet up and 100 seeds of each species sown at 10 mm depth from the rim of the tray, in 1 or 2 rows per species. Each tray represented a replicate, except at Trangie and Tamworth where additional species necessitated using two trays per replicate.

Table 11. Tropical species sown at each site

Species and cultivar	Trangie	Orange	Cowra	Wagga	Tamworth
Rhodes grass (*Chloris gayana*) cv. Katambora	X	X	X	X	X
Digit grass (*Digitaria eriantha*) cv. Premier	X	X	X	X	X
Panic (*Megathyrsus maximus*[1] cv. Gatton	X	X	X	X	X
Bambatsi panic (*Panicum coloratum* var. *makarikariense* L.) cv. Bambatsi	X	X	X	X	X
Paspalum (*Paspalum dilatatum*)	X				
Kikuyu (*Cenchrus clandestinum* Hochst. ex Chiov.)[2] cv. Whittet	X				
Urochloa[3] hybrid (*Urochloa decumbens* x *U. ruziziensis* x *U. brizantha*) cv. Mulato II					X
Desmanthus (*Desmanthus virgatus*) cv. Marc					X
Desmanthus (*D. virgatus*) cv. JCU2					X
Desmanthus (*D. bicornutus*) cv. JCU4					X
Desmanthus (*D. leptophyllus*) cv. JCU7					X
Desmanthus (*D. pernambucanus*) cv. JCU9					X
Total number of entries	*6*	*4*	*4*	*4*	*10*

[1] Syn *Panicum maximum*

[2] Syn *Pennisetum clandestinum*

[3] Syn *Brachiaria*

In the field, trays were buried in the soil so that the tray rim was aligned with the soil surface to allow water movement over the trays without ponding if significant rainfall was received. The number of emerged seedlings were counted on day 3, 7, 10 and 14 after sowing. Micro-dataloggers (Thermochron iButon, Whitewater USA) were placed into each tray at 10 mm to monitor soil temperature at the sowing depth. The soil surface was kept moist for 14 days by applying 80% of the daily potential evapotranspiration recorded at the nearest Bureau of Meteorology site using an automatic watering system with micros-prays.

4.5.2 Data analyses

Air and soil temperature data. For each site we collated air temperatures from SILO (https://www.longpaddock.qld.gov.au/silo/) for the 14-day experimental period each month and the long-term monthly averages. Soil temperatures measured by micro-dataloggers were also collated for the 14-day experimental period each month.

Seedling emergence contour plots. The cumulative number of plants that emerged over the 14-day assessment period in each month from August to July were adjusted to a percentage of the maximum emergence achieved at any of the five sites in any month. For the additional species, emergence was shown as the percentage of the maximum emergence in any month at the site where sown (Tamworth or Trangie). These emergence percentages were plotted to produce annual emergence contour plots using the filled.contour function in the R graphics package (R core team 2020). Bivariate interpolation was used [interp function in R package akima (akima 2022)] to smooth the contour plots, with the jitter option used to account for collinear x and y points due to having three replicate emergence values for each sample day by month.

Emergence response to temperature. Day 10 data were used to model response to temperature as they represented the period emergence is commonly observed in the field. For each species at each site, total emergence on day 10 of each month was calculated as a percentage of the maximum emergence at any site. Average monthly emergence was plotted against average soil temperature (days 1–3) for each species with each plot divided into warming (August–January soil temperatures) and cooling soil temperatures (January–July), as peak soil temperatures were recorded in January. Combining all site data, provided a total of 30 and 35 data points in the warming and cooling temperature figures, respectively, for each core species. Curves and standard errors were fitted to the data for warming and cooling soil temperatures using the "lowess" command from the R package 'stats' (R core team 2020). The same procedures were used for the extra species sown at Trangie and Tamworth with data for the five desmanthus entries pooled, providing 30 and 35 data points for the warming and cooling curves respectively. To determine the 'emergence window' for each species, temperatures at which 50% of maximum emergence occurred in both warming and cooling soils were determined.

4.6 Tropical perennial grass seedling establishment and persistence

The objective of this study was to identify the most suitable season to sow tropical perennial grasses and the role of stored soil moisture for optimum seedling emergence and persistence of tropical grasses in the central west of NSW.

The experiment was conducted at the Trangie Agricultural Research Centre (31°59'45" S, 147°56'18" E, elevation 214 m above sea level) on a red Chromosol soil with pH 5.1 ($CaCl_2$). Treatments consisted of six grasses (Makarikari grass cv. Bambatsi; Rhodes grass cv. Katambora; digit grass cv. Premier; panic cv. Gatton, kikuyu cv. Whittet and common paspalum) sown at three times: spring (mid-October 2018), summer (mid-January 2019) and autumn (late-March 2019) under two contrasting stored soil moisture profile levels. The contrasting stored soil moisture treatments were 'high stored soil moisture' (HSSM) and 'low stored soil moisture' (LSSM). The HSSM treatment was achieved by irrigating the treatment plots in the weeks prior to sowing while the LSSM plots were not irrigated. Soil moisture levels at the time of sowing are shown in Table 12.

Table 12. Stored soil moisture levels (mm) at varying depths for the low (LSSM) and high stored soil moisture (HSSM) treatments at the three sowing times; spring, summer and autumn.

	Spring		Summer		Autumn	
Depth (cm)	LSSM	HSSM	LSSM	HSSM	LSSM	HSSM
0-20	41.2	51.5	21.2	42.8	16.9	44.7
20-80	126.5	176.1	124.2	172.0	119.7	169.4
80-150	150.5	207.0	157.4	204.1	157.1	203.4

The experimental design was a split-split plot design with soil moisture level as the whole (main) plot, sowing time as the sub-plot and grass species as sub-sub plots with three replications. At each sowing time, seed were sown at ~10 mm using cone seeder, sugar cane straw applied evenly to the plots (2000 kg/ha) to provide ground cover and irrigation (25 mm) applied to aid germination.

Daily rainfall and temperature were measured at a weather station located near the experimental site. Pasture establishment densities (plants/m^2) were estimated from plant counts recorded six weeks after emergence. Seedling survival was assessed by recording the presence/death of five tagged plants per plot every 3 months for a 12-month period from 6 weeks of age old. Herbage mass was assessed using BOTANAL (Tothill et al. 1992) in winter after all treatments had established (18 July 2019) and autumn the following year (25 March 2020) following good rainfall.

4.7 Impact of cover on tropical perennial grass establishment

The aim of this study was to investigate the effect of residual oat stubble of different quantities and management on the emergence of Bambatsi panic. Our hypothesis was that cover provided by cereal stubble and tillage can improve establishment when compared to bare fallow.

The experiment was conducted at the Trangie Agricultural Research Centre (31°59’45” S, 147°56’18” E, elevation 214 m above sea level) on a red Chromosol soil with pH 5.1 ($CaCl_2$) during 2021-22. There were six treatments with three replicate plots arranged in a split plot with tillage as the whole plot and ground cover as the sub-plot with three replicates. The tillage treatments were tilled (stubble incorporated) and not tilled. The ground cover levels were bare (nil oat stubble), grazed (~0.1 m) stubble and un-grazed (0.15-0.2 m) stubble.

The plots (7 x 2 m) were sown with forage oats cv. Eurabbie (80 kg/ha) on 31 March 2021 on 0.33 m row spacing. The bare ground treatment was sprayed with MCPA (570 g/L a.i. at 1.1 L/ha) two weeks after sowing to remove the oats. The oats were mown on 8 July to simulate grazing. The grazed treatment was mown again on 17 August then sprayed with MCPA to kill the forage oats leaving ~0.1 m stubble. The un-grazed treatment was sprayed on 9 September leaving a 0.15-0.2 m stubble. Bambatsi panic was hand sown (4 kg/ha bare seed) into farrows located between the oat rows on 27 October 2021. Irrigation was applied on 27 October and 29 October to initiate germination (total 30 mm).

Establishment plant counts were conducted on 2 December 2021 (5 weeks after sowing) and 16 February 2022. The number of seedlings were counted in eight 50 x 10 cm quadrats randomly placed over the middle two rows of each plot. Data were converted to seedlings/m^2 and analysed by ANOVA (Tillage, Graze and Tillage:Graze).

4.8 Water use and production of tropical and temperate species in Central West NSW

This study was initiated as part of our design led thinking practices following feedback and discussion with producers and agronomists. It investigated the herbage production, soil water dynamics and water use efficiency (WUE) of three tropical perennial grasses, lucerne and an annual summer forage over two growing seasons (2020-21 and 2021-22) in Central West NSW.

4.8.1 Study site

The experiment was conducted at the Trangie Agricultural Research Centre (31°59'40.53"S, 147°56'20.65"E, 215 m above sea level) on a is brown Chromosol soil (Isbell 1996) with soil pH 5.1 ($CaCl_2$) and 1% organic carbon (Boschma et al. 2018). Average annual rainfall in the area is 496 mm with slight summer dominance (57% falling October to March) (BoM 2022).

4.8.2 Experimental design and establishment

The experiment consisted of three tropical perennial grasses, a tropical annual forage grass and a temperate perennial legume arranged in a randomised complete block design with three replicates (Table 13). The perennial species treatments were sown in plots (4.4 x 5 m) using a tyned seeder in November 2019 and sugarcane mulch applied at 2000 kg/ha to provide some ground cover. Lucerne seed was inoculated with commercial strain of rhizobia prior to sown. Irrigation was applied over a 4 week period to assist establishment. Sudan grass was sown in mid-November 2020 and 2021. Plots were fertilised each spring: single superphosphate (125 kg/ha; 9% P, 11% S) to all plots and urea (100 kg/ha; 46% N) to the grass plots only. In August 2020 an aluminium access tube (2 m long, 50 mm outside diameter x 3.0 mm wall thickness tube) was installed in the centre of each plot to provide access for a neutron moisture meter to estimate soil water content.

Table 13. Experimental treatments and sowing rate (kg/ha).

Treatment	Species	Cultivar	Sowing rate (kg/ha)
T1	Bambatsi panic (*Panicum coloratum*)	Bambatsi	4.0
T2	Digit grass (*Digitaria eriantha*)	Premier	10.0
T3	Gatton panic (*Megathyrsus maximus*)	Gatton	5.0
T4	Sudan grass (*Sorghum sudanense*)	Bankers	9.8
T5	Lucerne (*Medicago sativa*)	SARDI Grazer	3.5

4.8.3 Data collection

Rainfall and temperature data were collected from a weather station located near the study site. All other data were collected over two growing seasons: 2020-21 and 2021-22. Growing degree days (GDD) were calculated for the period 1 August to 30 May in both growing seasons using minimum and maximum base temperatures of 15 and 35°C (Arnold 1960).

Herbage production was assessed every 6-weeks from October to May each growing season. A calibrated visual assessment technique with 4 strata per plot was used, similar to that described by Murphy et al. 2018. After each assessment the plots were cut with a rotary mower and herbage removed. All plots were cut to 50 mm height, except Sudan grass which was cut to 70 mm. Frequency of occurrence of live plant (Brown 1954; plant frequency) was assessed in 1 m^2 fixed quadrats (100 cells, each 0.1 x 0.1 m) in spring and autumn each year.

A neutron moisture meter (CPN 503DR Hydroprobe; Boart Longyear Co., Martinez, CA, USA) was used to estimate soil water content every 3-weeks. Readings were taken in 0.2 m layers down the soil profile (i.e., 0.1–0.3, 0.3–0.5,…,1.7–1.9 m) and converted to volumetric soil water content (m^3/m^3) using a locally derived calibration (McKenzie et al. 1990). Profile (0.1–1.9 m) total stored soil water (mm) was calculated by summing values for each layer. Total herbage production and changes in total stored soil water were determined for the 2020-21 (13 August 2020 to 27 May 2021) and 2021-22 (13 August 2021 to 17 May 2022) growing seasons. Water use efficiency (kg DM/ha/mm) of total herbage production (kg DM/ha) was calculated by dividing total dry matter by total water use, i.e., total evapotranspiration, which was determined by soil water balance.

Plots of soil water content at the start and end of the growing season (August–May) for each treatment were used to determine the volume and depth of extraction, that is, estimate maximum plant root depth (Murphy and Lodge 2006). For each growing season, the maximum extractable water (MEW, mm) was calculated as the difference between high and low values of SSW, which occurred in a continuous drawdown (Murphy and Lodge 2006; Murphy et al. 2018). Values of MEW for each soil layer and treatment were summed to give values for the upper (0.1–0.7 m), middle (0.7–1.3 m), lower (1.3–1.9 m) and full profile (0.1–1.9 m) (Neal et al. 2012). Rainfall refill efficiency during winter was calculated by dividing stored soil water refill during the period when the pastures were not actively growing (i.e., 27 May–12 August 2021) by total rainfall during the refill period.

4.9 Herbicides for control of broadleaf weeds in desmanthus pastures

Three experiments were conducted to test the tolerance of desmanthus (*Desmanthus virgatus* cv. Marc) to a range of herbicides. The experiments were conducted at Tamworth Agricultural Institute (-30.1444° 150.9677°, 400 m above sea level) on desmanthus pastures at different stages of development:

a. Pre-pasture emergent,
b. Seedling pasture (<3-months old) and
c. Established pasture (>9-months old)

In each experiment desmanthus was sown with a narrow tyned cone seeder into plots 1.5 m wide (6 rows, each 0.25 m apart) and at least 3 m long. Seed was sown at 4 kg/ha (germinable) at 10 mm depth. Each experiment was conducted as a randomised complete block design with four replicates.

In each experiment, four rates of each herbicide were applied: nil, half (0.5x), standard (1x) and twice (2x) the standard rate for legume pastures. The half and standard rates, and sometimes the double rate were within the registered label application rate for other pasture legumes or related species.

4.9.1 Experiment 1 – Pre-pasture emergent

Desmanthus was sown dry on 23 February 2016. Four herbicides were applied: Trifluralin was applied 5 days prior to sowing and incorporated to ~50 mm; the other three herbicides were applied 4 days after sowing. The herbicide details are provided in Table 14. The experiment was irrigated with 74 mm over a 7-day period after the herbicide treatments had been applied to assist establishment. Seedling density (plants/m^2) was assessed 3 weeks after sowing by counting the number of plants in nine lengths of 0.3 m row (2.7 m of row) and converting to plants per m^2.

Table 14. Herbicides, application rates (/ha) and details (including active ingredient, kg/ha a.i.) of their application in the pre-pasture emergent experiment.

Herbicide and concentration of active ingredient	Example Trade name	Rate of application (/ha) & active ingredient (a.i. kg/ha)			Water rate (L/ha)	Application details	Group
		0.5x	1x	2x			
Trifluralin 480 g/L	Treflan™	0.85 (0.41[1])	1.7 (0.82)	3.4 (1.63)	135	Applied pre-sowing (18 Feb 16) and incorporated	3
Imazethapyr 700 g/kg	Spinnaker® 700 WG	0.05 (0.04)	0.1 (0.07)	0.2 (0.14)	148	Applied post-sowing (29 Feb 16)	2
S-metolachlor 960 g/L	Dual Gold®	0.7 (0.72)	1.5 (1.44)	3.0 (2.88)	148	Applied post-sowing (29 Feb 16)	15
Pyroxasulfone 850 g/kg	Sakura® 850 WG	0.06 (0.05)	0.12 (0.10)	0.24 (0.20)	148	Applied post-sowing (29 Feb 16)[2]	15

[1] Rate of active ingredient (kg/ha a.i.)

[2] Not the recommended application

Seedling herbage mass was assessed on 29 March 2016, 5 weeks after sowing to estimate seedling vigour. On 10 May 2016, prior to the first frost when the pasture was 11 weeks old, herbage mass was assessed. The plants were left to allow set seed, then mown with a rotary mower to 0.1 m and the herbage removed from the experimental area once frosts had commenced. Spring regrowth was assessed on 17 November 2016.

All herbage mass assessments were conducted using a calibrated visual estimate, similar to that used by Boschma et al. (2021). Fifteen quadrats (0.4 x 0.4 m) were selected representing the range in total herbage mass present in the experiment. Each quadrat was given a score for total herbage production (where 0 = nil, 5 = highest) and proportion (%) of desmanthus of the total production. Each plot was divided into 3 equal strata, and herbage production and proportion desmanthus assessed in each. The calibration quadrats were cut to 10 mm, herbage sorted into desmanthus and other and dried in a dehydrator at 80°C for 48 hr. The dried samples were weighed and estimates converted to dry matter (kg DM/ha) and actual percentage (%) using linear and quadratic regressions ($R^2 \geq 0.83$) to determine the herbage mass of desmanthus.

4.9.2 Experiment 2 – Seedling pasture

Desmanthus was sown December 2018. Five herbicides at four rates were applied to the 9-week-old pasture on 7 February 2019 (Table 15). All herbicides were applied with 162 L water/ha. Data collected included:

1. Phytotoxicity, a score (0-10) of plant damage, was assessed weekly for 4 weeks following treatment application (Table 16).
2. Herbage mass in autumn prior to first frost (1 April 2019) using the calibrated score method described for experiment 1
3. Phenological development. A plot assessment was conducted 8 times over the period 7 March–29 April using the scoring system 0 = plants vegetative, 1= buds present, 2 = flowers present, and 3 = pods present.
4. Proportion (%) of pods on the plant that had matured in June 2019 once frosts had commenced.

Table 15. Herbicides, application rates (/ha) and details (including active ingredient, kg/ha) applied to seedling desmanthus on 7 February 2019.

Herbicide and concentration of active ingredient	Example Trade name	Application rate (/ha) and active ingredient (a.i., kg/ha)			Group
		0.5x	1x	2x	
2,4-D amine 720 g/L	Zulu® evo 720	0.75 (0.54[1])	1.5 (0.08)	3.0 (2.16)	4
MCPA 750 g/L	MCPA 750	0.65 (0.49)	1.3 (0.98)	2.6 (1.95)	4
Flumetsulam 800 g/kg	Broadstrike™	0.025 (0.02)	0.05 (0.04)	0.1 (0.08)	2
Fluroxypyr 333 g/L	Fluroken 333	0.3 (0.1)	0.6 (0.2)	1.2 (0.40)	4
Bromoxynil 200 g/L	Bromocide 200	0.7 (0.14)	1.4 (0.28)	2.8 (0.56)	5

[1] Rate of active ingredient (kg/ha)

Table 16. Phytotoxicity scores to rate sown plant (crop) damage up to 4 weeks after herbicide application (modified from Vanhala et al. 2004).

Score	Criteria
0	No crop reduction or damage
1	Slight discolouration or stunting
2	Some discolouration or stunting
3	Slight crop damage
4	More pronounced crop damage
5	Moderate crop damage
6	Moderately high crop damage
7	More pronounced crop damage
8	Heavy crop damage
9	Heavy crop damage with potential plant losses
10	Potential total crop death

4.9.3 Experiment 3 – Established pasture

Six herbicides were applied to 10-month old desmanthus cv. Marc on 16 November 2017. The herbicide details and application rates are provided in Table 17. Plant damage was assessed 7, 14 and 29 days after treatment using the phytotoxicity score provided in Table 16. The extent of brown out (proportion of plant brown, %) was also assessed on the plots applied with paraquat. Herbage mass was assessed on three occasions: 15 December 2017, 1 February and 8 March 2018 (4, 11 and 16 weeks after application, respectively). The plots were mown after each assessment to 0.1 m with a flail mower and the herbage removed from the experimental area. Herbage mass was assessed using the visual assessment method described in experiment 1.

Table 17. Herbicides, application rates (/ha) and details (including active ingredient, kg/ha) applied to established desmanthus on 16 November 2017.

Herbicide and concentration of active ingredient	Example Trade name	Application rate (/ha) and active ingredient (a.i., kg/ha)			Group
		0.5x	1x	2x	
Paraquat 250 g/L	Explode 250	0.8 (0.20[1])	1.6 (0.40)	3.2 (0.80)	22
Isoxaflutole 750 g/kg	Palmero® 750	0.05 (0.04)	0.1 (0.08)	0.2 (0.15)	27
2,4-DB 500 g/L	Buttress®	0.7 (0.35)	1.4 (0.70)	2.8 (1.40)	4
Terbuthylazine 875 g/kg	Terbyne® Xtreme®	0.5 (0.44)	1.0 (0.88)	2.0 (1.75)	6
Imazethapyr 700 g/kg	Spinnaker® 700 WG	0.05 (0.04)	0.1 (0.07)	0.2 (0.14)	2
Bromoxynil 200 g/L	Bromoxynil 200	0.7 (0.14)	1.4 (0.28)	2.8 (0.56)	6

[1] Rate of active ingredient (kg/ha)

4.9.4 Data analyses

For experiment 1 seedling counts and the herbage mass were analysed by analysis of variance (AOV) with herbicide, rate of herbicide (0,0.5,1,2 x recommended rate) and their interaction as explanatory factors and replicate as a blocking factor. Herbage mass at sampling times 2 and 3 (10 May and 17 November 2016) were square root transformed to meet the assumption of homogeneity of variance.

For experiment 2 and 3, the phytotoxicity scores and herbage mass were analysed by AOV as described for experiment 1. Additionally for experiment 2, % pod maturity and rate of flowering were also analysed by AOV in the same manner as experiment 1. Phenological development was assessed 8 times and by the last assessment all plots had a score of 3 (pods present). To assess the rate of development we used the method of Simco and Piepho (2012) to calculate an area under a curve (AUC). Plots that flowered faster had a higher AUC.

4.10 Quality of ensiled tropical perennial grasses

This component of research consisted of 2 experiments. This research was published in *Agronomy* earlier this year: Piltz et al. (2022) (https://doi.org/10.3390/agronomy12071721). Our hypotheses were that (a) good quality, well fermented silages can be produced from chopped or unchopped tropical grasses if adequately wilted; and (b) addition of a silage bacterial inoculant improves the fermentation quality of wilted tropical grass silage.

The experiments were conducted at Tamworth Agricultural Institute, Tamworth (31.14592°S, 150.96802°E) to assess the quality and fermentation characteristics of silages produced from tropical grass species. The pastures were grown under dryland conditions with limited supplementary irrigation to achieve an established sward for harvesting.

4.10.1 Experiment 1

Five tropical grasses were sown as pure swards in November 2018 at commercial sowing rates. The grasses were: Rhodes grass cv. Katambora, panic cv. Gatton, Makarikari grass cv. Bambatsi (Bambatsi panic), digit grass cv. Premier and kikuyu cv. Whittet. Due to low rainfall, irrigation was applied to assist establishment. All grasses established well, except for Bambatsi panic which had a lower population.

Silages were produced on two occasions: November 2019 and March 2020. In October 2019, the experimental area was mown (0.1 m) and herbage removed. Fertiliser was applied on 22 October (11, 13.8 and 46 kg/ha of P, S and N respectively) and 57 mm irrigation applied. On 5 November, the experimental area was mown again, herbage removed, and 100 mm irrigation applied. All grasses were cut for ensiling on 27 November (22 days regrowth). In 2020 the plots were mown, and herbage removed on 29 January and 24 February. Fertiliser was applied on 31 January (65 kg/ha N) with 50 mm irrigation, and 17 February (11, 13.8 and 100 kg/ha of P, S and N respectively) with 25 mm rainfall. All forages were cut for ensiling on 11 March 2020 (16 days regrowth) except kikuyu which was cut on 19 March. Bambatsi panic was not ensiled in 2020.

On the day of ensiling, forages were cut to 0.1 m, except Whittet kikuyu which was cut to 0.05 m, using an Allan scythe. The forage was left undisturbed on the cut area to wilt for 3-5 hours in 2019 and 18-24 hours in 2020. Random samples of fresh and wilted forage were collected at cutting and at the time of ensiling (n = 2 per sample type) and frozen (-18°C). The wilted forage was manually collected and chopped into ~45 mm lengths with a Ryobi® 2400W electric mulching shredder (Ryobi Limited, Fuchu, Hiroshima, Japan) then 3-6 kg of forage ensiled in plastic bag mini-silos (n = 3 per species) made of 100 µm polyethylene (Wilson and Wilkins 1972). The chopped forage was compacted, air evacuated from the bag with a vacuum cleaner and the bag opening tied securely to obtain an airtight seal. Each bag was then placed inside a second bag of the same type and the vacuuming and tying process repeated. The bags were packed into 200 L drums surrounded and topped with damp sand to maintain weight on the bags. All silages were opened on 22 July 2020, the silage was thoroughly mixed, and a subsample was taken to determine dry matter (DM) content and chemical composition.

4.10.2 Experiment 2

This experiment was conducted on a 6-year-old Premier digit grass sward. Fertiliser (100 kg/ha N) was applied on 13 January 2021 and the sward was mown and the cut material removed on the 28 January 2021. On 16 February 2021 (19 days regrowth, 675 kg DM/ha), average plant growth stage was 3.5 leaves, with some tillers on ~30% of plants commencing stem elongation. A section of the pasture was cut to 0.1 m using an Allan scythe and allowed to wilt. The high temperatures resulted in a rapid wilt. Random samples of wilted forage were collected manually when DM content reached approximately 350 (11.35 am) and 450 g/kg (2.00 pm) on the same day. Hereafter These samples are hereafter referred to as W1 and W2 and the unwilted forage referred to as W0. Random samples of fresh and wilted forage were collected at cutting and at the time of ensiling (n = 2 per sample type) and stored frozen as in Experiment 1.

The forage was ensiled either chopped (both W1 and W2) using the mulcher described in Experiment 1, or unchopped (only W2). Therefore, there were three forage treatments (chopped at 350 g/kg DM, chopped at 450 g/g DM or unchopped at 450 g/kg DM). There were also three additive treatments: nil (Control), Pioneer® 1174 and Lallemand® Magniva Classic bacterial inoculant; hereafter referred to as Control, 1174 and Classic respectively. The 1174 contained selected strains of *Lactobacillus plantarum* and *Enterococcus faecium* and was applied at the rate of 250,000 colony forming units (CFU)/g fresh forage. Classic contained selected strains of *L. plantarum* and *Pediococcus pentosaceus* in a ratio of 9:1 and was applied at 200,000 CFU/g fresh forage. These were applied at 100 ml inoculant per 25 kg of fresh forage, adjusted to provide the recommended rate of bacteria per tonne of fresh forage. The Control silages had the same rate of water applied. Forages were ensiled in plastic bag mini-silos (n = 3 per treatment) and stored using the same procedure as described in Experiment 1. Silages were opened on 17 July 2021 and the silage was thoroughly mixed and subsampled as in Experiment 1.

4.10.3 Chemical analyses

Thawed forage samples were dried at 80°C to determine DM content and (1 mm screen) prior to analyses. The following were determined (details are provided in Piltz et al. 2022 and Appendix 9): Water soluble carbohydrates content, nitrogen, crude protein, organic matter, starch, acid detergent fibre (ADF) and neutral detergent fibre (NDF), predicted *in vivo* digestibility (digestible organic matter (DM basis): IVDOMD) and metabolisable energy (MJ/kg DM: ME) content.

Silage samples were dried at 80°C to determine DM content. The following were determined: pH, nitrogen, WSC content, ammonia nitrogen (NH_3-N), protein fractions and volatile fatty acids.

4.10.4 Statistical analyses

Data were analysed using the REML function within Genstat for both experiments. In Experiment 1, species, year (2019 or 2020), sample type (at cutting or after wilting) and all interactions were the fixed effects for forages; species, year (2019 or 2020) and their interaction were the fixed effects for silages; and species, year (2019 or 2020), sample type (at cutting, after wilting or silage) and all interactions were the fixed effects for the analyses of protein fractions. In Experiment 2, wilt was the fixed effect for forages, while treatment (i.e., individual DM, inoculant and chop length combination) was the sole fixed effect for silages. Protein fractions were analysed with each combination of sample type (forage or silage) and level of wilting as individual data points for fixed effects. There were no random effects fitted.

4.11 Understanding nitrogen fertility in tropical perennial pastures

4.11.1 Experimental design

A study commenced at the Tamworth Agricultural Institute (31.1450°S, 150.9678°E) in 2012. The experiment was prepared as a 10-year program; concluding with final soil sampling in autumn 2022. (NB: Year 1; 2012–13: Year 10; 2021–22).

Digit grass cv. Premier was sown in November 2012 into plots (4.5 x 4.5 m) in a randomised block design with 3 replicates. Seed was sown at 1 kg/ha with a disc seeder on 0.25 m row spacing. The experiment consisted of five treatments (Table 18). Nitrogen was applied as a split application in spring and summer each year coinciding with rainfall to minimise volatilisation. Phase 1 commenced in spring 2013 and ran to autumn 2017. Phase 2 commenced in spring 2017, with treatments 2 and 3 receiving 100 and 200 kg N/ha each year respectively for the remainder of the study. Superphosphate (250 kg/ha; 8.8% P, 11% S) was applied to all treatments every spring from spring 2013.

Table 18. Annual nitrogen regimes applied to treatments in the rundown experiment from 2012 to 2022 at Tamworth Agricultural Institute.

Treatment ID	Treatment label	N application regimes (kg N/ha)	
		Phase 1 (2012–2017	Phase 2 (2017–2022)
1	nil N	0	0
2	nil N/100 N	0	100
3	nil N/200 N	0	200
4	100 N	100	100
5	200 N	200	200

4.11.2 Data collection

An automatic weather station located in the same paddocked as the experimental site collected daily rainfall. These were summed to produce monthly totals.

Herbage mass (kg DM/ha) was assessed every 6 weeks during the growing season (October–May). After each assessment the experimental area was either crash grazed by sheep and/or mown to about 0.1 m and the material removed from the experimental area. Plant persistence was monitored by assessing plant frequency of digit grass in autumn and spring each year (Brown 1954). We placed quadrats (1 m^2) in each of two fixed locations and assessed presence/absence in one hundred cells (each 0.1 x 0.1 m).

A single soil core was collected to 2.0 m from each plot at the start and end of the growing season (generally, October and May), with final samples taken in March 2022. Samples were collected before the spring N application was applied. Cores are divided into six depths (0–0.1, 0.1–0.3, 0.3–0.6, 0.6–1.0, 1.0–1.5, 1.5–2.0 m) then dried at 40°C until consistent weight was achieved. The samples were ground and analysed for total carbon (C), total N and nitrate N by NSW DPI Laboratory Services.

Following significant rainfall after the 2018–20 drought we collected forage samples for analysis of nutritive value at the three assessments conducted until the end of the growing season: 20 February, 2 April and 5 May 2020. These samples were opportunistically collected to evaluate the impact of fertiliser regime on forage quality after an extended period of drought. Herbage was collected from each plot as random grab samples of green leaf. The samples were stored in a chilled esky then dried in a dehydrator for 48 hr at 60°C. The samples were ground and analysed by NSW DPI Feed Laboratory in Wagga Wagga for neutral detergent fibre (NDF), acid detergent fibre (ADF), crude protein (CP) and metabolisable energy (ME) using standard Australian Fodder Industry Association methods.

4.12 Hard seed breakdown patterns of temperate and tropical legumes in northern inland NSW

Little is known of the hard seed breakdown of both temperate and tropical legumes in the summer dominant rainfall zone. The aim of this study was to quantify the hard seed breakdown patterns of a range of tropical and temperate legumes in northern inland NSW.

Two experiments were conducted on a brown Chromosol soil at Tamworth Agricultural Institute (31.1451°S 150.9686°E, 400 m above sea level): tropical and temperate legumes. Both experiments included seed production then the hard seed breakdown experiment.

4.12.1 Tropical legumes

On 12 December 2013, seed of eight tropical legumes (Table 19) were seed increased in plots 2 x 10 m. The plots were irrigated (100 mm) over a six week period to assist establishment and fertilised with soluble fertiliser [37.5 kg/ha nitrogen (N), 7.5 kg/ha phosphorus (P), 13.2kg/ha potassium (K), and 6.75 kg/ha sulphur (S)]. Super Sweet Sudan was sown around each block and cages covered with small aperture insect netting (Saint-Gobain ADFORS fibreglass small insect screen FCS8503-M) erected over desmanthus plots to minimise air and pollen movement to prevent cross pollination. All plants were allowed to flower and set seed, and the annual species were allowed to senesce. Mature pod was harvested from late-March (desmanthus cv. Marc) until July (all legumes except desmanthus both cultivars).

Table 19. Tropical legumes seed increased in northern NSW (Tamworth) and southern Queensland (Toowoomba) and included (✓) in the experiments at both locations.

Common name	Botanical name	Cultivar	Northern NSW	Southern Qld	Seeds /bag
Burgundy bean	*Macroptilium bracteatum*	B1	✓	-[4]	200
Butterfly pea	*Clitoria ternatea*	Milgarra	✓	✓	200
Desmanthus	*Desmanthus virgatus*	Marc	✓	✓	500
Desmanthus	*D. virgatus*	JCU2[1]	✓	✓	500
Caatinga stylo	*Stylosanthes seabrana*	Primar	✓	✓	500[3]
Caatinga stylo	*S. seabrana*	Unica	-[2]	✓	500[3]
Fine stem stylo	*S. guianensis* var. *intermedia*	-	✓	✓	500[3]
Siratro	*M. atropurpureum*	Aztec	✓	-[4]	200

[1]www.progardes.com.au; [2]Poor plant establishment; [3]seed in hull; [4] Insufficient seed produced

These legumes were also seed increased at Gatton, Queensland (27.5394°S, 152.3389°E, about 90 m alt) in 2013-14. A proportion of seed of all legumes from each site was swapped to test whether there was any effect of location of seed production on hard seededness or hard seed breakdown pattern. The southern Queensland softening experiment was conducted 60 km south west of Toowoomba (27.7258°S, 151.3500°E, alt about 380 m). The Queensland experiment was not part of this project and the results are not reported.

In September-October 2014, the seed were gently cleaned of debris to avoid scarification. Seed of each legume and seed in hull of the three stylo entries, were placed in individual nylon bags made of small insect flyscreen mesh (Adfors small insect flyscreen; 90 x 100 mm); 500 seeds of all species except burgundy bean, butterfly pea and siratro which had 200 seeds per bag (Table 19). There was a total of 13 legume entries in the experiment (7 and 6 from the NSW and southern Queensland seed increases respectively, Table 19). A nylon bag of each legume entry was strung onto 1 m lengths of wire, each wire representing a sampling time. The position of legumes along the wire was randomised.

The wires strung with bags were placed in the field 0.6 m apart on 17 November 2014 in a randomised complete block design with 11 sampling times and four replicates. Each bag was placed 10 mm below the soil surface and lightly covered with soil. The sampling times when seed packets were exhumed were November 2014 (initial, S0 and not placed in the field), every 2 months to autumn 2015 (S1-S2; January and March 2015), every 3 months to spring 2015 (S3-S4; June and September 2015), every 4 months to autumn 2016 (S5-S6; January and May 2016), then every 5-7 months until spring 2018 (S7-S11; October 2016, May and October 2017, and May and October 2018).

At each sampling time, the wire and attached nylon bags were removed from the field. The bags were washed with water to remove dirt, then hung overnight to dry. Seed were removed from each packet and placed in sealable plastic containers lined with two sheets of unbleached paper towel (225 x 210 mm) wet with about 35 mm water. The containers were sealed and placed in a growth cabinet at 30/25^{o}C. The trays were checked after 4-5 and 8-10 days and germinated seedlings removed. After 14 days the number of seeds which had not imbibed (i.e., hard seeds) were recorded.

Two temperature probes (Tain Electronics; https://www.tain.com.au) were installed at 10 mm depth at the site in November 2014 and temperature recorded every 30 min. Rainfall (0.5 mm pluviometer at 30 min intervals) was recorded by an automatic weather station located 100 m from the site.

4.12.2 Temperate legumes

Seed of eight legumes (Table 20) were seed increased similarly to the tropical legumes. The legumes senesced naturally and seed were harvested November (barrel medic)-December 2015 (remainder of legumes).

In May-June 2016, seed of each legume entry was prepared similarly to the tropical legumes except seed was not removed from the pod of the serradella or medic species. One hundred seeds, or an estimated equivalent number of seed in pod, of each legume were placed in individual nylon bags and strung on 1 m length of wire in a randomised order. The number of pods or seed placed in each bag is shown in Table 20. On 15 June 2016, the seed bags strung on wire were placed in the field in a randomised complete block design with 10 sample times and four replicates. The sample times when seed were exhumed were June 2016 (initial, S0), then every 2.5 months during the first summer (S1-S4; October and December 2016, February and May 2017), then every 3.5 months over the second and third summers (S5-S10; October 2017, January, May and October 2018, January and May 2019).

Similar to the tropical legumes, a wire and all attached nylon bags were removed from the field on the specified date. The seed bags were washed, dried and seed or pod placed in plastic containers lined with paper towel and placed in a cabinet at 20^{o}C for 14 days. The trays were checked every 4-5 days and germinated seedlings removed. On day 14 seed were removed from pods, and the number of seed which had not imbibed (i.e., hard seeds) was recorded.

Table 20. Temperate legumes and cultivars and the number of seeds or pod in each nylon bag.

Common name	Botanical name	Cultivar	Seeds or pods/bag[1]
Subterranean clover	*Trifolium subterraneum* subsp. *brachycalycinum*	Clare	100
Subterranean clover	*T. subterraneum* subsp. *subterraneum*	Dalkeith	100
Arrowleaf clover	*T. vesiculosum*	Cefalu	100
Bladder clover	*T. spumosum*	Bartolo	100
Biserrula	*Biserrula pelecinus*	Casbah	15[2]
Woolly pod vetch	*Vicia villosa*	Haymaker	100
Yellow serradella	*Ornithopus compressus*	Santorini	13[2]
French serradella	*O. sativus*	Margurita	100
Barrel medic	*Medicago truncatula*	Caliph	13[2]
Snail medic	*M. scutellata*	Silver	20[2]

[1] The number of seeds and pods/bag were doubled for S8-10 (October 2018, January and May 2019) [2] Pod

4.12.3 Statistical analyses

Plots of proportion of hard seed *vs*. time for each legume showed a range of responses of which there were many possible choices of curve that could be fitted. A three-parameter Weibull curve was chosen for ease of interpretation and consistency across both experiments. The three-parameter Weibull equation used for the tropical legumes was:

$$\frac{HS}{total} = d * \exp\left(- \exp\left(b * (\log(time) - \log\,(e))\right)\right)$$

where *HS* is number of hard seeds, *total* is total number of seeds, *time* is number of days after seed were placed in the field, *d* is the initial hard seed value (i.e when time = 0), *b* is the Weibull slope or shape parameter, and *e* is the scale parameter. The model was fitted in R (R Core Team 2020) using package drc using the “drm” command with option type=”binomial” (Ritz *et al*. 2015).

The Weibull slope (*b*) is always >0. When *b* = 1 hard seed breakdown occurs at a constant rate, however, when *b* < 1 hard seed breakdown is initially high but decreases with time, while when *b* > 1, initial hard seed breakdown rate is slow and increases with time. The scale parameter (*e*) is also always >0 and has the same units as *time*. Higher relative values of *e* indicate the hard seed breakdown pattern is elongated and hard seed break down occurs over a long period of time while low values of *e* indicate that breakdown occurs over a shorter period of time. Legumes with low *e* values have more rapid breakdown rates than those with high values.

Among the temperate legumes, seed of the serradella and medic entries were contained in pods, therefore, it was not possible to count the initial total number of seeds. Instead the average number of seeds per pod were determined and the number of pods to achieve a minimum of 100 seeds added to each nylon bag. This expected number of seed per nylon bag (based on the number of pods and average number of seeds er pod) was the *total* used in the analysis, except on one occasion where the recorded hard seed level slightly exceeded the total. For this case the total was increased to match the hard seed value.

Values of percent hard seed and their standard errors were predicted at the last sampling date (i.e., 15 October 2018 and 2 May 2019 for the tropical and temperate legumes respectively). The number of days to achieve 50% of initial hard seed (i.e., 50%*d*) was also predicted.

4.13 Competitive ability of tropical grasses and tropical legumes seedlings during establishment

The competitive ability of desmanthus and stylos (*Stylosanthes* spp.) seedlings in mixes with tropical grasses is not well understood, but important for successful establishment and the long-term survival of the legumes. Two glasshouse experiments were conducted at the Agricultural Research and Advisory Station, Glen Innes (29°41.430’S 151°41.598’E). These experiments investigated the hypothesis that the tropical perennial legumes, desmanthus species and stylo species would be competitive and allow the successful establishment in mixtures with a range of tropical perennial grasses

Experiment 1 (Expt 1) consisted of binary mixes of tropical grasses with desmanthus cultivars and experiment 2 (Expt 2) binary mixes with stylos. The four tropical grasses used in both experiments were digit grass cv. Premier, panic grass cv. Megamax 059, Rhodes grass cv. Katambora and *Cenchrus ciliaris* (buffel grass) cv. USA. The five desmanthus cultivars were: *D. virgatus* cvv. Marc, Ray and JCU2, *D. bicornutus* cv. JCU4 and *D. leptophyllus* cv. JCU7. The five stylo cultivars were: *S. seabrana* cv. Unica, *S. hamata* cv. Amiga, *S. guianensis* var. *guianensis* cv. Beefmaker, *S. guianensis* var. *intermedia* cv. Oxley and *S. scabra* cv. Seca.

In both experiments seeds of each grass and legume were germinated in a germination cabinet. Seedlings were transplanted (8-12 days after germination) into polystyrene boxes (300 x 450 x 180 mm deep) filled with potting mix. Seedlings were transplanted at a density of 40 seedlings/box in a 5 x 8 configuration (~50 mm between plants). The species were arranged in grass: legume ratios of 0:1, 1:3, 1:1, 3:1 and 1:0 with each species evenly distributed. The experiment was arranged in a randomised complete block design with 3 replicates. There was a total of 300 boxes in the experiment, arranged in a 15 x 20 array in the glasshouse.

Temperatures in the glasshouse ranged from 23–38^{0}C during the day and 10–16^{0}C of a night. Each box was watered daily and fertilised weekly (1.5 g Thrive (Yates Australia); 27% N, 5.5% P and 9% K) with holes in the bottom of each box to allow free drainage.

Plants were first harvested at 94 days after transplanting then every 30-35 days. At each harvest most grass plants in each box were either stem elongating or flowering. Plants were cut to a height of approximately 50 mm above the soil surface, sorted into species, dried at 80^{0}C for 48 hours and weighed. Experiment 1 and 2 were harvested 3 and 2 times respectively.

Herbage mass (dry weight, g/box) of all species mixtures for harvests 2 and 3 in Expt 1 and harvest 2 in Expt 2 were used to derive parameters of the de Wit non-linear competition model (de Wit 1960) as described by Machin and Sanderson (1977), using non-linear least-squares regression that minimised the sum of squares of the residuals. The equation for each pair of species in the de Wit model can be written as: Y=MkU/[(k-1)U=1] and Z=N(1-U)/[(t-1)U+1] where the parameters Y and Z were the dry weight yield (g/box) of species i [legume species (competitor)] and j (tropical grass species), respectively, in the proportions U and 1-U. The parameters M and N were the monoculture dry weight for species i and j, respectively. The de Wit relative crowding coefficient, k, provides a measure of the aggressiveness of species i towards species j in the mixture (i.e., kij), and t is the inverse of the de Wit relative crowding coefficient of species j towards species i (i.e., 1/kji).

Relative yield total (RYT) is the product of the respective crowding coefficients (kij.kji) for each species (Harper 1977; Hill and Gleeson 1988) where RYT=1 indicates that both species make the same demand on the same limiting resource, RYT>1 implies that species either have different demands on resources, and RYT<1 indicates mutual antagonism (Harper 1977).

Full details of the models used and tested are provided in Harris et al. (Appendix 12). Harper (1977) summarised the biological interpretations of the models used as:

(i) if $k = t = 1$ each species contributed to total herbage mass in direct proportion to its ratio in the mixture and both species were either equally competitive, or their numbers were too low for competition to occur.

(ii) if $k = t \neq 1$, both species were competing for the same environmental resources and one adversely affected the yield of the other, while its own herbage mass was unaffected.

(iii) if $k \neq t$ and RYT <1, the yield of each species was inhibited by the presence of the other and under-yielding occurred, since neither species contributed its expected share of RYT.

(iv) if $k \neq t$ and RYT >1, the species were not competing for the same environmental resources or niches and so they may have avoided some measure of competition with each other, resulting in RYT being higher than expected, i.e., overyielding.

4.14 Establishing legumes into existing perennial grass pastures

In this study, we conducted two experiments on each of two pasture types: a tropical grass pasture sown ~4 years earlier and a native perennial grass pasture located within 800 m of one another on similar soil types with the same rainfall (Table 21). The tropical grass pasture was dominated by digit grass (*Digitaria eriantha*) cv. Premier, Makarikari grass (*Panicum coloratum* var. *makarikariense*) cv. Bambatsi (Bambatsi panic), while the native grass pasture was dominated by redgrass (*Bothriochloa macra*), wiregrass (*Aristida ramosa*), and wallaby grass (*Rytidosperma* spp). The close location of the sites allowed us to conduct our experiments on contrasting pasture types, yet both with similar soils and exposed to the same weather. In addition, the varying histories of these paddocks provided the opportunity to compare and contrast the results.

Table 21. Pasture types, locations and soil types of experimental sites in the Tamworth area.

Pasture type	Location		Soil type	Elevation (m)
	Latitude	Longitude		
Tropical perennial grass	30.91315° S	150.72708° E	Red Chromosol	406
Native perennial grass	30.91651° S	150.73517° E	Red Chromosol	386

4.14.1 Experimental design

Two were conducted on the two pasture types (i.e., total of four experiments):

- establish winter growing temperate legumes, and
- establish summer growing tropical legumes.

Each experiment had two factors: three legume species and three soil water accumulation treatments, replicated three times, resulting in 27 plots per experiment. Plots were arranged in a randomised complete block design with three replicates. Each plot was 6 x 9 m with a central 3 x 9 m fallow strip, where soil water accumulation treatments were applied and the legumes sown. The existing pasture (1.5 x 9 m strip) remained on both sides of treatment area.

The three temperate legume treatments sown in autumn: lucerne cv. Venus (4 kg/ha), barrel medic cv. Caliph (11.5 kg/ha), and woolly pod vetch cv. Haymaker (35 kg/ha). The three tropical legume treatments were: lucerne cv. Venus (4 kg/ha), desmanthus cv. Marc (3.5 kg/ha), and desmanthus cv. JCU2 (3.5 kg/ha).

Three fallow lengths before sowing gave three soil water accumulation treatments (Table 22). The increasing length of fallow was expected to accumulate increasing stored soil water before sowing. The fallow treatments were: 16-week, 8-week and 0-week fallow (i.e., spray immediately before sowing).

4.14.2 Sowing window

The sowing 'window' for both temperate and tropical pasture legumes in this environment can be broad. For these experiments, we defined our optimal time for sowing temperate and tropical legumes as a 30-day window in autumn (1–30 May) and spring (1–30 November), respectively. We defined these windows on research (e.g., Lodge and Harden 2009; Harris *et al*. 2018) and local experience. The opening and closing dates for each fallow period of 16- and 8-weeks to meet the sowing windows are in Table 22.

The trigger for commencement of the fallow treatments was a substantial rainfall event 16-weeks before the sowing window. For the autumn sowing, this was at least 50 mm over 7 days from the week beginning 10 January 2020 (Table 22). For the spring sowing, fallow was triggered by at least 25 mm over 7 days from the week beginning 13 July 2020 (Table 22). Soil water accumulation was achieved by applying glyphosate to initiate the fallow period for each treatment and continued until sowing if subsequent germination of annual grass and broadleaf weeds occurred. In addition, a flail mower managed excessive herbage mass to simulate grazing.

Table 22. Starting dates of the three fallow periods to achieve three levels of soil water accumulation before sowing in the autumn (1–30 May 2020) and spring (1–30 November 2020) sowing windows.

Fallow	Winter legumes		Summer legumes	
period (weeks)	Open	Close	Open	Close
16	10-Jan-20	06-Feb-20	13-Jul-20	09-Aug-20
8	06-Mar-20	02-Apr-20	07-Sep-20	04-Oct-20
0	01-May-20	29-May-20	02-Nov-20	30-Nov-20

The 16-week fallows commenced on 6 February 2020 and 21 July 2020 for the autumn and spring sowings respectively. The winter growing legumes were sown in autumn on 28 May 2020 and the summer growing legumes on 10 November 2020. The 3 m wide treatment area was sown with a disc seeder. Seed were placed ~10 mm below the soil surface on 0.25 m row spacings (total of 12 rows).

4.14.3 Measurements

Stored soil water. We used the EM38 to measure electrical conductivity (EC_a, dS/m) in the vertical orientation to indicate changes in stored soil water from the start of the 16-week fallow treatment and then at 4-week intervals to the end of the growing season. EC_a was measured along a transect across each plot (i.e., at 0.0, 1.5, 3.0, 4.5 and 6.0 m across each plot), giving measurements in the existing pasture and at the margin and centre of the fallow strip.

Ground cover. Ground cover was assessed at the time of sowing using a visual estimation technique (Murphy and Lodge 2002). Assessments were made along a transect (i.e., at 0.0, 3.0 and 6.0 m) to determine the impact of fallow treatments in the sowing strip compared with the existing pasture.

Plant counts. Approximately 4-6 weeks after legume germination, we took seedling counts at 4 locations in 4 of the sowing rows (rows 1, 5, 8 and 12) to determine the seedling density and any differences in density across the sowing strip. Each count sampled a 40 cm length of sowing row.

Herbage mass. Standing herbage mass was assessed at the commencement of the 16-, 8- and 0-week fallow treatments, then three times during the legume growing season coinciding with peak herbage mass for each sown legume. The assessment was conducted using a visual scoring method (e.g., Murphy et al. 2019) to estimate the total herbage mass and proportion of sown legume and annual weed above 0.1 m. Herbage mass was assessed by two assessors, each assessing the existing pasture on either side of the treatment strip, and the centre of each treatment strip along 2 separate transects. Following the three assessments conducted before sowing and glyphosate application (i.e., the 16-, 8- and 0-week fallow treatments), a flail mower cut and removed herbage material from the site. After sowing, the pastures grew unchecked for the entire growing season to avoid disturbing the establishing legumes and allow maximum seedset.

4.14.4 Reducing tropical grass competition to improve desmanthus establishment – desmanthus establishment #2

A secondary experiment on the tropical perennial grass site tested the dual hypotheses that later sowing and using a post-emergent group 1 herbicide would enhance summer legume establishment. In addition, the later sowing aimed to further reduce tropical grass competition by obtaining a better kill by applying glyphosate when the grasses were in active growth. Further, using a post-emergent group 1 herbicide aimed to suppress tropical grass regrowth after the desmanthus had germinated. Suppressing the tropical grass would give the desmanthus every opportunity to flower and set seed before the end of the season.

The experiment had two factors in a split-plot design with three replicates. There were three water accumulation periods (main plots), each with and without a Group 1 herbicide applied post-emergence of the desmanthus. Main plots and replicates were arranged in a 3 x 3 configuration. The plots were the same width as in the other experiments, vis. a 3 m wide treatment strip with 1.5 m strip of existing pasture on either side, and 8-m long to allow for the split-plot Group 1 herbicide treatments (each 4 m long).

A total of 51 mm of rainfall in late July and early August triggered the start of the 16-week fallow treatment on 9 August 2021. This start date was 4-weeks later in the season compared with the commencement of fallows to sow the summer legume experiment (Table 23). Desmanthus cv. Marc was sown at 3.5 kg/ha on 6 December 2021 using the same method as the initial experiments. Haloxyfop (520 g/L a.i at 150 ml/ha) was applied on 21 January 2022.

3.15 Proportion of digit grass and lucerne in mixes to optimise dry matter, water productivity and nitrogen fixation

This study was conducted to determine the optimum proportion of digit grass and lucerne in a mixed pasture to maximise herbage and water productivity. A secondary study was conducted during the 2020-21 growing season to determine the effect of the grass/legume ratio on N_2-fixation by lucerne from the atmosphere.

Table 23. Starting dates of the fallow periods to achieve high, medium and low soil water accumulation before the sowing window in early summer (29 November to 27 December 2021). The window for applying Group 1 herbicide is 6-weeks after sowing.

Fallow period	Start of fallow		Group 1	
(weeks)	Open	Close	Open	Close
16	09-Aug-21	5-Sep-21	10-Jan-22	6-Feb-22
8	04-Oct-21	31-Oct-21	10-Jan-22	6-Feb-22
0	29-Nov-21	27-Dec-21	10-Jan-22	6-Feb-22

4.15.1 Site and spaced plants

The experiment was initiated in spring 2018 at Tamworth Agricultural Institute (31°08'43" S, 150°58'06" E) on a brown Vertosol (Isbell 1996). A replacement series study (de Wit 1960) was designed with five treatments in a randomised complete block design with three replicates. All treatments were established at 8 plants/m^2, but with differing ratios of digit grass and lucerne (vis. 8-0, 6-2, 4-4, 2-6, 0-8 plants/m^2 of digit grass and lucerne, respectively). Two-month-old seedlings of digit grass cv. Premier and lucerne cv. Venus were transplanted into plots (4 x 4 m) in November 2018 in the defined proportions (total of 128 plants/plot). Plots were irrigated to minimise transplant shock ands Sick or dead plants were replaced during the first four weeks.

4.15.2 Measurements

Soil water content. An aluminium access tube was installed in the centre of each plot to a depth of 1.9 m to enable volumetric soil water content to be estimated using a neutron moisture meter calibrated for local soil conditions as per Boschma et al. (2019). Soil water content was assessed at 3-week intervals from transplanting (27 November 2018) until 27 April 2022 at 20 cm intervals down the soil profile representing soil layers 20 cm thick to 190 cm (i.e., 10–30, 30–50,…,170–190 cm). Total stored soil water for the profile (SSW, mm, 10–190 cm) was calculated by summing values for each layer.

Agronomy

We assessed herbage mass at 6-week intervals by harvesting all herbage above a height of 100 mm in a 1 x 1 m quadrat rotated through one of four quadrants adjacent to the access tube (e.g., Boschma et al. 2019). The herbage of digit grass and lucerne was cut separately and then oven dried at 80°C (except 2020-21 growing season) for 48 hr and plant dry matter (kg DM/ha) was determined. After each assessment the plots were mown to 100 mm in height and the herbage removed.

In autumn and spring, plant frequency of digit grass and lucerne were assessed (Brown 1954) in two fixed locations per plot. Quadrats (1 m^2) consisted of 100 cells (each 0.1 x 0.1 m) were used to determine the presence/absence of live plant material.

N fixation (2020-21 growing season)

Herbage mass was assessed 7 times from October 2020 to May 2021 as described above. Herbage of grasses were also collected from 4 unfertilised locations outside the experimental area. The N in these grasses was accessed from the soil only, whereas the N in the legumes inside the experiment had access to both soil N and atmosphere-derived N (through rhizobia). The two N sources have different ^{15}N 'signatures' allowing the proportion of legume N from each source to be determined.

All samples were dried at 65°C for 48 hours, ground to <5 mm, and a sub-sample finely ground to <0.5 mm. Total N and C were determined by combustion analysis followed by analysis of the proportion of ^{15}N to ^{14}N in the sample using a mass spectrometer. The ^{15}N is a stable isotope of N that naturally occurs in the atmosphere (N_2) at a concentration of 0.3663% (^{14}N is 99.6337%). Soil N taken up by plants has a different $^{14}N/^{15}N$ ratio to that of the atmosphere, so we can calculate the amount of legume N derived from the air (through N_2 fixation by rhizobia) and that sourced from the soil (Unkovich *et al.* 2008).

The N content of the samples was calculated by multiplying herbage DM weight by the total N concentration. The amount of N in the legume derived from the atmosphere (Ndfa) was calculated by multiplying the DM weight by the N concentration by the %Ndfa.

When N_2-fixing legumes are grown in mixed swards with grasses, legume N may be transferred to the grass as legume roots decompose. This transfer affects the proportion of ^{15}N in the grass samples and can give an indication that some of the digit grass N content has come from the legume.

Soil cores were also taken at the start and end of the growing season (September 2020, May 2021). Soil mineral N, total N (and C) and ^{15}N natural abundance were measured on the initial samples and soil mineral N only on the final samples.

4.15.3 Data handling and analysis

Growing degree days

To interpret plant growth conditions through each growing season, we calculated growing degree days (GDD) as Arnold (1959) proposed with a base and maximum temperature of 15 and 35°C, respectively. Each season, we accumulated GDD from 1 September to 30 April, capturing the main growing period of digit grass.

Soil water content, extraction, root depth, and refill

Changes in soil water content and total herbage production were determined for 27 November 2018–27 April 2022. We determined the maximum extractable water in each growing season, signified by the largest continuous decline in stored soil water, without full profile refill. During the non-growing season (typically, May–August), we calculated the increase in stored soil water and determined rainfall refill efficiency (increase in stored soil water divided by the total rainfall expressed as %). Plant rooting depth was determined by change in soil water content and estimated as the maximum depth where soil water content decreased by >0.02 m^3/m^3.

Using the soil water balance equation, we estimated actual evapotranspiration (mm) otherwise known as 'water use' for each period between soil water content measures and on an annual basis (1 July to 30 June) (e.g., Murphy et al. 2022). Water losses by surface runoff and deep drainage were assumed to be zero. When well-covered, the self-mulching clay soil on the site had a low runoff coefficient which enhanced infiltration, and a low sub-soil saturated hydraulic conductivity that precluded rapid water movement to depths of >1.9 m (maximum depth of measurement with the neutron moisture meter). Water use efficiency (WUE, kg DM/ha/mm) of total herbage production was calculated by dividing total dry matter by total evapotranspiration.

Herbage mass

Total herbage mass for each treatment was accumulated on an annual basis and for the entire experiment. The contributions of each species in each mixture were represented separately.

N fixation (2020-21 growing season)

Statistical differences for aboveground biomass and biomass N content of the different pasture mixture treatments were determined for (i) digit grass alone, (ii) lucerne alone, and (ii) lucerne and digit grass combined. Comparisons were done for the material collected at each sampling time, also for cumulative material. Proportion of Ndfa was analysed for lucerne only.

4.16 Persistence and productivity of leucaena in northern and central NSW

This project provided an opportunity to continue the evaluation of leucaena in Northern Inland NSW and Central West NSW. This continued assessment of the experiments combined with the previous data (Boschma *et al*. 2018) provide data for ten growing seasons, thus providing new knowledge to better understand the long-term persistence, production, and agronomy of this species in summer-dominant and aseasonal rainfall environments. Our hypothesis was that leucaena would exhibit long-term persistence and production.

4.16.1 Sites

Three existing leucaena experimental sites were located near Bingara and Manilla (Northern Inland NSW) and Trangie (Central West) NSW. A summary of the site locations, soil types and conditions are provided in Table 24 and more detailed description of the sites in can be found in Boschma *et al*. (2018) and Harris et al. (2019).

Table 24. Latitude, longitude, annual average rainfall (AAR, mm), elevation (m), soil type, and soil chemical properties [pH ($CaCl_2$), phosphorus (P, Colwell, mg/kg) and sulphur (S, KCl_{40}, mg/kg)] for the leucaena experimental sites in Northern Inland NSW and Central West NSW (Harris et al. 2019).

Site	Latitude	Longitude	AAR (mm)	Elevation (m)	Soil Type	Soil chemical properties (0–0.1 m)		
						pH ($CaCl_2$)	P Colwell (mg/kg)	S KCl_{40} (mg/kg)
Bingara	29°42’39” S	150°27’07” E	743	297	Brown Chromosol	5.0	50	3.2fs
Manilla	30°42’11” S	150°30’10” E	576	412	Brown Chromosol	6.1	36	4.2
Trangie	31°59’45” S	147°56’18” E	493	214	Brown Chromosol	5.1	10	3.0

4.16.2 Species and experimental design

Each experiment comprised of four commercial cultivars of leucaena (Cunningham, Peru, Tarramba and Wondergraze) and one experimental line (S&D#36) developed by the University of Queensland for tolerance to psyllids (*Heteropsylla cubana*). The three experimental sites were designed as randomised complete blocks with three replicates. Each plot consisted of 16 plants of a cultivar/line of leucaena positioned 0.5 m apart in twin rows (1 m between rows). Each row and plot were 4 m in length and each replicate was 20 m long (5 cultivars/line x 4 m each) with an additional 1 m row of leucaena (i.e., two plants) at each end of both twin rows as a buffer. The replicates were 6 m apart. Plants were established in January 2013 (Bingara and Manilla) and November 2013 (Trangie).

Digit grass (*Digitaria eriantha*) cv. Premier was sown in the 6 m alleys at Bingara and Manilla in December and November 2013 respectively and at Trangie in October 2013. It failed to establish at all sites. Digit grass was resown at the Manilla site in November 2014 and successfully established. Subsequent attempts to establish digit grass at Bingara failed and the experiments at Bingara and Trangie continued without a sown grass in the alleys.

4.16.3 Site Management

Single superphosphate [8.8% phosphorus (P), 11% sulfur (S)] was applied at 200 kg/ha in spring–early summer at each site each year from 2013. In September each year, the dead frosted stems were cut to a height of 0.3 m and the woody material removed from the experiment. Leucaena pods were removed from plants during the growing season and destroyed to eliminate the risk of recruitment throughout the experiment.

4.16.4 Data collection

Data collected in this project were from the start of the 2017–18 growing season to the end of the 2021–22 growing season, nonetheless data were pooled with that of Boschma *et al*. (2018) and are presented for 10 growing seasons over 2013–2022 in this report.

Rainfall data were recorded either manually (Bingara) or by automatic weather station (Manilla and Trangie). Long-term average monthly and annual rainfall data for all sites were determined from Bureau of Meteorology (BOM) sites (054004, 55331 and 51049).

Persistence of individual leucaena plants was assessed in spring and autumn each year by recording their presence and health. Plants were categorised as present (alive) or absent (dead). At Bingara a third category of present but in poor condition (ill thrift compared to other plants) was also recorded and notes were made on the nature of the poor condition and photos taken.

Leucaena edible herbage mass (herein referred to as herbage mass) was assessed from spring to autumn each growing season whenever the tallest leucaena plants reached approximately 1.8 m in height. Plants were typically harvested 2–3 times per growing season at each site. At each assessment the number of stems was recorded for eight plants. A representative stem on each assessed plant was selected, cut at the point where the stem diameter was about 10 mm and bagged. All leaves from the remainder of this stem were also removed to the base of the plant and placed in the same bag. This harvested stem and leaf material represented the edible proportion of the plant and was dried in a dehydrator for 48 h at 80°C then weighed to calculate herbage dry weight (g DM/plant and kg DM/ha). After each assessment all leucaena plants were cut back to a height of 0.8 m and material removed from the plots in lieu of grazing.

4.17 Herbage and water productivity of lucerne, desmanthus, leucaena and digit grass in pure and mixed and swards

In this study we compared the herbage and water productivity of digit grass, lucerne, desmanthus and leucaena grown as pure swards and in binary mixtures of digit grass with each of legume.

4.17.1 Experimental design and establishment

The experiment was located at Tamworth Agricultural Institute (31°08’43” S, 150°58’06” E, 400 m above sea level) on a Brown Vertosol (Isbell 2002). It was arranged in three replicates of 9 treatments (plots 6 x 9 m). The treatments (Fig. 19) included digit grass cv. Premier, desmanthus cv. Marc, leucaena cv. Tarramba, and lucerne cv. Venus that were sown as pure swards of each species and then as binary mixes of digit grass with each legume. The final two treatments were digit grass sown in the alley >3 m from plots of leucaena, whether as pure or as a mix with digit grass.

Full details are provided in Murphy et al. (2022). In summary, digit grass, desmanthus and lucerne pure and mixed sward treatments were sown on 19 November 2014 into a prepared seedbed. Nine-week old leucaena seedlings were transplanted into twin rows (1.0 m apart and 9.0 m in length) at 0.5 m intervals (equivalent 3333 trees/ha) on 21 November 2014). The soil surface of the pure sward leucaena (LE) plots, was maintained weed free and covered with sugar cane mulch at 1500 kg DM/ha for the duration of the experiment to prevent soil erosion. For the mixture with digit grass (LE-DI), the twin rows were perpendicular to the grass sowing rows, which were sown to within 1.0 m from the leucaena rows.

All plots received 200 kg/ha single superphosphate (8.8% phosphorus, 11% sulphur) in spring each year from 2014-18 and the pure digit grass treatment (DE) received 110 kg/ha urea (46% N) applied in both spring and summer (total of 220 kg/ha, timed to occur with rainfall to minimise volatilisation). Digit grass in mixtures or in the alley between leucaena rows (LE-IR, LE-DI IR) were not fertilised with N.

In the establishment year (2014-15) treatments of digit grass and desmanthus set seed. At the final herbage assessment each growing season (usually in May), desmanthus was left ungrazed to allow seed set. At the beginning of the next growing season, usually in September, treatment plots were mown to remove residual frosted material and the leucaena plants trimmed to 0.3 m height except for 2016 when the plants remained green throughout the uncommonly mild winter.

Table 25. Description, sowing rate (kg/ha viable seed or plants/ha) and species configuration, also neutron moisture meter access tube location for treatments in the experiment at Tamworth Agricultural Institute (Murphy et al. 2022).

Treatment	Code	Cultivar	Sowing rate (kg/ha, plants/ha)		Configuration	Description	Access tube location
			Grass	Legume			
Digit grass	DI	Premier	2	-	Pure sward	Digit grass sown in every drill row	Plot centre
Desmanthus	DE	Marc	-	4	Pure sward	Desmanthus sown in every drill row	Plot centre
Desmanthus + digit grass	DE-DI	Marc + Premier	1	2	Alternate rows 1:1	Desmanthus and digit grass sown in alternate rows	Plot centre
Lucerne	LU	Venus	-	2	Pure sward	Lucerne sown in every drill row	Plot centre
Lucerne + digit grass	LU-DI	Venus + Premier	1	1	Alternate rows 1:1	Lucerne and digit grass sown in alternate rows	Plot centre
Leucaena	LE	Tarramba	-	3333	Leucaena twin rows 1 m apart	Leucaena seedlings transplanted at 0.5 m intervals into twin rows 1 m apart on 12 m spacing. Digit grass sown no closer than 2.5 m from leucaena.	Plot centre, between leucaena rows
Leucaena inter-row sown to digit grass	LE-IR	Premier	2	-	Pure sward	Digit grass sown in the inter-row between leucaena rows	6 m from centre of leucaena rows
Leucaena + digit grass	LE-DI	Tarramba + Premier	2	3333	Leucaena twin rows 1 m apart, digit grass pure sward 1.0 m from leucaena	Leucaena seedlings transplanted at 0.5 m intervals into twin rows 1 m apart on 12 m spacing. Digit grass sown up to 1.0 m from leucaena.	Plot centre, between leucaena rows
Leucaena + digit grass inter-row sown to digit grass	LE-DI IR	Premier	2	-	Pure sward	Digit grass sown in the inter-row between leucaena rows	6 m from centre of leucaena rows

4.17.2 Data collection and statistical analyses

Soil water content was measured with a neutron moisture meter (NMM, CPN503–DR Hydroprobe, Boart Longyear Co., Martinez, CA) from an aluminium access tube installed in each plot to 1.9 m depth. Over the period 20 November 2014–9 May 2018 there were 52 sample dates.

Herbage production (kg DM/ha) was estimated using a calibrated visual score (Murphy et al. 2022) at approximately 6-week intervals during the pasture growing period (September-May). Annual herbage production was determined by accumulating values from 1 July-30 June for each of 4 growing years. The physical dimensions (width and height) of the leucaena shrubs were recorded and herbage production determined using a standard visual technique (e.g., Murphy et al. 2017). The edible material from the typical cane was classified as leaf and stem <10 mm diameter.

After each herbage assessment, the experiment was crash grazed with sheep to about 0.1 m residual height and a flail or rotary used to remove any residual material >0.1 m in height. Fences around the leucaena plots were used to control sheep access and prevent overgrazing of leucaena plants. After grazing, long stems that were beyond the reach of sheep were trimmed to a height of 1.2 m.

Plant frequency (Brown 1954) of digit grass, lucerne and desmanthus were assessed in spring and autumn each year using two fixed quadrats (1.0 x 1.0 m, total 100 cells each 0.1 x 0.1 m). Leucaena plants in each row were counted to record any losses.

A range of statistical analyses were used to analyse the data. Details are provided in Murphy et al. (2022).

4.18 Rotational versus continuous grazing for persistence of tropical pastures

4.18.1 Pasture and site establishment

Digit grass cv. Premier and desmanthus cv. Progardes were sown in a mixed pasture in alternate species rows (0.25 m row spacing) in a 2 ha paddock on 20 November 2018. Cultivar Progardes 'southern blend' consisted of *D. virgatus* cv. JCU 2, *D. bicornutus* cv. JCU 4, *D. leptophyllus* cv. JCU 7 and *D. pernambucanus* cv. JCU 9. The paddock was located at the Tamworth Agricultural Institute near Tamworth on a brown Chromosol soil (Table 26).

Table 26. Location and soil characteristics (0-10 cm) of the grazing experimental site.

Location	31.146°S 150.967°E
Soil type	Brown Chromosol
pH ($CaCl_2$, 0-10 cm)	5.2
Total nitrogen (%)	0.2
Sulfur (KCl_{40}, mg/kg)	20
Phosphorus (Colwell, mg/kg)	45
Organic carbon (%)	1.8
Potassium (cmol(+)/kg)	1.1

Fences were erected in 2019 to create plots (15 x 10 m) for an experiment consisting of four treatments with three replicates. The plots within each replicate were positioned side by side, with a laneway between replicates. Fences were constructed to allow communal grazing of all replicate plots of pairs of treatments. Gates were installed so that plots could be closed to exclude grazing as required. The experiment was due to commence in spring 2019, delayed 12 months due to the ongoing drought. The plots were mown and the herbage removed in August and October 2020 to reset the pasture.

4.18.2 Treatment details

The desmanthus grazing study was conducted November 2020-May 2021. Following poor plant presence of desmanthus recorded in all plots in spring 2021, the objective of the grazing study was adjusted and the fertilised digit grass experiment was conducted November 2021–April 2022. Details of the treatments for each experiment are listed below.

Desmanthus grazing experiment – 2020-21 growing season

The desmanthus grazing study was conducted November 2020-May 2021. Treatments were implemented using an open communal grazing design (Kemp et al. 2000) and consisted of two continuous and two rotational grazing treatments. Within each grazing system, one of the treatments included an extended rest period. This rest period was to provide an opportunity for desmanthus to set seed and/or seedling regeneration and anticipated to be 8-12 weeks. The treatments are listed in Table 27a.

Table 27. Grazing treatments imposed in the (a) desmanthus-digit grass grazing experiment 2020-21 and (b) fertilised digit grass grazing experiment 2021-22.

ID	Treatment
	(a) Desmanthus grazing experiment – 2020-2021
T1	Continuously grazed (nil opportunity for seed set or seedling regeneration)
T2	Treatment 1 with a rest period to allow set seed/seedling regeneration
T3	Rotationally grazed with high stock numbers then rested until desmanthus regrew to minimum 0.25 m height
T4	Treatment 3 with an additional rest period to allow for seed set/seedling regeneration
	(b) Fertilised digit grass grazing experiment – 2021-2022
T1	+Nitrogen (100 kg/ha N), continuously grazed
T2	+Nitrogen (100 kg/ha N), rotationally grazed (pasture rested when green leaf fell to ~800 kg DM/ha and reopened for grazing when pasture regrew to average 3-4 green leaves/tiller?
T3	-Nitrogen (0 kg/ha N), continuously grazed
T4	-Nitrogen (0 kg/ha N), rotationally grazed (rest periods applied as per Treatment 2)

The stocking rate was varied using a put and take method involving adjusting sheep numbers to match pasture growth rate and maintain green herbage mass suitable for livestock production with a minimum of 0.8 t DM/ha green leaf herbage mass. Stocking rates for each communal grazing area were adjusted independently. The extended rest period (treatments 2 and 4) was applied to allow for seed set and recruitment of desmanthus. These factors are required for successful regeneration of the legume.

Six-month old Merino wether lambs were placed on the plots on 4 November 2020. The continuously grazed plots were grazed until 3 May 2021. Sheep were vaccinated with 5 in 1 for clostridial diseases, drenched to control internal parasites and backlined as a preventative against fly strike throughout the experimental period.

Nitrogen fertilised digit grass grazing experiment – 2021-22 growing season

The fertilised digit grass experiment was conducted November 2021–April 2022. Treatments consisted of two nitrogen fertilised treatments (100 kg N/ha; +N) and two unfertilised treatments (0 kg N/ha; -N) (Table 27b). Within each N treatment one was continuously grazed and the other rotationally grazed. The rotationally grazed plots were closed (destocked) when herbage mass fell to ~800 kg DM/ha green leaf and reopened for grazing when the pasture had regrown to 3-4 green leaves/tiller.

Nitrogen fertiliser (100 kg N/ha) was broadcast onto the +N fertilised areas (plots, laneways and additional area) on 28 October 2021 and single superphosphate (125 kg/ha, 8.8% phosphorus and 11% sulphur) applied to the whole experimental area. The experiment was flail mown to about 0.15 m and herbage removed from the plots on 1 November to reset the pasture. The experiment commenced on 3 November 2021 when 5-month old first cross Poll Dorset lambs were placed on the plots.

Faecal egg counts were conducted regularly to monitor internal parasites. Lambs were drenched and vaccinated with 5 in 1 for clostridial diseases before commencing grazing. Barbervax (purified *Haemonchus contortus* antigen min 5 µg/ml) vaccine was used to prevent Barber's Poll worm (*Haemonchus contortus*) infestation. Lambs were also drenched with multicombination oral drench to control internal parasites and backlined as a preventative against fly strike.

4.18.3 Data collection

Similar methodology was used for data collection for both studies.

Herbage production

Herbage production was generally assessed at least fortnightly, before grazing plots were open or closed (rest periods or rational grazing), or there was a change in green herbage mass availability. Dry matter was assessed using a calibration score technique similar to Boschma et al. (2021) with 6 assessments per plot. A subset of the calibration quadrats containing digit grass were sorted into green leaf, green stem, dead leaf and dead stem to better estimate the available feed. All samples were dried at 80^{o}C for 48 hr and dry weights used to convert scores to kg DM/ha.

The herbage mass data were used to determine stocking rates with the aim to maintain at least ~800 kg DM/ha of green leaf. Stock numbers were determined using the calculation:

$$\text{Number of sheep} = \frac{S - R + G * T}{DMI * 30}$$

Where *S* was the average standing green biomass of the same treatment before grazing (kg DM/ha), R was the residual herbage mass (kg DM/ha), G was the estimated growth rate (kg DM/ha/d), *T* was the time period for grazing (days), and *DMI* was the dry matter intake (kg DM/sheep/d) and set at 1.5 DM/sheep/d.

Pasture persistence

Frequency of occurrence (Brown 1954) of desmanthus and digit grass was assessed October 2020, October 2021 and April 2022. Plant frequency was assessed using 1 m^2 grid consisting of 100 cells (each 0.1 x 0.1 m) in four fixed locations in each plot.

Sheep weights

Sheep were weighed whenever stocking rates were adjusted but generally every ~2 weeks when pasture herbage mass was assessed. When large numbers of sheep were added to the rotational grazing treatment plots, a subset of ~20 sheep were weighed at each assessment. The sheep were ear tagged so that they could be easily identified to ensure the same animals were weighed. Daily growth rate (g/day/hd), total number of grazing days (number sheep/ha * number of days), lamb weight gain/ha (kg/ha; change in sheep weight * number sheep/ha) and daily weight gain/grazing day (kg/ha/grazing day; weight gain/ha/number of grazing days) were calculated.

Pasture quality – 2021-22 growing season only

At each herbage mass assessment, forage samples from each communal grazing treatment were collected for nutritive value assessment (i.e., +N and -N only). Pluck samples of the material was selected that represented what the animals were eating i.e., green leaf. Samples were ground (2 mm sieve) and analysed for crude protein, metabolisable energy, and neutral and acid detergent fibre (NDF and ADF) at a NATA accredited laboratory.

Freshly defecated faecal samples were collected from each communal grazing area whenever herbage mass was assessed/stocking rate adjusted. The samples were stored in a cooled esky then oven-dried at 60°C. The samples were sent to NSW DPI Feed Service laboratory for analysis as part of the LPP NIR project (P.PSH.1202 New generation NIRS calibrations to improve diet evaluation and animal growth). These data are not reported.

Weather

Month and long-term average (LTA) rainfall data were sourced from Bureau of Meteorology site 055325.

4.19 Temperate legumes in tropical grass mixes in southern NSW

4.19.1 Sites and treatments

Four sites were selected in central and southern NSW to provide a contrast in environmental conditions: Orange, Cowra, Wagga and Yanco (Table 28). At each site 2-3 tropical perennial grasses were sown in mixes with seven annual and perennial temperate legumes in a randomised complete block designed experiment, replicated three times. The grasses were chosen to provide variation in grass habit, each anticipated to be persistent in the selected environments based on experience and literature. The companion temperate legumes were selected to provide a range of species adapted to the target environments with potential for late spring sowing as hard seed. All species offered a range of summer- and winter-growing habits. The species sown at each site are listed in Table 29 and sowing rates and seed characteristics are shown in Table 30. All legume species were sown at commercial rates and inoculated with the appropriate strain of rhizobia immediately prior to sowing.

Table 28. Site location, elevation (m), average annual rainfall (AAR, mm), also soil classification, and pH (in $CaCl_2$), Colwell P (mg/kg) and effective cation exchange capacity (ECEC, cmol(+)/kg) (0.0.1 m) for the experimental sites.

Location (nearest town and region)	Site coordinates	Elevation (m)	AAR (mm)	Soil Classification[1]	pH_{Ca}	Colwell P (mg/kg)	ECEC (cmol(+)/kg)
Cowra, Central Slopes	33°48.372’S 148°42.625’E	360	625	Red Chromosol	5.0	33	4.3
Orange, Central Tablelands	33°19.549’S 149°4.834’E	922	920	Brown Ferrosol	5.5	35	6.2
Wagga Wagga, Eastern Riverina	35°2.538’S 147°19.036’E	189	504	Kandosol	5.0	69	7.4
Yanco, Central Riverina	34°38.067’S 148°25.560’E	152	427	Red/Brown Chromosol	6.2	70	8.7

[1] Australian Soil Classification (Isbell 1996)

Table 29. Tropical grass and companion temperate legume species sown at Cowra, Orange, Wagga and Yanco (indicated by X). The tropical grass and legumes were sown in a factorial combination with each grass also sown as a control without a companion legume.

Species	Cowra	Orange	Wagga	Yanco
Topical grasses				
Makarikari grass (*Panicum coloratum*) cv. Bambatsi		X		
Digit grass (*Digitaria eriantha*) cv. Premier	X	X	X	X
Rhodes grass (*Chloris gayana*) cv. Katambora	X	X	X	X
Companion legumes				
Biserrula (*Biserrula pelecinus*) cv. Casbah	X	X	X	X
Bladder clover (*Trifolium spumosum*) cv. Bartolo	X	X	X	X
French serradella (*Ornithopus sativus*) cv. Margurita	X	X	X	X
Yellow serradella (*Ornithopus compressus*) cv. Avila	X	X		
Yellow serradella (*O. compressus*) cv. King			X	X
Gland clover (*Trifolium glanduliferum*) cv. Prima	X	X	X	X
Rose clover (*Trifolium hirtum*) cv. Hykon	X	X	X	X
Lucerne (*Medicago sativa*) cv. Titan 9	X	X		
Lucerne (*M. sativa*) cv. Aurora			X	X

Table 30. Thousand kernel weight (TKW), germination percentage (Germ, %), seeding rate (kg/ha), seeds per kilogram and seeds sown (/m^2) for species used in the tropical grass mixtures experiments.

Species	TKW (g)	Germination (%)	Sowing rate (kg/ha)	Seeds/kg	Seeds sown (/m^2)
Biserrula cv. Casbah	3.20	100	30	312500	938
Bladder clover cv. Bartolo	2.80	12	30	357143	1071
French serradella cv. Margurita	4.30	2	30	232558	698
Yellow serradella cv. Avila	4.80	18	30	208333	625
Gland clover cv. Prima	0.80	16	30	1250000	3750
Rose clover cv. Hykon	4.40	56	30	227273	682
Lucerne cv. Titan 9	4.60	86	4	217391	87
Lucerne cv. Aurora	NA[1]	NA	4	NA	NA
Digit grass cv. Premier	2.24	NA	5	447027	224
Rhodes grass cv. Katambora	0.43	NA	1	2347418	235
Makarikari grass cv. Bambatsi	0.98	NA	2	1016088	203

[1] NA, not assessed

The Cowra experiment was sown on 6 November 2019 with 14.3 kg/ha nitrogen (N), 12 kg/ha phosphorus (P) and 10.5 kg/ha sulfur (S) applied at sowing. The area sown had been chemically fallowed and 3.5 t/ha lime applied and incorporated on 23 August. Plots measured 1.8 x 7.5 m and were sown with narrow points and press wheels on 17 cm row spacing. Irrigation (20 mm) was applied the day after sowing, followed by three irrigations at weekly intervals totalling 60 mm. The site was sprayed with 25 g/ha flumetsulam (800 g/kg active ingredient) to control emerging broadleaf weeds four weeks post sowing.

The Orange mixture experiment was sown on 14 January 2020. Plots measured 1.4 x 6 m and were sown with narrow points and press wheels on 17 cm row spacing. Fertiliser was applied at sowing

(14.3, 12 and 10.5 kg/ha N, P and S respectively). Sowing was delayed from November to ensure there was enough moisture for successful establishment. No irrigation was applied.

The experiments at Wagga and Yanco were sown in late October 2019. Fertiliser was applied at sowing (14.3, 12 and 10.5 kg/ha N, P and S respectively). Due to the dry conditions experienced both before and after sowing the experiments were irrigated to establish.

4.19.2 Establishment, persistence, herbage production and climate observations

Emergence counts were assessed 3-4 weeks after emergence by counting the numbers of seedlings in two adjacent rows along a 0.5 m length. For each species this was conducted in four locations in each plot and converted to plants/m^2. Legume seedling regeneration was assessed using the same method.

Plant persistence was measured through assessments of basal frequency in autumn of each year at each site (Brown 1954). Fixed quadrats (1.0 x 1.0 m) divided into 100 cells (each 0.1 x 0.1 m) were located centrally in each plot. The number of cells which contained a live plant base was counted. For Rhodes grass, nodes which were anchored by roots within a cell were also included in the cell count and expressed as a percentage (%) of squares occupied by at least one anchored live plant. Temperate and tropical species were assessed separately.

Herbage dry matter (DM) production was visually estimated by scoring the total herbage and estimating the percentage of sown species every 4–6 weeks during the growing season (Lodge and Harden 2011). Plots were divided into three or four strata, depending on variability, and assessments made in each. Assessments of DM were calibrated by cutting 10–15 representative quadrats to 1 cm, encompassing the full range of scores given at each site, and sorting into sown species and other herbage. Each sample was dried at 60˚C for 48 hrs and weighed. Visual scores were converted to kg DM/ha using a regression function between visual scores and the calibrated dry matter sample for each site. After each herbage production assessment all plant material was removed by mowing, leaving 5-10 cm of residual biomass on each plot. Following the peak spring herbage production assessment, annual legume species were allowed to set seed without further dry matter removal.

Rainfall and temperature were recorded daily at each site or at a nearby weather station. Monthly total for rainfall and average maximum and minimum temperatures were determined.

4.20 Enablers and constraints to trialling and successful management of tropical grasses

The aim of this component was to conduct social research to identify and understand the key enablers and constraints to the trialling and ‘successful’ management of tropical grass-based pastures across inland NSW with a focus on central and southern NSW. The key research questions were:

1. To what extent are producers across inland NSW trialling and managing tropical grasses, and for those who have not trialled, are interested in trialling those grasses?
2. What are the key property, personal and social factors enabling or constraining trialling; and “successfully” managing tropical grasses.
3. What are the key benefits and challenges to establishing; and “successfully” managing tropical grasses.

This research was conducted in three stages using a mix of qualitative and quantitative data collection methods in three stages. Stage 1 (qualitative) involved workshops with purposively selected experienced and inexperienced producers and key informants. In Stage 2 (quantitative) survey was undertaken of a broader range of producers to build on the insights gained from Stage 1. Stage 3 (qualitative) involved semi-structured interviews with purposively selected producers and service providers.

4.20.1 Stage 1 – producer workshops

Workshops were held in five regions across NSW: Purlewaugh near Coonabarabran, Bingara, Dubbo, Orange and Cowra. The first three workshops were with producers who had experience establishing and managing tropical grass pastures (i.e., 'experienced'). The last two workshops were with producers who were interested in tropical grasses or who may have recently trialled a small area of these grasses (i.e., 'inexperienced').

Producers were purposefully selected with advice from industry experts to obtain a diversity of experiences with tropical grasses. The producers ran different enterprises on properties located across a range of soil types and climatic conditions and had different years of experience establishing and managing these grasses.

Experienced producer workshops

Producers at these workshops, producers were asked a series of questions to reveal their knowledge about and experience with tropical grasses. Key questions included:

- Can you describe your first experience in establishing tropical grasses?
- What is your current establishment practice and grazing management strategy?
- What are the benefits and challenges associated with these grasses?
- What are the three most important practical lessons you would pass on to producers considering trialling tropical grasses?

Inexperienced producer workshops

At these workshops, producers were presented with the value proposition for adding tropical grasses to their feedbase. Robert Freebairn, agricultural consultant and producer with extensive experience with tropical grass pastures, presented the business case. A producer and early adopter of tropical grasses from the district, also shared their experiences.

Workshop participants were then asked to respond to a series of questions to better understand their level of interest in tropical grasses, and the support they would require if they were to trial these grasses. Key questions included:

- What do they see as the benefits and challenges from adding tropical grasses to your farming system?
- What are three things you need to know before you would trial these grasses?
- What support would you need in your decision-making about introducing these grasses on your farm?
- What support would you need to trial these grasses?

4.20.2 Stage 2 – Producer survey

A survey instrument was developed largely based on information from the Stage 1 workshops. The main topics in the survey were:

- Level of awareness, intentions, and experience with tropical grasses
- Knowledge about tropical grasses and general agronomic practices
- Benefits and concerns about growing tropical grasses
- Farm structure and business enterprise
- Values attached to the property
- Long-term plans for the property.
- Concerns about issues affecting their property and district.

The survey was pre-tested and revised to incorporate suggested changes.

The survey was randomly distributed by hand to 200 mailboxes in each of five districts centred on the towns Boggabri, Cassilis, Cowra, Forbes and Trangie (total 1000 surveys). These districts were selected to achieve a distribution across summer/winter dominant rainfall zones and east/west geography. Three reminder/thankyou cards were mailed at weekly intervals. Non-respondents were mailed a second survey booklet followed by a reminder/thank you card a week later (Curtis et al. 2005). An online equivalent survey was also made available. There are 115 usable mail out surveys (12% response rate) and 45 usable online surveys (total of 160).

Descriptive statistics including median, means and frequencies were used to summarise the data. Kruskal Wallis rank sum test is used to test differences on a 5 Likert scale variable based on a grouping variable (e.g., between districts, between experienced/inexperienced producers). ‘Not applicable/Don’t know’ and missing responses are removed from the calculation of mean scores out of 5 and the statistical analyses. Pairwise comparisons are used to test for relationships between variables (i.e., all survey items). To simplify the presentation of the Likert-type scale data in summary tables, the categories ‘important’ and ‘very important’, ‘agree’ and ‘strongly agree’, ‘likely and highly likely’ and ‘sound knowledge’ and ‘very sound knowledge’ were combined.

4.20.3 Stage 3 – Semi structured interviews

Interviews were conducted with southern NSW producers who had recently sown tropical grasses and service providers in that area with an interest in tropical grasses.

An interview guide was developed for the producers and this was modified for the service providers. The interviews explored the (a) decision-making process used by producers to trial tropical grasses, (b) factors influencing their decision to trial, and (c) the benefits and challenges in establishing and managing their tropical grass-based pastures.

Four full-time producers and two service providers were interviewed in total. The service providers had previous experience with tropical grasses from time spent in the northern NSW. Both service providers believed these grasses could be an option in southern NSW and were encouraging producers to consider tropical grasses.

5. Results

5.1 Determining the potential distribution of tropical species in current and future climates

This section focuses on the baseline and 2050 climate distributions as the 2030 distributions had the same trend as the 2050 distributions. All modelled predictions are presented in Appendix 1.

5.1.1 Kikuyu

Baseline climate distribution

Based on climate alone, the proportion of area modelled as suitable and highly suitable for kikuyu under the baseline climate was highest in the SE states (i.e., NSW, ACT, Victoria and Tasmania) (42–89%, total 56.84 M ha) (Fig. 5, Table 31). The area classified as unsuitable for kikuyu was >80% in Queensland, Western Australia (WA) and SA, with 100% of the land in the NT classified as unsuitable (Fig. 5a, Table 5a).

For the combined model, there was little change in area classified as unsuitable for Queensland, NT, WA and SA with all still >80% (total area 658.71 M ha). However, the SE states of Victoria, Tasmania, ACT and to a lesser extent NSW showed a large increase in area classified as unsuitable. The areas classified as highly suitable for kikuyu declined for all states and the ACT, but the decrease in highly suitable areas was greatest for the SE states of Victoria, Tasmania, ACT and to a lesser extent NSW (Fig. 5b, Table 31b).

The total area modelled as highly suitable to kikuyu under the baseline climate and combined models in Australia is 19.6 M ha; 8.17 M ha in NSW and 4.17 M ha in Queensland. Based on the greatest proportion of the state highly suitable under the baseline climate and combined models, kikuyu is best suited to SE Australia (total 10.78 M ha).

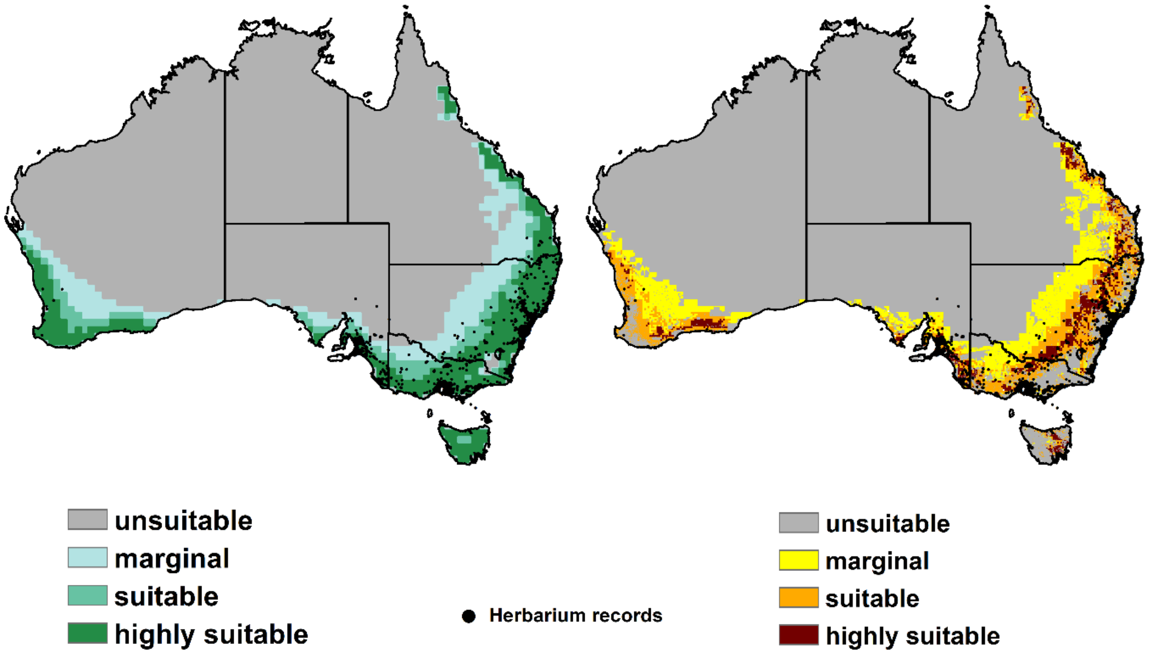


Fig. 5. Distribution of kikuyu modelled as unsuitable, marginal, suitable and highly suitable based on baseline (a) climate and (b) combined climate-soil pH-land use models.

Table 31. State and territory area (M ha) and proportion (%) modelled as unsuitable, marginal, suitable and highly suitable for kikuyu under baseline (a) climate conditions and (b) combined climate-soil pH-land use conditions.

State	Unsuitable		Marginal		Suitable		Highly suitable	
	M ha	%	M ha	%	M ha	%	M ha	%
				(a) Climate				
NSW	29.26	37	17.11	21	8.91	11	24.77	31
QLD	139.57	81	16.28	9	4.10	2	12.33	7
NT	133.39	100	0.00	0	0.00	0	0.00	0
WA	214.60	85	14.30	6	8.35	3	15.04	6
SA	84.42	86	4.99	5	3.92	4	4.60	5
VIC	2.26	10	3.22	14	4.59	20	12.64	56
TAS	0.67	10	0.00	0	0.46	7	5.29	82
ACT	0.07	28	0.00	0	0.00	0	0.17	72
				(b) Combined climate-soil pH-land use				
NSW	38.35	48	17.25	22	16.17	20	8.17	10
QLD	145.96	85	15.36	9	6.87	4	4.17	2
NT	134.29	100	0.00	0	0.00	0	0.00	0
WA	222.67	88	15.48	6	11.15	4	2.60	1
SA	86.63	89	6.15	6	2.92	3	2.03	2
VIC	9.52	42	5.10	23	6.14	27	1.82	8
TAS	4.83	74	0.17	3	0.74	11	0.79	12
ACT	0.15	87	0.00	0	0.01	4	0.01	8

Distribution in 2050 climate

The proportion of states and territories classified as unsuitable for the climate model increased (5–15 percentage units) in Queensland for both MIROC-H and CSIRO-MK 3.0 scenarios (Fig. 6, Table 32). Under the MIROC-H scenarios the proportion classified as highly suitable in the SE states increased up to 14 and 7 percentage units for the climate and combined models respectively. In contrast under the CSIRO-MK 3.0 scenarios the area classified as highly suitable decreased in NSW, remained similar in Victoria and increased in Tasmania (Table 32).

The total area classified as highly suitable using the combined model for kikuyu in Australia by 2050 under the MIROC-H and CSIRO-MK 3.0 scenarios averaged 24.87 (3%) and 8.82 M ha (1%), while in SE Australia, highly suitable area averaged 16.57 and 4.69 M ha respectively.

Table 32. State and territory area (M ha) and proportion (%) modelled as unsuitable, marginal, suitable and highly suitable for kikuyu under current climate and climate scenarios centred on 2050 for (a) climate and (b) climate + soil pH + land use. Climate scenarios are: Baseline, MIROC-H A1B (MHA1B), MIROC-H A2 (MHA2), CSIRO-MK 3.0 A1B (CA1B) and CSIRO-MK 3.0 A2 (CA2).

State	Unsuitable (%)					Marginal (%)					Suitable (%)					Highly suitable (%)				
	Baseline	MHA1B	MHA2	CA1B	CA2	Baseline	MHA1B	MHA2	CA1B	CA2	Baseline	MHA1B	MHA2	CA1B	CA2	Baseline	MHA1B	MHA2	CA1B	CA2
(a) Climate																				
NSW	37	30	31	58	57	21	18	18	15	14	11	13	13	7	8	31	39	38	20	22
QLD	81	86	85	96	95	9	7	8	2	3	2	3	3	1	1	7	3	4	1	1
NT	100	100	100	100	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
WA	85	84	84	87	86	6	6	6	5	5	3	4	4	3	3	6	7	7	6	6
SA	86	84	84	90	90	5	6	6	4	4	4	3	3	2	2	5	6	6	4	4
VIC	10	5	5	16	16	14	12	12	14	12	20	14	14	15	15	56	70	70	55	57
TAS	10	10	10	10	10	0	0	0	0	0	7	0	0	0	0	82	90	90	90	90
ACT	28	28	28	28	28	0	0	0	0	0	0	0	0	0	0	72	72	72	72	72
(b) Combined climate-soil pH-land use																				
NSW	48	40	41	70	69	22	20	19	16	15	20	23	23	11	12	10	17	17	3	4
QLD	85	89	88	98	97	9	7	8	2	2	4	3	3	0	0	2	1	1	0	0
NT	100	100	100	100	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
WA	88	87	87	91	90	6	7	7	5	5	4	4	4	3	3	1	2	2	1	1
SA	89	87	87	93	92	6	7	7	4	4	3	4	4	2	3	2	2	2	1	1
VIC	42	35	35	51	51	23	20	20	20	18	27	33	33	23	24	8	12	12	6	7
TAS	74	71	71	81	81	3	1	1	0	0	11	12	12	7	7	12	16	16	11	11
ACT	87	53	53	71	71	0	8	8	3	3	4	30	30	18	18	8	9	9	7	7

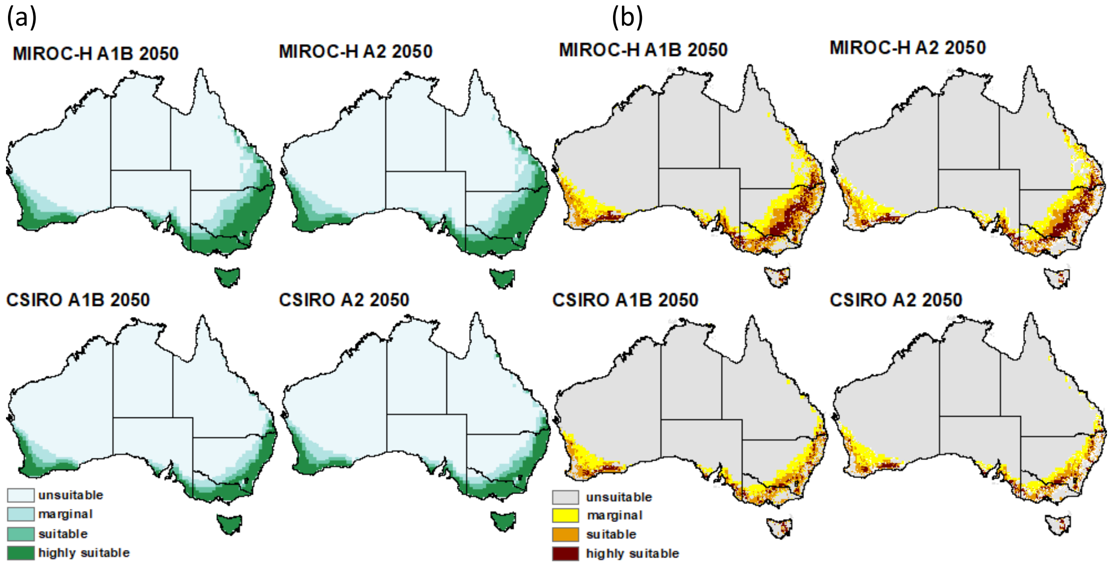


Fig. 6. Distribution of kikuyu based on 2050 projected (a) climate and (b) combined climate-soil pH-land use models. Climate scenarios are: current MIROC-H A1B, MIROC-H A2, CSIRO-MK 3.0 A1B and CSIRO-MK 3.0 A2.

5.1.2 Rhodes grass

Baseline climate distribution

Under the baseline climate, Tasmania and Victoria had the smallest proportion of area classified as unsuitable for Rhodes grass by climate alone. Conversely these states had the highest proportion classified as suitable and highly suitable (50–59%) (Fig. 7a). All of the ACT and the majority of SA were unsuitable (100 and 89% respectively) (Table 33a).

For the combined model, Victoria and NSW had smallest area classified as unsuitable (45 and 53% respectively), while the ACT and SA had the highest proportions (100% and 90% respectively). Queensland and NSW had the highest proportion of area classified as highly suitable and suitable (27–34%, combined total of 77.05 M ha) (Fig. 7b, Table 33b).

Total area modelled as highly suitable to Rhodes grass under the baseline climate and combined models in Australia is 39.08 M ha (5%) with 21.35 M ha located in Queensland. In the SE states, Rhodes grass was modelled as highly suited to 7.58 M ha (7% of the combined area).

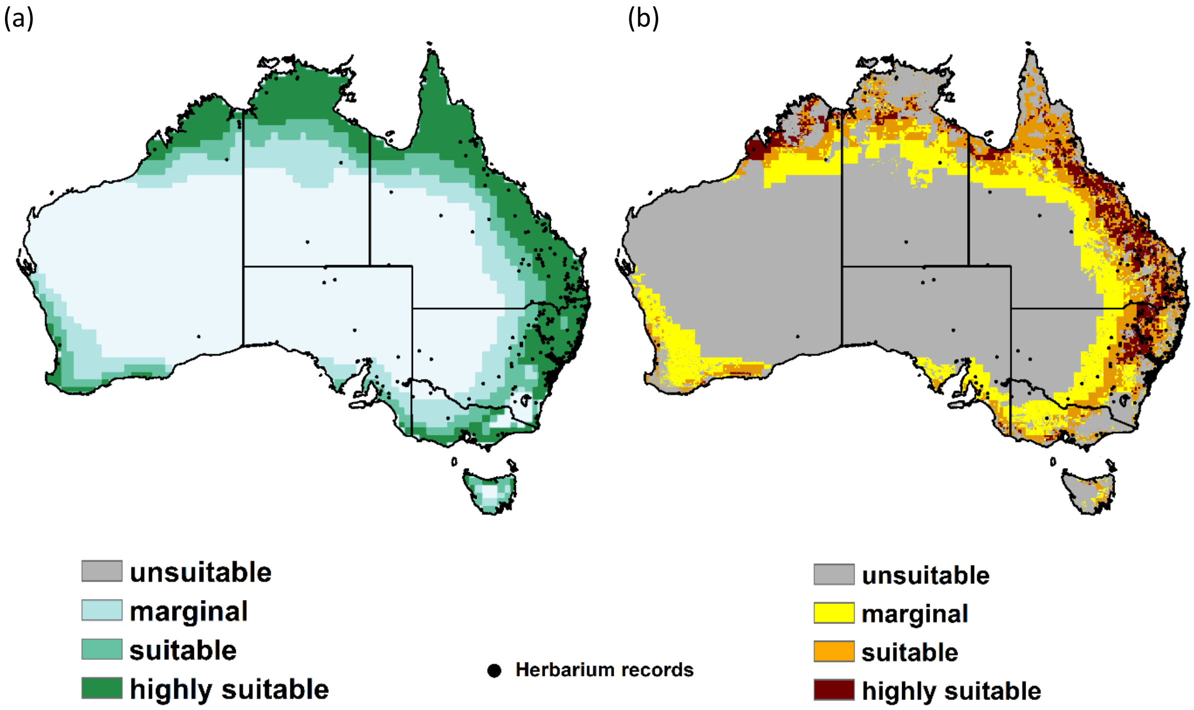


Fig. 7. Distribution of Rhodes grass modelled as unsuitable, marginal, suitable and highly suitable based on baseline (a) climate and (b) combined climate-soil pH-land use models.

Table 33. State and territory area (M ha) and proportion (%) modelled as unsuitable, marginal, suitable and highly suitable for Rhodes grass under baseline (a) climate conditions and (b) combined climate-soil pH-land use conditions.

	Unsuitable		Marginal		Suitable		Highly suitable	
	M ha	%	M ha	%	M ha	%	M ha	%
				(a) Climate				
NSW	35.86	45	13.44	17	10.87	14	19.69	25
QLD	66.55	39	23.56	14	21.71	13	59.73	35
NT	67.68	51	22.21	17	13.52	10	29.52	22
WA	184.30	73	28.93	12	19.31	8	18.64	7
SA	86.56	89	7.13	7	3.29	3	0.42	<1
VIC	5.19	23	6.09	27	4.86	22	6.36	28
TAS	1.39	22	1.15	18	2.57	41	1.10	18
ACT	0.24	100	0.00	0	0.00	0	0.00	0
			(b) Combined climate-soil pH-land use					
NSW	41.07	53	15.10	19	14.32	18	6.95	9
QLD	80.94	48	30.48	18	34.44	21	21.35	13
NT	96.96	74	17.84	14	13.47	10	3.27	2
WA	201.35	81	28.65	12	11.54	5	6.75	3
SA	87.74	90	7.29	8	1.79	2	0.14	0
VIC	9.48	45	6.78	32	4.16	20	0.53	3
TAS	4.66	77	0.50	8	0.77	13	0.09	1
ACT	0.24	100	0.00	0	0.00	0	0.00	0

Distribution in 2050 climate

The area classified as unsuitable for Rhodes grass in 2050 using the MIROC-H scenarios in SE Australia decreased in both the climate and combined models, that is, NSW, ACT, Victoria and Tasmania (Fig. 8, Table 34). The area classified as unsuitable in Queensland and the NT where Rhodes grass has traditionally been sown was projected to increase. Under the CSIRO-MK 3.0

scenarios the area classified as unsuitable will increase for all states. Only the ACT is modelled to change – from 100% unsuitable under the baseline climate to 83% in 2050 climate.

Using the MIROC-H scenario, about 33% of the area of Queensland and SE Australia were classified as highly suitable for the climate model. The highly suitable area was projected to increase by 2050 for all these states except Queensland which will decline from 22% (baseline climate) to 13% (climate model). For the combined model, highly suitable areas in NSW, ACT and Tasmania are projected to increase but only to maximum of 14%.

Suitability based on the climate model using the CSIRO-MK 3.0 scenario indicated highly suitable areas of all states will decrease except Tasmania which will increase to 26–29% and WA and SA which have ≤2% area classified as highly suitable.

In the combined model total average area in Australia classified as highly suitable is 34.41 M ha (5%) for the MIROC-H scenario in 2050. NSW has the largest proportion of the state classified as highly suitable (14%, 10.86 M ha), with Queensland having the largest area (18.89 M ha). Under the CSIRO-MK 3.0 scenarios total area in Australia classified as highly suitable is modelled to be 15.70 M ha (2%); Queensland with the highest proportion of land classified as highly suitable (7%, 11.80 M ha), followed by NSW (3–4%, average 2.65 M ha), both declining from current estimates.

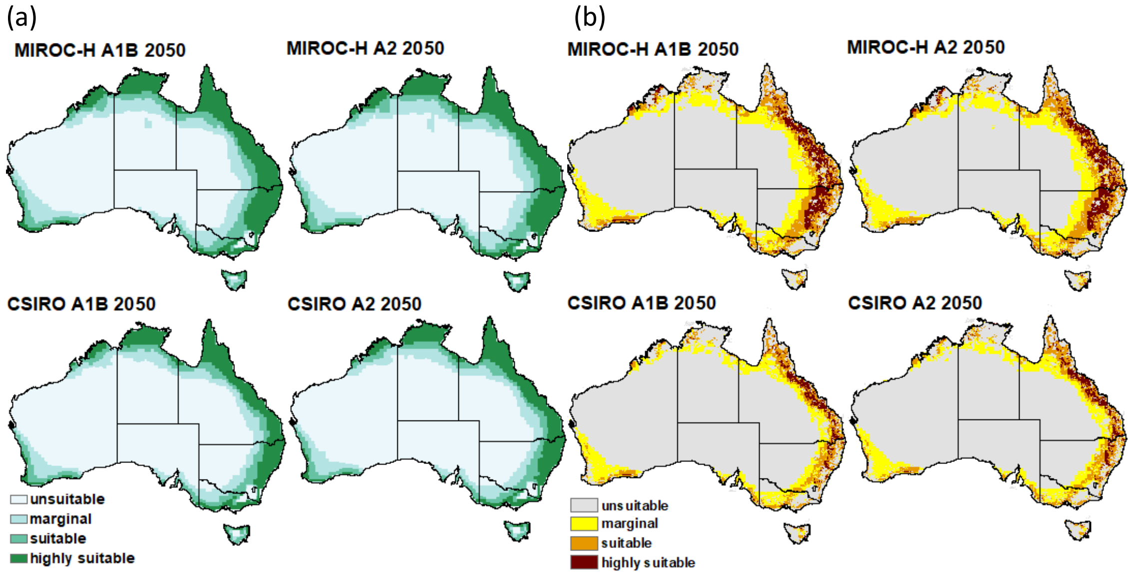


Fig. 8. Distribution of Rhodes grass based on 2050 projected (a) climate and (b) combined climate-soil pH-land use models. Climate scenarios are: current MIROC-H A1B, MIROC-H A2, CSIRO-MK 3.0 A1B and CSIRO-MK 3.0 A2.

Table 34. State and territory area (M ha) and proportion (%) modelled as unsuitable, marginal, suitable and highly suitable for Rhodes grass under current climate and climate scenarios centred on 2050 for (a) climate and (b) climate + soil pH + land use. Climate scenarios are: Baseline, MIROC-H A1B (MHA1B), MIROC-H A2 (MHA2), CSIRO-MK 3.0 A1B (CA1B) and CSIRO-MK 3.0 A2 (CA2).

State	Unsuitable (%)					Marginal (%)					Suitable (%)					Highly suitable (%)				
	Baseline	MHA1B	MHA2	CA1B	CA2	Baseline	MHA1B	MHA2	CA1B	CA2	Baseline	MHA1B	MHA2	CA1B	CA2	Baseline	MHA1B	MHA2	CA1B	CA2
										(a) Climate										
NSW	45	35	36	58	58	17	17	17	11	11	14	13	13	11	12	25	34	34	19	20
QLD	39	43	42	58	57	14	15	15	12	13	13	10	10	7	7	35	32	32	23	24
NT	51	68	66	76	73	17	13	14	9	11	10	6	6	5	5	22	13	14	10	11
WA	73	76	76	83	82	12	12	11	8	8	8	7	7	7	7	7	5	5	2	2
SA	89	87	88	92	92	7	7	7	4	4	3	5	5	3	3	0	1	1	0	0
VIC	23	15	14	28	27	27	23	27	26	27	22	29	26	23	22	28	33	33	23	24
TAS	22	14	14	14	18	18	4	11	18	14	41	50	42	39	42	18	33	33	29	26
ACT	100	45	45	67	67	0	22	22	0	0	0	0	0	33	33	0	33	33	0	0
										(b) Combined climate-soil pH-land use										
NSW	53	44	48	70	69	19	18	17	14	13	18	23	21	13	14	9	14	14	3	4
QLD	48	52	55	70	68	18	19	18	13	14	21	17	16	10	11	13	12	11	7	7
NT	74	84	85	92	90	14	12	12	6	8	10	3	3	2	2	2	1	1	0	0
WA	81	83	84	89	89	12	12	11	8	8	5	4	4	2	3	3	1	1	0	0
SA	90	89	90	94	94	8	8	7	5	5	2	3	3	2	2	0	0	0	0	0
VIC	45	39	46	64	64	32	32	30	24	24	20	26	20	11	12	3	4	3	1	1
TAS	77	74	82	82	84	8	6	4	7	5	13	15	11	9	9	1	5	3	2	3
ACT	100	75	76	83	83	0	0	0	10	10	0	16	10	7	7	0	9	14	0	0

5.1.3 Digit grass

Baseline climate distribution

Based on climate alone, the area modelled as highly suitable for digit grass under the baseline climate was highest in Queensland (70.44 M ha), then the NT, NSW and WA (28.83–30.52 M ha each) (Fig. 9a). The proportion of the state considered either suitable or highly suitable for climate averaged 52% for NSW and Queensland and 70% for both Victoria and Tasmania (Table 35). In the combined model, the area suitable and highly suitable declined to 36–39% for Queensland, NSW and Victoria, and 18% in Tasmania. Under the baseline climate for both the climate and combined models, all of the ACT was unsuitable for digit grass. SA and WA also had large areas unsuitable 87 and 76% respectively for the combined model. Total area modelled as highly suitable for digit grass under the baseline climate and combined models in Australia is 52.61 M ha (7%). In the SE states, digit grass was modelled as highly suited to 16.33 M ha (16% of the combined area).

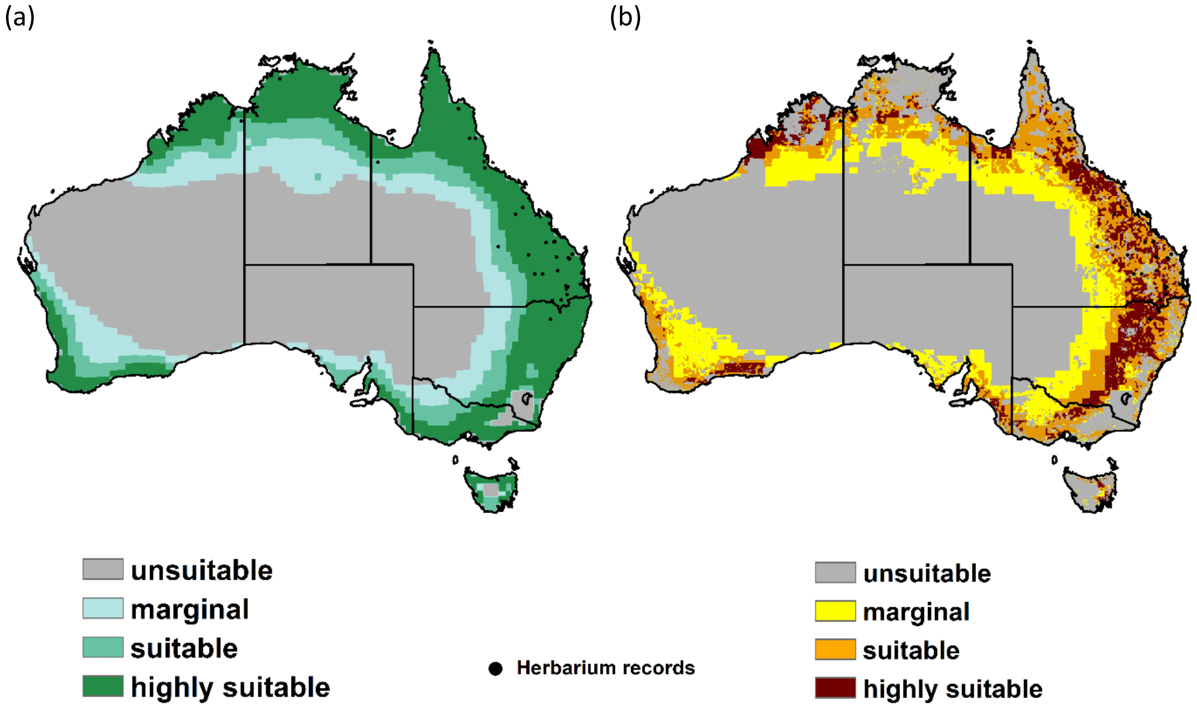


Fig. 9. Distribution of digit grass modelled as unsuitable, marginal, suitable and highly suitable based on baseline (a) climate and (b) combined climate-soil pH-land use models.

Table 35. State and territory area (M ha) and proportion (%) modelled as unsuitable, marginal, suitable and highly suitable for digit grass under baseline (a) climate conditions and (b) combined climate-soil pH-land use conditions.

State	**Unsuitable**		**Marginal**		**Suitable**		**Highly suitable**	
	M ha	**%**	**M ha**	**%**	**M ha**	**%**	**M ha**	**%**
(a) Climate								
NSW	26.36	33	13.28	17	10.34	13	30.08	38
QLD	58.92	34	22.37	13	20.54	12	70.44	41
NT	62.19	47	26.24	20	14.44	11	30.52	23
WA	171.00	68	32.24	13	20.22	8	28.83	11
SA	82.86	85	6.82	7	4.74	5	3.51	4
VIC	3.22	14	3.34	15	5.25	23	10.90	48
TAS	1.59	25	0.46	7	1.12	18	3.24	51
ACT	0.24	100	0.00	0	0.00	0	0.00	0
(b) Combined climate-soil pH-land use								
NSW	32.34	42	14.63	19	16.15	21	14.19	18
QLD	73.90	44	31.41	19	39.05	23	22.45	13
NT	94.19	72	19.91	15	13.89	11	3.41	3
WA	189.56	76	32.72	13	16.36	7	9.33	4
SA	84.36	87	7.88	8	3.43	4	1.09	1
VIC	7.95	38	5.33	25	6.14	29	1.54	7
TAS	4.66	78	0.24	4	0.49	8	0.60	10
ACT	0.24	100	0.00	0	0.00	0	0.00	0

Distribution in 2050 climate

The models indicate that the changes projected in 2030 would continue to 2050. In the two MIROC-H scenarios, the area classified as unsuitable increased for the NT and Queensland and decreased in SE Australia (Table 36, Fig. 10). The area in Victoria and Tasmania classified as unsuitable in the 2050 climate model declined to 9–13%, although in the combined model this rose significantly to 35–73% as much of the climatically suitable area is classified as forest or nature conservation. The modelled total area classified as highly suitable for digit grass in Australia by 2050 under the two MIROC-H scenarios averaged 51.28 M ha (7%) while highly suitable area in SE Australia averaged 22.79 M ha.

In the CSIRO-MK 3.0 scenarios, the unsuitable area increased in all states and territories except the ACT and Tasmania. The area classified as highly suitable decreased in Queensland and NSW for both the climate and combined models. In the NT, WA and SA ≤6% of the area was classified as either highly suitable or suitable (Table 36). The total area classified as highly suitable for digit in Australia by 2050 under the CSIRO-MK 3.0 scenarios averaged 27.68 M ha (4%). The modelled highly suitable area for digit grass in SE Australia averaged 10.37 M ha.

Table 36. State and territory area (M ha) and proportion (%) modelled as unsuitable, marginal, suitable and highly suitable for digit grass under current climate and climate scenarios centred on 2050 for (a) climate and (b) climate + soil pH + land use. Climate scenarios are: Baseline, MIROC-H A1B (MHA1B), MIROC-H A2 (MHA2), CSIRO-MK 3.0 A1B (CA1B) and CSIRO-MK 3.0 A2 (CA2).

State	Unsuitable (%)					Marginal (%)					Suitable (%)					Highly suitable (%)				
	Baseline	MHA1B	MHA2	CA1B	CA2	Baseline	MHA1B	MHA2	CA1B	CA2	Baseline	MHA1B	MHA2	CA1B	CA2	Baseline	MHA1B	MHA2	CA1B	CA2
(a) Climate																				
NSW	33	26	27	52	49	17	13	13	10	11	13	13	13	9	8	38	48	47	30	31
QLD	34	38	38	54	53	13	15	15	13	13	12	11	11	8	8	41	36	36	25	26
NT	47	66	64	75	72	20	15	15	10	12	11	6	7	5	4	23	13	14	10	12
WA	68	71	70	80	79	13	12	12	8	8	8	8	8	6	7	11	9	9	6	6
SA	85	83	83	89	89	7	6	6	3	4	5	5	5	4	4	4	6	6	4	4
VIC	14	9	10	20	17	15	11	10	11	14	23	23	25	23	23	48	57	55	46	46
TAS	25	10	13	14	14	7	4	3	4	11	18	11	14	21	14	51	75	69	61	61
ACT	100	45	45	67	67	0	0	22	0	0	0	22	0	0	0	0	33	33	33	33
(b) Combined climate-soil pH-land use																				
NSW	42	35	36	60	58	19	15	15	12	13	21	24	24	18	18	18	26	26	10	11
QLD	44	48	48	64	63	19	20	20	15	16	23	20	21	13	14	13	12	12	7	8
NT	72	82	81	90	87	15	14	14	8	10	11	3	4	2	3	3	1	1	0	0
WA	76	79	79	86	85	13	12	13	8	8	7	6	6	5	5	4	2	2	1	1
SA	87	86	86	90	90	8	7	7	5	5	4	4	4	3	3	1	2	2	1	1
VIC	38	35	36	42	40	25	25	25	24	26	29	31	29	28	28	7	10	10	6	6
TAS	78	73	73	73	73	4	4	3	6	6	8	10	10	9	9	10	14	14	11	12
ACT	100	75	75	77	77	0	0	0	0	0	0	16	16	15	15	0	9	9	8	8

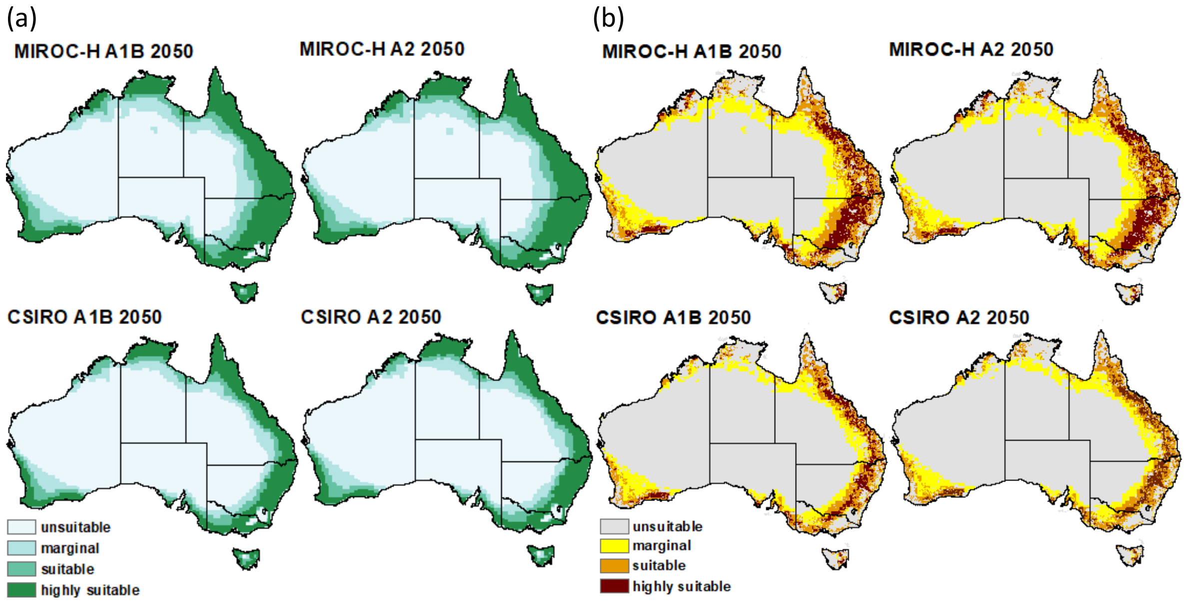


Fig. 10. Distribution of digit grass based on 2050 projected (a) climate and (b) combined climate-soil pH-land use models. Climate scenarios are: current MIROC-H A1B, MIROC-H A2, CSIRO-MK 3.0 A1B and CSIRO-MK 3.0 A2.

5.1.4 Panic grass

Baseline climate distribution

Based on the modelling of climate alone, Victoria and Queensland had the smallest proportions of the state classified as unsuitable for panic grass under the baseline climate (33 and 39% respectively). Both SA and ACT were largely classified as unsuitable, 91 and 100% respectively (Fig. 11a, Table 37a). Queensland had the greatest area and proportion classified as suitable or highly suitable based on the climate-only model (82.01 M ha, 47%).

For the combined model, Victoria and Queensland had the smallest areas classified as unsuitable (47%), with ACT and SA the highest proportions (100 and 92% respectively). Queensland and NSW had the highest proportion of land classified as highly suitable and suitable (37 and 22 respectively, with combined area of 78.69 M ha). WA, Tasmania, SA and ACT all had less than 10% area classified as highly suitable or suitable. The NT, Victoria and NSW were intermediate with 15, 20 and 22% respectively of their area classified as highly suitable or suitable (Fig. 11b and Table 37b).

The total area modelled under the baseline climate as highly suitable for panic grass was 57.07 M ha (8%). In the SE states, panic grass was modelled as highly suited to 8.79 M ha (8% of the combined area).

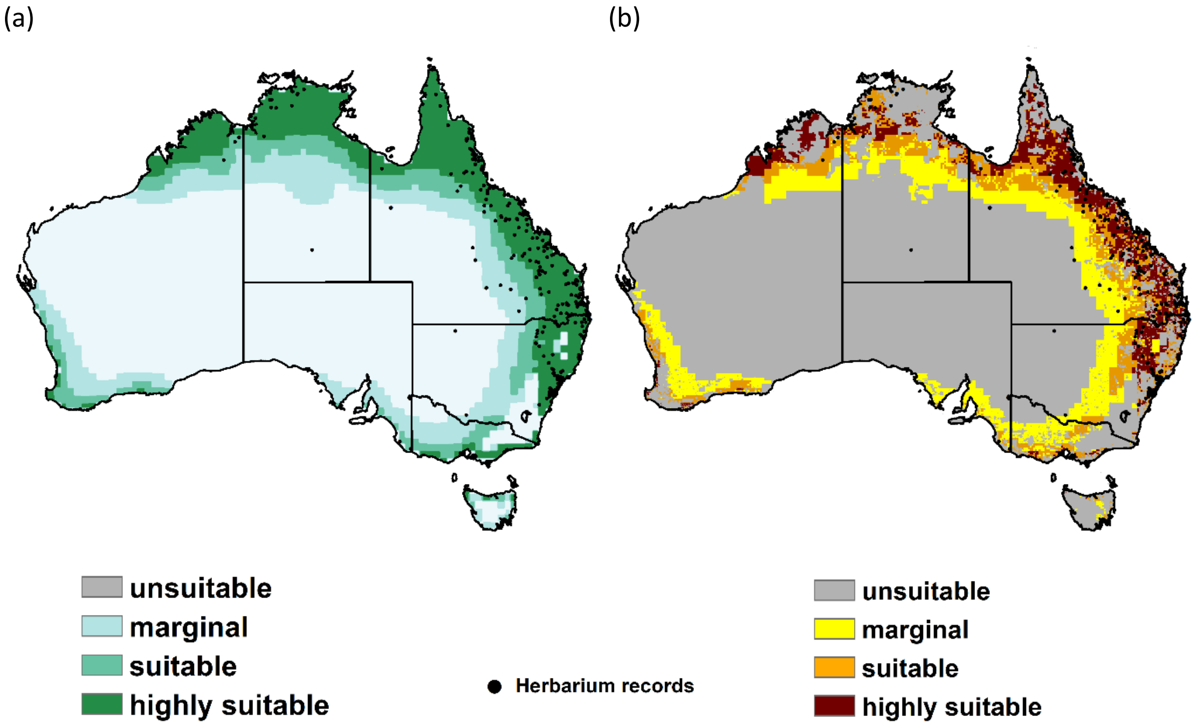


Fig. 11. Distribution of panic grass modelled as unsuitable, marginal, suitable and highly suitable based on baseline (a) climate and (b) combined climate-soil pH-land use models.

Table 37. State and territory area (M ha) and proportion (%) modelled as unsuitable, marginal, suitable and highly suitable for panic grass under baseline (a) climate conditions and (b) combined climate-soil pH-land use conditions.

State	Unsuitable		Marginal		Suitable		Highly suitable	
	M ha	%	M ha	%	M ha	%	M ha	%
				(a) Climate				
NSW	42.40	53	14.41	18	7.18	9	16.07	20
QLD	66.78	39	23.48	14	21.29	12	60.72	35
NT	67.69	51	22.50	17	13.56	10	29.64	22
WA	188.52	75	28.30	11	18.63	7	16.83	7
SA	89.16	91	6.92	7	1.85	2	0.00	0
VIC	7.56	33	7.10	31	4.93	22	3.12	14
TAS	2.73	43	2.25	35	0.92	14	0.51	8
ACT	0.24	100	0.00	0	0.00	0	0.00	0
				(b) Combined climate-soil pH-land use				
NSW	45.98	59	14.18	18	9.68	12	8.08	10
QLD	78.69	47	28.25	17	27.84	17	33.09	20
NT	95.43	72	16.83	13	12.87	10	6.70	5
WA	204.42	82	24.24	10	11.47	5	8.49	3
SA	90.02	92	6.71	7	0.68	1	0.00	0
VIC	9.97	47	6.97	33	3.63	17	0.63	3
TAS	4.99	82	0.57	9	0.44	7	0.08	1
ACT	0.24	100	0.00	0	0.00	0	0.00	0

Distribution in 2050 climate

The combined climate-soil pH-land use model indicates that the changes projected in 2030 would be similar for 2050. Under the MIROC-H scenarios, the area classified as unsuitable increased for Queensland and NT but decreased or remained the same for the SE states (Table 38b, Fig. 12b). Under this scenario the area of land classified as highly suitable increased (2–6 percentage units) in the SE states, while declining slightly in NT. Under the combined model and CSIRO-MK 3.0 scenarios for 2050, the unsuitable area increased or remained the same in all states and territories except Victoria where the unsuitable declined (8 percentage units). The area classified as highly suitable decreased or stayed the same in all states and territories except for Tasmania where it increased slightly. In the 2050 climate scenarios, the total area classified as highly suitable for panic grass in Australia under the MIROC-H and CSIRO-MK 3.0 scenarios were 52.22 (7%) and 30.08 M ha (4%) respectively. In SE Australia, the highly suitable area was 15.20 and 5.36 M ha for the MIROC-H and CSIRO-MK 3.0 scenarios respectively.

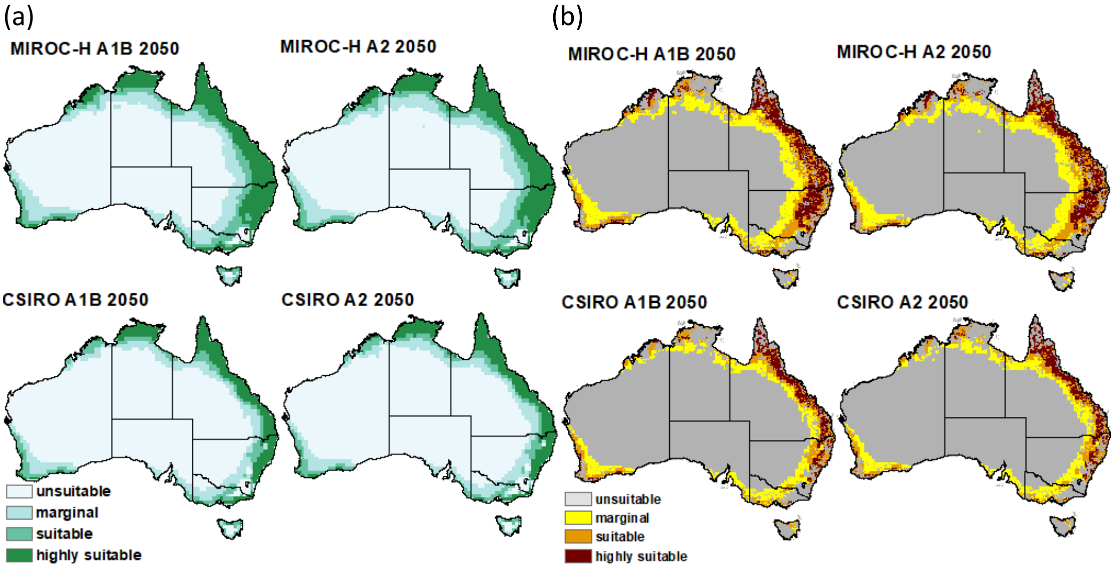


Fig. 12. Distribution of panic grass based on 2050 projected (a) climate and (b) combined climate-soil pH-land use models. Climate scenarios are: current MIROC-H A1B, MIROC-H A2, CSIRO-MK 3.0 A1B and CSIRO-MK 3.0 A2.

Table 38. State and territory area (M ha) and proportion (%) modelled as unsuitable, marginal, suitable and highly suitable for panic grass under current climate and climate scenarios centred on 2050 for (a) climate and (b) climate + soil pH + land use. Climate scenarios: Baseline, MIROC-H A1B (MHA1B), MIROC-H A2 (MHA2), CSIRO-MK 3.0 A1B (CA1B) and CSIRO-MK 3.0 A2 (CA2).

State	Unsuitable (%)					Marginal (%)					Suitable (%)					Highly suitable (%)				
	Baseline	MHA1B	MHA2	CA1B	CA2	Baseline	MHA1B	MHA2	CA1B	CA2	Baseline	MHA1B	MHA2	CA1B	CA2	Baseline	MHA1B	MHA2	CA1B	CA2
(a) Climate																				
NSW	53	38	38	62	61	18	18	19	15	16	9	13	13	8	8	20	31	30	15	16
QLD	39	43	43	58	57	14	15	15	12	13	12	10	10	7	7	35	32	32	23	24
NT	51	68	66	76	73	17	13	14	9	11	10	6	6	5	5	22	13	14	10	11
WA	75	77	77	84	84	11	12	12	8	8	7	7	7	6	6	7	4	4	2	2
SA	91	89	89	93	92	7	8	8	6	6	2	4	3	2	2	0	0	0	0	0
VIC	33	21	22	34	34	31	33	32	32	33	22	27	28	22	20	14	19	18	12	13
TAS	43	28	32	39	43	35	21	21	18	14	14	38	34	32	32	8	13	13	11	11
ACT	100	100	100	100	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
(b) Combined climate-soil pH-land use																				
NSW	59	45	45	69	68	18	19	20	15	16	12	18	17	10	11	10	18	18	6	6
QLD	47	51	51	66	64	17	19	18	13	14	17	13	13	9	9	20	18	18	13	13
NT	72	83	82	89	87	13	11	12	7	8	10	5	5	3	4	5	2	2	1	1
WA	82	84	84	89	89	10	10	10	6	7	5	4	4	3	4	3	2	2	1	1
SA	92	90	90	94	94	7	8	8	6	6	1	1	1	1	1	0	0	0	0	0
VIC	47	40	40	50	50	33	36	36	35	34	17	19	19	13	14	3	5	5	2	2
TAS	82	78	79	81	82	9	6	6	4	3	7	12	11	12	12	1	4	4	3	3
ACT	100	100	100	100	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

5.1.5 Makarikari grass

Baseline climate distribution

The baseline modelling of climate alone indicated that Victoria and Tasmania had the smallest proportions of the state classified as unsuitable for Makarikari grass (19–25%), followed by NSW and Queensland (40–46%). The remaining states or territories had ≥70% classified as unsuitable, with the ACT classified as 100% unsuitable. The states with the largest areas classified as suitable and highly suitable were those in SE Australia and Queensland (Fig. 13a, Table 39a).

Under the combined model, the area classified as unsuitable increased in all states and the NT. Victoria, NSW and Queensland had the smallest proportions classified as unsuitable, although these areas were all >50%. The states with the highest areas classified as suitable and highly suitable were NSW and Queensland (23 and 27% respectively) (Fig. 13, Table 39b). The total area of Australia classified as highly suitable for Makarikari grass was 31.42 M ha (4%) with 10.20 M ha of the SE states modelled as highly suitable.

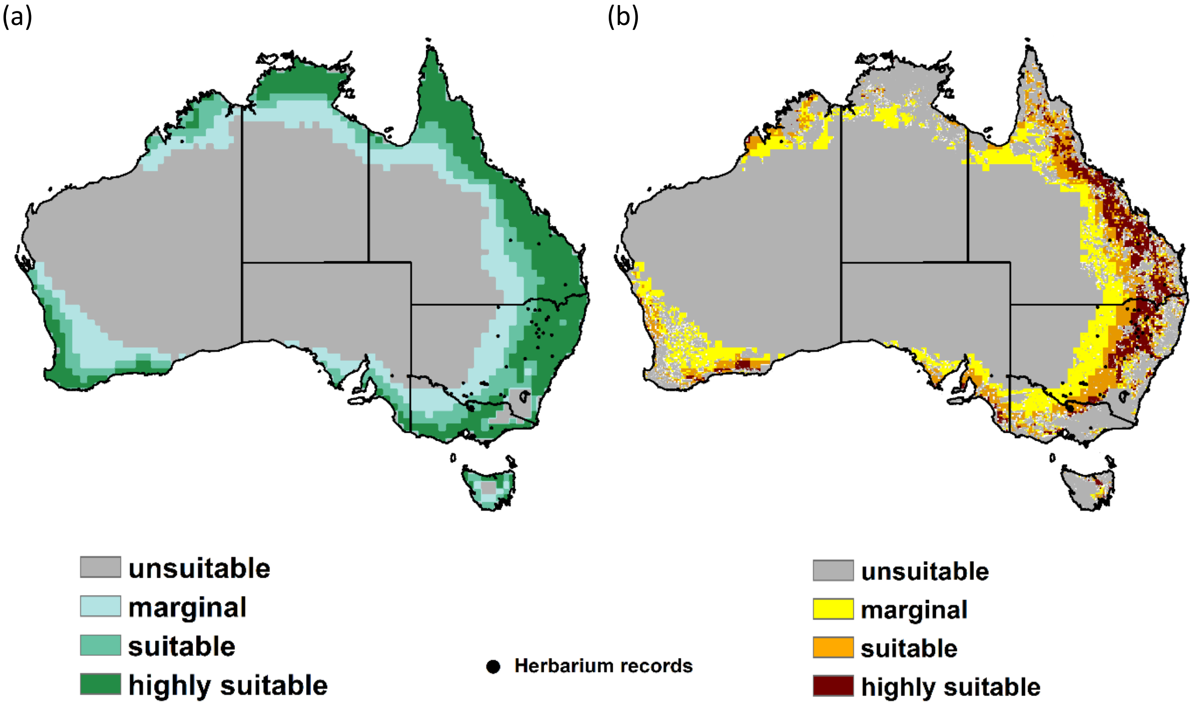


Fig. 13. Distribution of Makarikari grass modelled as unsuitable, marginal, suitable and highly suitable based on baseline (a) climate and (b) combined climate-soil pH-land use models.

Table 39. State and territory area (M ha) and proportion (%) modelled as unsuitable, marginal, suitable and highly suitable for Makarikari grass under baseline (a) climate conditions and (b) combined climate-soil pH-land use conditions.

State	Unsuitable		Marginal		Suitable		Highly suitable	
	M ha	%	M ha	%	M ha	%	M ha	%
				(a) Climate				
NSW	32.09	40	13.61	17	11.12	14	23.24	29
QLD	80.05	46	23.85	14	18.54	11	49.82	29
NT	97.56	73	15.84	12	6.04	5	13.95	10
WA	195.34	77	27.12	11	17.69	7	12.14	5
SA	85.38	87	6.39	7	4.31	4	1.85	2
VIC	4.25	19	4.73	21	5.56	24	8.17	36
TAS	1.59	25	1.15	18	2.02	31	1.66	26
ACT	0.24	100	0.00	0	0.00	0	0.00	0
				(b) Combined climate-soil pH-land use				
NSW	41.01	53	15.13	20	11.96	16	9.05	12
QLD	103.12	62	24.31	15	19.42	12	18.43	11
NT	123.75	94	6.79	5	1.20	1	0.18	0
WA	214.01	87	21.79	9	9.33	4	1.84	1
SA	87.18	90	5.26	5	3.44	4	0.77	1
VIC	11.82	56	5.34	25	3.23	15	0.79	4
TAS	5.04	81	0.36	6	0.44	7	0.36	6
ACT	0.24	100	0.00	0	0.00	0	0.00	0

Distribution in 2050 climate

By 2050, the combined model indicates that the changes projected for 2030 would be similar for 2050. Under the MIROC-H scenarios, the area classified as unsuitable increased for Queensland, NT and WA, but decreased or remained the same for the SE states (Table 40b, Fig. 14b). Under this same scenario the area of land classified as highly suitable increased (by 2–7 percentage units) in the SE states, while declining slightly in Queensland, NT and WA. Under the combined model and CSIRO-MK scenarios for 2050, the unsuitable area increased or remained the same in all states and territories except for the ACT where the unsuitable area declined (by 23 percentage units). The area classified as highly suitable decreased or stayed the same in all states and territories except for Tasmania and ACT where it increased (by 2 and 8 percentage units respectively) (Fig. 14b, Table 40b).

Like 2030 climate projections for 2050 (both MIROC-H and CSIRO-MK 3.0 scenarios) Makarikari grass will be suited to an increased area of SE Australia, that is, 16.18 and 4.38 M ha for the two scenarios respectively.

Table 40. State and territory area (M ha) and proportion (%) modelled as unsuitable, marginal, suitable and highly suitable for Makarikari grass under current climate and climate scenarios centred on 2050 for (a) climate and (b) climate + soil pH + land use. Climate scenarios: Baseline, MIROC-H A1B (MHA1B), MIROC-H A2 (MHA2), CSIRO-MK 3.0 A1B (CA1B) and CSIRO-MK 3.0 A2 (CA2).

State	Unsuitable (%)					Marginal (%)					Suitable (%)					Highly suitable (%)				
	Baseline	MHA1B	MHA2	CA1B	CA2	Baseline	MHA1B	MHA2	CA1B	CA2	Baseline	MHA1B	MHA2	CA1B	CA2	Baseline	MHA1B	MHA2	CA1B	CA2
(a) Climate																				
NSW	40	31	31	58	57	17	16	16	10	11	14	13	13	11	10	29	40	40	21	23
QLD	46	53	53	70	69	14	14	14	9	9	11	8	8	4	5	29	24	25	17	17
NT	73	85	85	87	87	12	5	5	5	5	5	6	6	6	6	10	3	4	1	2
WA	77	80	80	85	85	11	11	10	7	7	7	5	5	4	4	5	5	5	4	4
SA	87	85	85	91	91	7	6	6	4	4	4	5	5	3	4	2	3	3	2	2
VIC	19	11	12	21	21	21	15	14	23	23	24	30	30	22	22	36	45	45	34	34
TAS	25	14	14	14	14	18	4	4	11	11	31	28	32	32	32	26	54	51	43	43
ACT	100	45	45	67	67	0	22	22	0	0	0	0	0	0	0	0	33	33	33	33
(b) Combined climate-soil pH-land use																				
NSW	53	44	44	71	70	20	18	18	13	13	16	19	19	13	12	12	19	19	4	5
QLD	62	68	67	81	80	15	13	13	8	8	12	9	9	6	7	11	10	10	5	6
NT	94	99	98	99	99	5	1	1	1	1	1	0	0	0	0	0	0	0	0	0
WA	87	88	88	91	91	9	8	8	6	6	4	3	3	3	3	1	1	1	1	1
SA	90	89	89	93	93	5	5	5	3	3	4	5	4	3	3	1	2	2	1	1
VIC	56	54	54	61	61	25	17	17	25	25	15	23	23	11	12	4	6	6	2	2
TAS	81	80	80	80	80	6	3	3	3	3	7	6	7	9	9	6	10	9	8	8
ACT	100	75	75	77	77	0	0	0	0	0	0	16	16	15	15	0	9	9	8	8

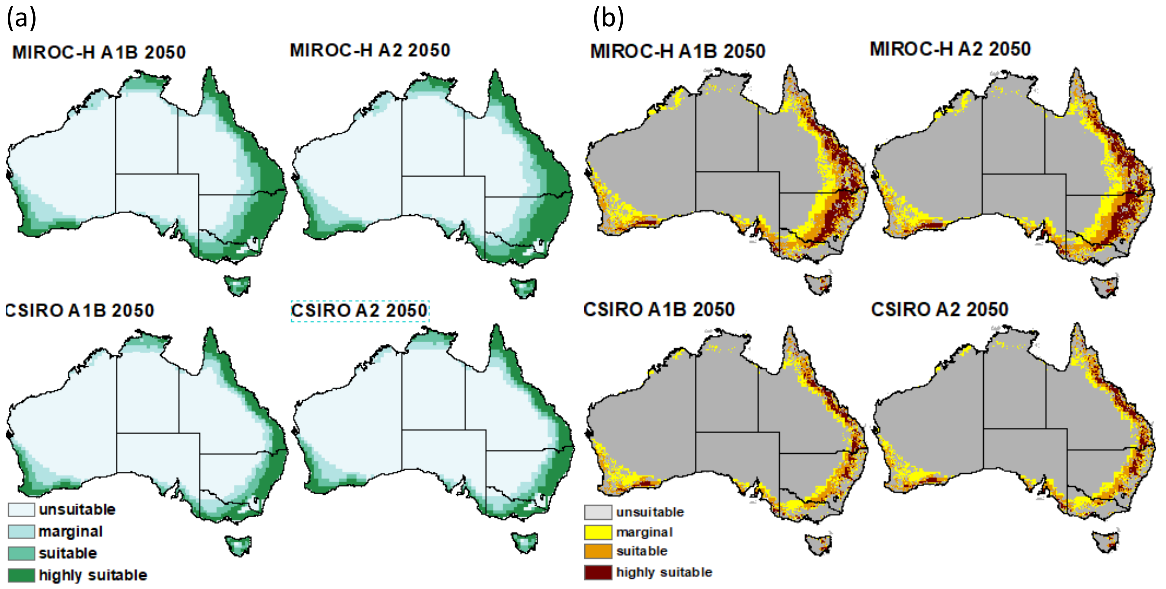


Fig. 14. Distribution of Makarikari grass based on 2050 projected (a) climate and (b) combined climate-soil pH-land use models. Climate scenarios are: current MIROC-H A1B, MIROC-H A2, CSIRO-MK 3.0 A1B and CSIRO-MK 3.0 A2.

5.1.6 Desmanthus

Baseline climate distribution

Using the baseline climate, the potential distribution of desmanthus in Queensland and Victoria were modelled as having the smallest proportion of the state classified as unsuitable based on climate-only (24 and 25% respectively). These states were followed by NT then NSW (30 and 41% respectively) (Fig. 15, Table 41a). The total area modelled as highly suitable for desmanthus under the baseline climate climate-only model in Australia was 192.80 M ha (25%). In the SE states, desmanthus was modelled as highly suited to 26.40 M ha.

Under the combined climate-soil pH-land use model, the area classified as unsuitable increased to 58% in Queensland and NSW with 28 and 20% of the area classified as suitable or highly suitable (total 63.72 M ha) (Fig. 15, Table 41b). The three northern Australia states/territory, Queensland, NT and WA had the largest areas classified as highly suitable for desmanthus (total 21.78 M ha), followed by NSW (6.88 M ha). In Victoria the area classified as unsuitable using the combined model increased substantially to 71%, indicating soil pH and particularly forestry and nature conservation were major restrictors of where desmanthus could potentially be sown in this state. The proportion of the state considered suitable or highly suitable for desmanthus was low at only 2% (Fig. 18b, Table 20b). Under the combined model >90% of SA and Tasmania, and 100% of ACT were classified as unsuitable for desmanthus with ≤2% of the area classified as suitable or highly suitable (Fig. 18b, Table 20b).

The total area modelled as highly suitable for desmanthus under the combined model in Australia is 28.70 M ha (4%), significantly less than the climate-only model projection. In the SE states, desmanthus was modelled as highly suited to 6.92 M ha under the combined model.

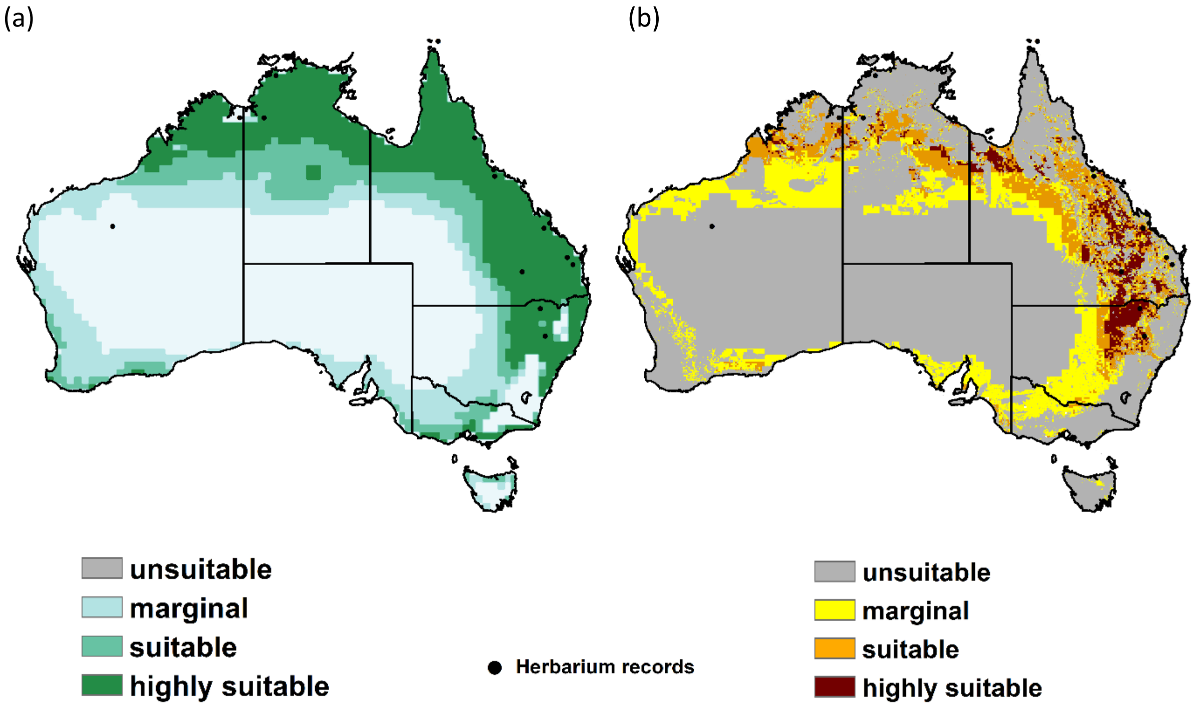


Fig. 15. Distribution of desmanthus modelled as unsuitable, marginal, suitable and highly suitable based on baseline (a) climate and (b) combined climate-soil pH-land use models.

Table 41. State and territory area (M ha) and proportion (%) modelled as unsuitable, marginal, suitable and highly suitable for desmanthus under baseline (a) climate conditions and (b) combined climate-soil pH-land use conditions.

State	Unsuitable		Marginal		Suitable		Highly suitable	
	M ha	%	M ha	%	M ha	%	M ha	%
				(a) Climate				
NSW	33.17	41	16.82	21	7.01	9	23.06	29
QLD	40.82	24	14.92	9	22.74	13	93.79	54
NT	40.34	30	14.93	11	29.93	22	48.19	36
WA	148.72	59	55.61	22	23.54	9	24.43	10
SA	85.70	88	10.38	11	1.85	2	0.00	0
VIC	5.60	25	8.28	36	5.48	24	3.35	15
TAS	3.62	56	1.57	24	1.23	19	0.00	0
ACT	0.24	100	0.00	0	0.00	0	0.00	0
			(b) Combined climate-soil pH-land use					
NSW	46.59	58	18.11	23	8.44	11	6.88	9
QLD	100.42	58	22.88	13	30.50	18	17.90	10
NT	101.15	76	15.75	12	14.16	11	2.50	2
WA	192.93	77	44.54	18	11.67	5	1.38	1
SA	88.45	91	8.40	9	0.58	1	0.00	0
VIC	15.96	71	6.22	27	0.42	2	0.04	0
TAS	6.05	96	0.27	4	0.00	0	0.00	0
ACT	0.24	100	0.00	0	0.00	0	0.00	0

Distribution in 2050 climate

The models indicate that the changes projected in 2030 would continue to 2050, with trends similar for both the climate and combined models. In the MIROC-H scenarios the area classified as unsuitable for desmanthus was projected to increase in NT, WA and Queensland (to 60–83%) (Fig. 16, Table 42). In contrast, the unsuitable area was projected to decrease substantially in NSW (i.e., from 58 (baseline climate) to 49%). In the CSIRO-MK 3.0 scenarios, the area classified as unsuitable increased for NT, Queensland, WA and NSW (unsuitable area ranging 38–80%) and remained largely unchanged in the other states.

The area classified as highly suitable and suitable was largest in NSW and Queensland (total 25.37 M ha) but only ranged 24–27% for each state under the MIROC-H scenarios and 13–15% under the CSIRO-MK scenarios (Fig. 16, Table 42). The total area classified as highly suitable for desmanthus in Australia by 2050 under the MIROC-H and CSIRO-MK 3.0 scenarios averaged 25.61 (3%) and 11.96 M ha (2%) respectively. The modelled highly suitable area for desmanthus in SE Australia averaged 9.49 and 2.92 M ha under the MIROC-H and CSIRO-MK 3.0 scenarios respectively.

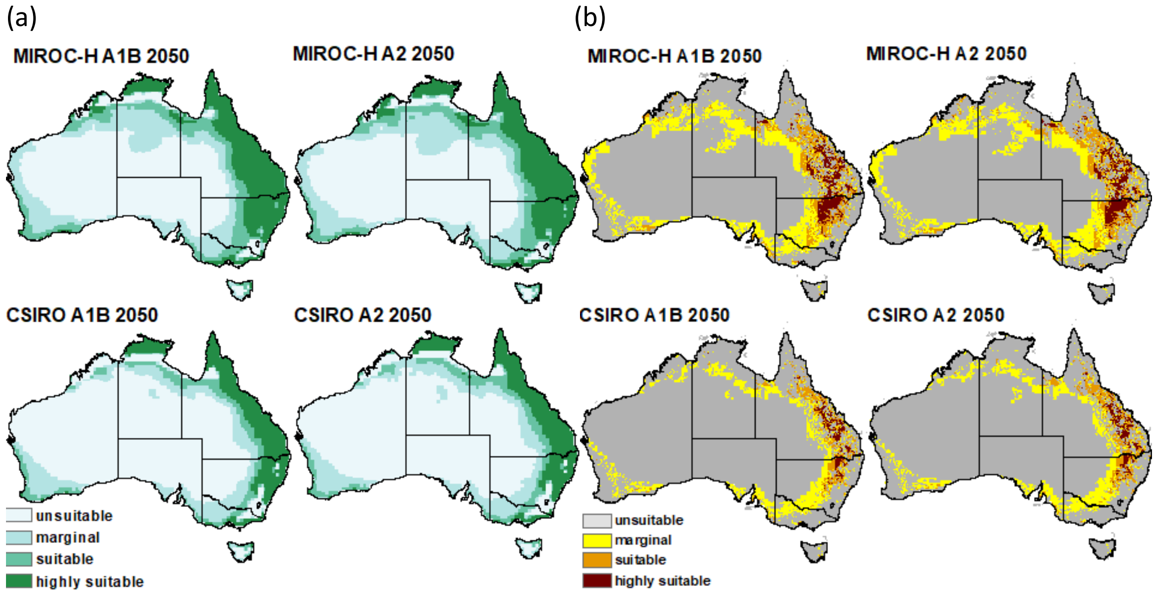


Fig. 16. Distribution of desmanthus based on 2050 projected (a) climate and (b) combined climate-soil pH-land use models. Climate scenarios: current MIROC-H A1B, MIROC-H A2, CSIRO-MK 3.0 A1B and CSIRO-MK 3.0 A2.

Table 42. State and territory area (M ha) and proportion (%) modelled as unsuitable, marginal, suitable and highly suitable for desmanthus under current climate and climate scenarios centred on 2050 for (a) climate and (b) climate + soil pH + land use. Climate scenarios: Baseline, MIROC-H A1B (MHA1B), MIROC-H A2 (MHA2), CSIRO-MK 3.0 A1B (CA1B) and CSIRO-MK 3.0 A2 (CA2).

State	Unsuitable (%)					Marginal (%)					Suitable (%)					Highly suitable (%)				
	Baseline	MHA1B	MHA2	CA1B	CA2	Baseline	MHA1B	MHA2	CA1B	CA2	Baseline	MHA1B	MHA2	CA1B	CA2	Baseline	MHA1B	MHA2	CA1B	CA2
(a) Climate																				
NSW	41	26	26	49	48	21	17	18	16	17	9	17	17	9	10	29	40	39	26	26
QLD	24	26	26	42	38	9	12	11	13	14	13	14	14	12	13	54	48	49	33	35
NT	30	45	43	71	67	11	34	32	13	15	22	9	12	7	7	36	12	12	10	10
WA	59	67	66	81	80	22	20	21	13	13	9	10	10	6	6	10	3	3	0	1
SA	88	84	84	89	88	11	12	12	9	9	2	4	3	2	2	0	0	0	0	0
VIC	25	13	14	21	22	36	42	41	47	43	24	22	22	15	18	15	23	23	17	17
TAS	56	43	43	43	43	24	21	21	28	31	19	28	28	26	23	0	8	8	3	3
ACT	100	100	100	100	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
(b) Combined climate-soil pH-land use																				
NSW	58	49	49	67	66	23	24	24	20	21	11	15	15	10	10	9	12	12	3	4
QLD	58	61	60	72	70	13	15	15	13	14	18	15	16	10	10	10	9	9	5	5
NT	76	81	81	92	89	12	18	17	8	10	11	1	2	0	0	2	0	0	0	0
WA	77	83	83	94	93	18	15	16	6	7	5	1	1	0	0	1	0	0	0	0
SA	91	88	88	92	91	9	10	10	8	8	1	2	1	1	1	0	0	0	0	0
VIC	71	68	68	72	71	27	29	29	27	27	2	3	3	1	1	0	0	0	0	0
TAS	96	92	92	93	93	4	6	6	6	6	0	1	1	1	0	0	0	0	0	0
ACT	100	100	100	100	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

5.2 The potential fit of tropical perennial grasses in farming systems in southern NSW

5.2.1 Climate data

Mean annual rainfall between the Far and Near climate groupings declined at all sites (29-40 mm) except Leeton (increased 11 mm) (Table 43). Closer examination of Leeton rainfall showed that the first two production years in the Far climate grouping recorded less than 5 mm annually. There was little difference in summer rainfall at each site between Far and Near climate (range -13-7 mm), but autumn rain declined for the Near climate grouping (20-37 mm); an amount similar to the overall decline in annual rainfall.

Table 43. Mean annual, summer and autumn rainfall (mm) and corresponding standard error of mean (se) for Far and Near climates at all five sites.

		Annual		Summer		Autumn	
Climate	Site	mm	se	mm	se	mm	se
Far	Tamworth	678	23.5	238	21.6	137	14.3
	Cowra	644	12.5	176	18.8	157	15.5
	Condobolin	470	23.8	129	17.3	121	13.1
	Wagga Wagga	589	11.2	131	13.5	151	14.6
	Leeton	403	70.2	92	11.9	112	11.8
Near	Tamworth	649	19.4	225	18.6	108	10.7
	Cowra	604	3.1	173	15.7	120	11.1
	Condobolin	438	8.8	129	12.9	89	11.3
	Wagga Wagga	551	8.4	129	11.6	119	12.6
	Leeton	414	19.0	99	9.5	92	10.9

Details of mean monthly rainfall, maximum and minimum temperatures at each site for Far and near climate are provided in Appendix 2. In summary, mean monthly rainfall for April and May declined from Far to Near climate, while June rainfall increased. Overall, summer rain was similar between Far and Near climate, but less rain fell in autumn for the Near climate. Minimum monthly temperatures also tended to increase, often during the late spring to summer period, except for Tamworth where minimum monthly temperatures decreased April–October.

5.2.2 Modelling results

Pasture growth rates

The mean daily pasture growth rates for each month were determined for the model runs where all pasture paddocks comprised the same pasture mix (i.e., LRC100, L100, RC100, TC100 and TRC100). At all sites for Near and Far climate groupings, the temperate pastures with the highest growth rates were LRC100 and L100 respectively (Table 44). Mean growth rates generally declined from Far to Near climate groupings, except for RC100 at Cowra and Condobolin, and TC100 and TRC100 at Condobolin and Wagga Wagga. TRC100 had the highest growth rates at Tamworth, Condobolin and Leeton for both climate groupings, and at Cowra for the Near climate. LRC100 at Wagga Wagga for both Far and Near climate, and Cowra for Far climate had the best growth rates.

Table 44. Mean daily growth rates (kg/ha/d) for all sites for LRC100, L100, RC100, TC100 and TRC100 pasture for Far and Near climate groupings.

Climate	Pasture	Tamworth	Cowra	Condobolin	Wagga Wagga	Leeton
Far	LRC100	9.41	15.08	8.35	15.62	8.47
	L100	8.00	13.27	6.91	12.03	5.95
	RC100	2.85	3.63	2.16	3.17	3.44
	TC100	17.04	9.14	7.58	6.97	7.29
	TRC100	19.31	13.60	9.77	10.20	10.95
	Mean	*11.32*	*10.94*	*6.95*	*9.60*	*7.22*
Near	LRC100	8.24	12.98	6.27	12.32	7.66
	L100	7.63	12.41	4.31	10.17	5.89
	RC100	2.81	4.98	2.74	3.13	2.84
	TC100	14.77	8.85	8.89	7.36	6.73
	TRC100	17.49	13.56	11.52	11.41	10.26
	Mean	*10.19*	*10.56*	*6.75*	*8.88*	*6.68*

Comparison of mean monthly modelled growth rates at each site for Far and Near climate in general showed peak growth of the temperate pastures in spring; the peak often lower and/or earlier in the Near climate. The lucerne pastures (LRC100 and L100) had the highest growth rates of those modelled. The tropical grass pastures (TRC100 and TC100) generally had peak growth rates in autumn; rates increasing at some sites in the Near climate. Mean daily growth rates for all sites during the Far and Near climate groupings are shown in Fig. 17.

The average daily growth rates for summer and autumn were determined for each pasture at each site and climate grouping (Table 45). Over these seasons, the RC100 pastures had the lowest growth rates at all sites. At Tamworth, Condobolin and Leeton, improved summer and autumn mean daily growth rates were obtained in the TC100 and TRC100 pastures. At the two wetter sites, Cowra and Wagga Wagga, the response was different. At Cowra, the lucerne based pastures L100 and LRC100 had similar average daily growth rates to TC100 and TRC100 in summer and lower for autumn. At Wagga Wagga, for the Far climate, L100 and LRC100 had higher summer average daily growth rates than TC100 and TRC100, and similar autumn average daily growth rates. For the Near climate summer average daily growth rates were similar for LRC100, L100, TC100 and TRC100, while TC100 and TRC100 had higher autumn average daily growth rates.

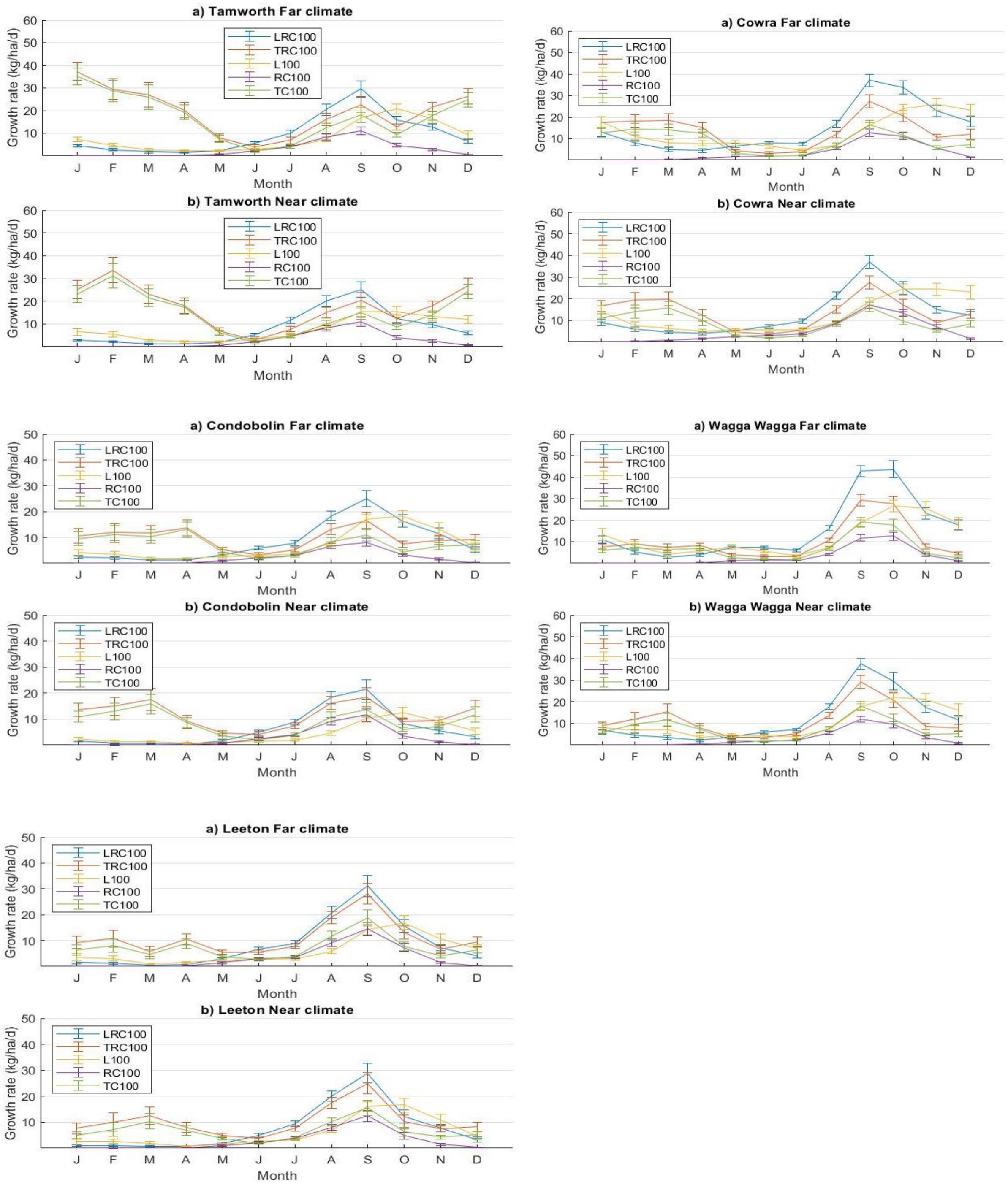


Fig. 17. Mean daily growth rates (kg DM/ha/d) at Tamworth, Cowra, Condobolin, Wagga Wagga and Leeton during the a) Far and b) Near climate groupings for LRC100, TRC100, L100, RC100 and TC100 pastures. Error bars are ± standard error of mean.

Table 45. Average daily growth rates (kg/ha/d) of LRC100, L100, RC100, TC100 and TRC100 pastures in summer, autumn and summer-autumn at each site in the Far and Near climate grouping.

Site	Climate	Season	Pasture				
			LRC100	L100	RC100	TC100	TRC100
Tamworth	Far	Summer	4.5	7.1	0.2	29.5	31.0
		Autumn	1.9	2.3	0.2	17.5	18.4
		Summer-Autumn	*3.2*	*4.7*	*0.2*	*23.5*	*24.7*
	Near	Summer	3.7	8.0	0.3	26.2	28.5
		Autumn	1.5	2.3	0.2	15.0	16.0
		Summer-Autumn	*2.6*	*5.1*	*0.2*	*20.6*	*22.3*
Cowra	Far	Summer	13.0	17.3	0.6	11.6	15.9
		Autumn	5.4	7.8	1.0	9.9	12.6
		Summer-Autumn	*9.2*	*12.5*	*0.8*	*10.7*	*14.3*
	Near	Summer	9.1	14.8	0.6	11.1	16.3
		Autumn	4.6	5.6	1.6	9.6	12.2
		Summer-Autumn	*6.8*	*10.2*	*1.1*	*10.3*	*14.2*
Condobolin	Far	Summer	3.2	4.6	0.1	9.3	10.6
		Autumn	1.9	2.1	0.4	9.3	10.2
		Summer-Autumn	*2.5*	*3.3*	*0.2*	*9.3*	*10.4*
	Near	Summer	1.8	3.0	0.1	11.8	14.2
		Autumn	0.9	0.9	0.3	9.2	10.4
		Summer-Autumn	*1.4*	*2.0*	*0.2*	*10.5*	*12.3*
Wagga Wagga	Far	Summer	11.4	13.3	0.4	5.3	7.0
		Autumn	4.7	5.8	0.5	5.3	6.5
		Summer-Autumn	*8.1*	*9.5*	*0.5*	*5.3*	*6.8*
	Near	Summer	7.7	10.3	0.4	6.9	9.7
		Autumn	3.2	5.1	0.6	7.1	8.9
		Summer-Autumn	*5.5*	*7.7*	*0.5*	*7.0*	*9.3*
Leeton	Far	Summer	2.4	4.5	0.1	7.0	9.8
		Autumn	1.4	1.6	0.6	5.9	7.2
		Summer-Autumn	*1.9*	*3.0*	*0.4*	*6.4*	*8.5*
	Near	Summer	1.8	3.3	0.1	5.8	8.7
		Autumn	1.1	1.4	0.4	7.0	8.5
		Summer-Autumn	*1.5*	*2.4*	*0.2*	*6.4*	*8.6*

Supplementary feeding

The supplementary feed requirements between the two climate groupings were compared. The proportion of total livestock intake that was supplementary feed was determined for the ewes and lambs for model runs where the pasture paddocks comprised the same pasture mix (i.e., LRC100, L100, RC100, TC100 and TRC100). At all sites except Leeton, mean annual supplementary feeding increased for both ewes and lambs from Near to Far climate; ewe requirements increasing more than the lambs (Table 46). There was minimal change in the proportion of supplementary feeding at Leeton.

Ewe supplementary feed requirements as a proportion of the total diet throughout the year were generally lowest in January and highest in winter at all sites in both climate groupings. Supplementary feed requirement commonly increased from Far to Near climate. Although the extent varied with site, ewes grazing L100 often had the highest supplementary feed requirement over winter and LRC100 the lowest during late winter-spring. Ewes and lambs grazing tropical grass pastures (TRC100 and TC100) commonly had the lowest supplement feed requirement during autumn and early winter (ewes only), although not always significant.

Table 46. Mean proportion of total diet as supplementary feed (%) for ewes and lambs at each site for LRC100, L100, RC100, TC100 and TRC100 pasture for the Far and Near climate groupings. The overall mean for each site, each climate grouping, and livestock class is presented.

Livestock	Climate	Pasture	Tamworth	Cowra	Condobolin	Wagga Wagga	Leeton
Ewes	Far	LRC100	20.3	16.9	25.6	16.7	28.2
		L100	28.6	19.5	31.2	19.7	40.6
		RC100	27.3	32.2	32.3	30.8	35.7
		TC100	21.6	20.6	28.8	22.6	31.8
		TRC100	18.4	19.7	26.2	20.2	26.8
		Mean	*23.2*	*21.8*	*28.8*	*22.0*	*32.6*
	Near	LRC100	23.1	22.0	29.9	24.9	27.1
		L100	30.9	24.7	44.4	29.9	39.7
		RC100	30.6	34.8	36.7	36.5	36.1
		TC100	25.0	25.5	32.9	29.9	30.7
		TRC100	22.4	22.3	28.2	24.9	26.1
		Mean	*26.4*	*25.9*	*34.4*	*29.2*	*31.9*
Lambs	Far	LRC100	14.4	11.4	19.6	13.5	21.3
		L100	13.7	10.8	19.6	13.5	20.7
		RC100	13.7	19.9	21.6	18.2	24.2
		TC100	8.8	8.5	15.8	10.3	16.9
		TRC100	8.9	8.5	16.2	11.3	16.6
		Mean	*11.9*	*11.8*	*18.6*	*13.4*	*19.9*
	Near	LRC100	16.3	17.3	21.9	18.2	21.3
		L100	15.5	14.6	21.3	17.1	22.4
		RC100	16.5	28.1	22.4	20.9	23.8
		TC100	11.1	11.2	16.6	14.1	18.9
		TRC100	11.3	11.5	16.4	14.0	17.5
		Mean	*14.1*	*16.5*	*19.7*	*16.9*	*20.8*

The mean monthly supplementary feed as a proportion of total diet for ewes and weaned lambs at Cowra are shown in Fig. 18 as an example of the results developed for each site. Results for the other sites are shown in Millar et al. (Appendix 2). In the Far climate, ewes at Cowra required more supplementary feed grazing RC100 than the other pastures from May to December, except for July, while LRC100 required less supplementary feed August-September for both Far and Near climate. Lambs grazing RC100 required more supplementary feed that the other pastures from January to April in both climate groupings; the proportion increasing in the Near climate. Less supplementary feed was required for lambs in the Near climate for TRC100 and TC100 for April.

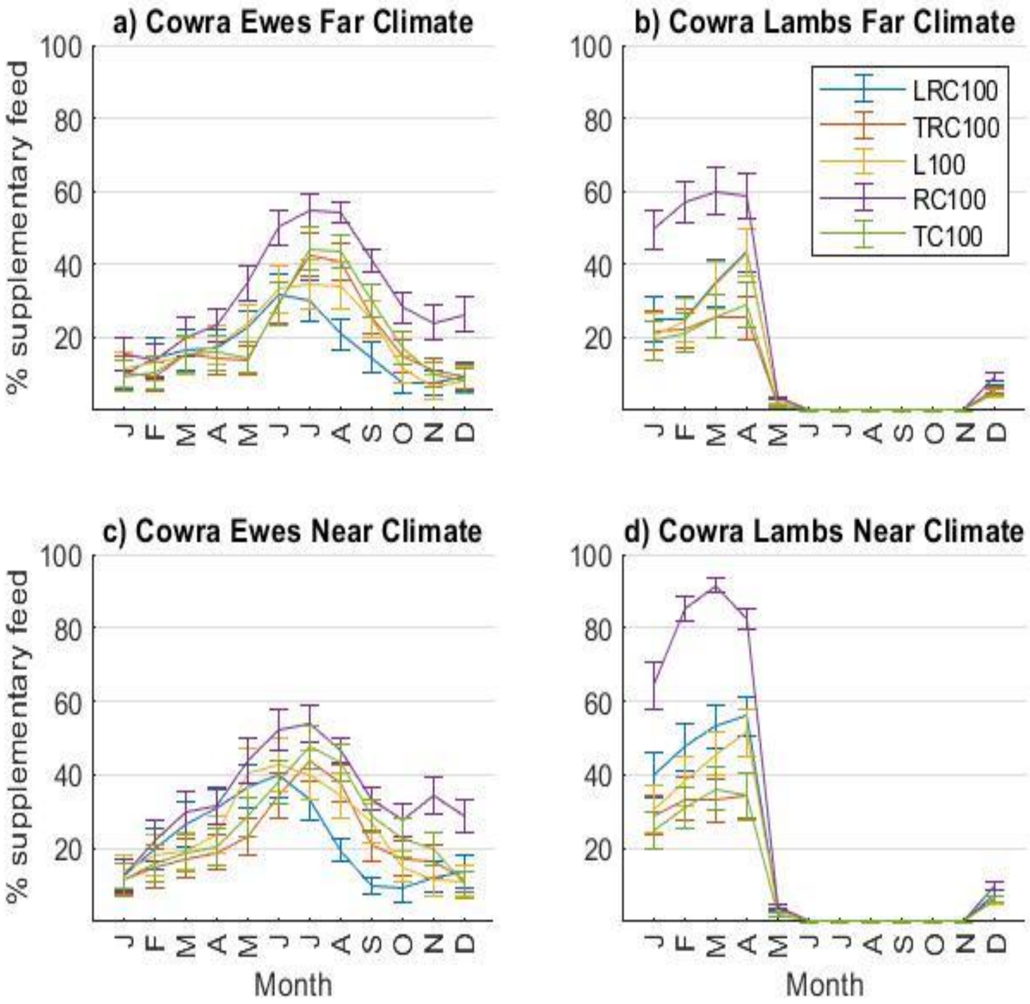


Fig. 18. Mean monthly supplementary feed as a proportion of total diet (%) for ewes (a, c) and weaned lambs (b, d) grazing LRC100, L100, RC100, TC100 and TRC100 pastures at Cowra in the Far (a, b) and Near (c, d) climate groupings. Error bars indicate ± standard error of mean.

Gross margins per hectare

Mean gross margin and mean total cost (ewe and lamb) of supplementary feeding per hectare varied between site, climate grouping and pasture comparison (Table 47). Gross margins decreased from Far to Near climate for all sites, while there was a corresponding increase in the cost of supplementary feeding. On average, the LRC v TRC pasture comparison produced the best gross margins per hectare.

There was a strong linear relationship between gross margin per hectare and cost of supplementary feed across all sites (Table 48); R^2 ranging from 0.85–0.93. At Cowra and Leeton the relationship between gross margin and cost of supplementary feed per hectare did not differ between Far and Near climate, while at the other sites the slope and constant increased for the Near climate.

Table 47. Mean gross margin per hectare (GM, \$) and mean total cost of supplementary feeding per hectare (Feed, \$) for each site, climate grouping and pasture comparison (LRC v TRC, RC v TC and L v TC).

Site	Climate	LRC v TRC		RC v TC		L v TC	
		GM (\$)	Feed (\$)	GM (\$)	Feed (\$)	GM (\$)	Feed (\$)
Tamworth	Far	289	108	274	126	265	119
	Near	267	125	254	142	245	137
Cowra	Far	427	126	372	163	410	132
	Near	392	150	337	191	370	160
Condobolin	Far	178	118	176	131	162	127
	Near	156	131	153	144	133	144
Wagga Wagga	Far	351	129	307	158	327	140
	Near	310	161	272	189	286	172
Leeton	Far	170	111	160	126	144	123
	Near	165	118	157	133	140	133

Table 48. Relationship between gross margin per hectare (GM\$) and cost of supplementary feeding per hectare (Feed\$) for all pasture combinations at each site for Far, Near and Combined (1960 to 2020) climate, for the equation: GM\$ = slope * Feed\$ + constant. Correlation coefficient (R^2) is shown for each relationship.

Site	Climate	Slope	Constant	R^2
Tamworth	Far	-1.41	442	0.87
	Near	-1.48	455	0.86
	Combined	-1.44	448	0.87
Cowra	Far	-1.51	616	0.91
	Near	-1.51	618	0.86
	Combined	-1.51	617	0.89
Condobolin	Far	-1.39	346	0.92
	Near	-1.46	351	0.90
	Combined	-1.42	348	0.91
Wagga Wagga	Far	-1.35	521	0.90
	Near	-1.54	558	0.90
	Combined	-1.45	539	0.90
Leeton	Far	-1.43	330	0.93
	Near	-1.41	335	0.85
	Combined	-1.42	332	0.89

Mean gross margins per hectare at Tamworth declined between Far and Near climate. The greater variation in gross margins occurring in the Near climate grouping, as indicated by the larger standard error of mean, meant there was no differences in gross margin for the Near climate grouping, but differences did occur for the Far climate grouping (Table 49). For both climate groupings, the LRC00TRC100 pasture combination had the highest gross margin (\$301/ha for Far climate, \$278/ha for Near climate), while L75TC25 had the lowest (\$240/ha for Far climate, \$222/ha for Near climate). Generally, across both climate groupings, increasing the proportion of tropical pasture (TRC or TC) increased gross margin, except for L75TC25 and RC75TC25. RC50TC50 in the Far climate also showed a reduction in gross margin compared to RC100TC00. This was not due to changes in the cost of supplementary feeding (Table 50). Closer investigation into sheep numbers indicated that the number of lambs sold had decreased in these instances as a result from lower condition score of ewes in March (pre-joining) and April (joining) leading to lower conception rates (Millar et al. Supplementary information Table 2 and 3, Appendix 2).

Table 49. Tamworth mean gross margin per hectare ($/ha) and standard error of mean (se) for each pasture comparison for the Far and Near climate groupings.

Pasture comparison and proportion (%)		Far climate gross margin ($/ha)		Near climate gross margin ($/ha)	
LRC	**TRC**	**Mean**	**se**	**Mean**	**se**
100	00	282	12.4	261	39.7
75	25	280	3.5	260	40.5
50	50	282	2.4	264	45.0
25	75	301	9.6	273	33.1
00	100	301	9.1	278	30.8
RC	**TC**	**Mean**	**se**	**Mean**	**se**
100	00	270	2.6	245	21.0
75	25	253	3.8	240	30.7
50	50	264	1.4	252	44.2
25	75	288	8.1	264	34.9
00	100	296	4.9	269	37.0
L	**TC**	**Mean**	**se**	**Mean**	**se**
100	00	247	10.8	233	54.1
75	25	240	16.7	222	44.5
50	50	270	12.6	244	42.8
25	75	281	10.4	257	27.3
00	100	289	7.6	267	28.8

The cost of supplementary feed at Tamworth increased from the Far to Near climate groupings, with increasing variation for the Near climate (Table 50). For both climate groupings, RC100TC00 required the most supplementary feeding, while LRC00TRC100 in the Far climate, and LRC75TRC25 and LRC00TRC100 in the Near climate required the least supplementary feed. The cost of supplementary feed generally decreased as the proportion of tropical pasture (TRC or TC) increased.

Table 50. Mean cost of supplementary feed per hectare ($/ha) and standard error of mean (se) for each pasture comparison for the Far and Near climate groupings at Tamworth. Overall pasture comparison means are presented in italics.

Pasture comparison and proportion (%)		Far climate feed cost ($/ha)		Near climate feed cost ($/ha)	
LRC	**TRC**	**Mean**	**se**	**Mean**	**se**
100	00	118	4.2	132	28.4
75	25	110	1.7	123	26.9
50	50	109	1.8	124	30.5
25	75	103	2.9	125	28.1
00	100	101	3.4	123	25.4
LRC v TRC mean		*108*		*125*	
RC	**TC**	**Mean**	**se**	**Mean**	**se**
100	00	141	2.7	159	18.7
75	25	140	0.5	153	23.9
50	50	129	0.4	138	28.5
25	75	116	5.3	135	25.6
00	100	105	3.0	126	26.7
RC v TC mean		*126*		*142*	
L	**TC**	**Mean**	**se**	**Mean**	**se**
100	00	133	6.0	148	36.4
75	25	123	6.1	144	31.2
50	50	118	4.3	135	26.1
25	75	114	3.7	133	25.0
00	100	109	3.7	126	27.5
L v TC mean		*119*		*137*	

At Cowra, mean gross margins per hectare declined from Far to Near climate, with greater variation in the Near climate grouping as indicated by the larger standard errors (Table 51). For the Far climate grouping, the LRC100TRC00 pasture combination had the largest gross margin ($446/ha), while for the Near climate, the best gross margin occurred for LRC00TRC100 ($377/ha). For both climate groupings the lowest gross margin occurred for the RC100TC00 pasture combination ($324/ha for Far climate, $276/ha for Near climate). Increasing the proportion of tropical pasture (TRC or TC) increased gross margin for the RC v TC pasture comparison for both climate groupings, and the LRC v TRC pasture comparison for the Near climate. For the other pasture comparisons, increasing the proportion of tropical to 50% decreased the gross margin, but gross margins increased when the proportion of tropical pasture exceeded 50% (i.e., proportions were 75 and 100% of the pasture mix). This was due to changes in the cost of supplementary feeding (Table 52).

The mean cost of supplementary feed per hectare at Cowra from the Far to Near climate groupings increased, with increasing variation for the Near climate (Table 52). For both climate groupings, RC100TC00 required the most supplementary feed, while LRC100TRC00 in the Far climate, and LRC00TRC100 in the Near climate required the least. Increasing the proportion of tropical pasture (TRC or TC) in the RC v TC pasture comparison for both climate groupings, and LRC v TRC pasture comparison for the Near climate, reduced the cost of supplementary feed. For the other pasture comparisons, the cost of supplementary feed initially increased as the proportion for tropical pasture increasing but decreased when there was 100% tropical pasture.

Table 51. Cowra mean gross margins per hectare ($/ha) and standard error of mean (se) for each pasture comparison for the Far and Near climate groupings.

Pasture comparison and proportion (%)		Far climate gross margin ($/ha)		Near climate gross margin ($/ha)	
LRC	**TRC**	**Mean**	**se**	**Mean**	**se**
100	00	446	0.3	376	37.7
75	25	424	3.8	392	39.3
50	50	409	13.9	393	43.3
25	75	419	11.2	395	48.6
00	100	435	1.3	406	46.8
RC	**TC**	**Mean**	**se**	**Mean**	**se**
100	00	324	30.1	276	25.0
75	25	332	11.5	327	20.4
50	50	369	3.0	327	21.2
25	75	412	15.9	368	31.4
00	100	424	16.9	385	46.6
L	**TC**	**Mean**	**se**	**Mean**	**se**
100	00	431	19.6	379	38.7
75	25	393	28.3	363	40.9
50	50	389	21.0	356	42.6
25	75	405	9.4	367	40.4
00	100	433	9.3	385	47.0

Table 52. Cowra mean cost of supplementary feed per hectare ($/ha) and standard error of mean (se) for each pasture comparison for the Far and Near climate groupings. Overall pasture comparison means are presented in italics.

Pasture comparison and proportion (%)		Far climate feed cost ($/ha)		Near climate feed cost ($/ha)	
LRC	**TRC**	**Mean**	**se**	**Mean**	**se**
100	00	119	0.6	157	24.1
75	25	122	5.4	147	24.2
50	50	137	0.1	151	29.1
25	75	132	0.6	149	30.1
00	100	121	2.8	144	31.5
LRC v TRC mean		*126*		*150*	
RC	**TC**	**Mean**	**se**	**Mean**	**se**
100	00	207	21.1	253	17.4
75	25	177	12.3	199	17.1
50	50	167	7.1	189	24.9
25	75	141	9.5	163	25.9
00	100	125	0.4	150	30.8
RC v TC mean		*163*		*191*	
L	**TC**	**Mean**	**se**	**Mean**	**se**
100	00	124	3.7	156	24.7
75	25	134	12.2	156	25.1
50	50	145	8.6	167	26.1
25	75	140	5.0	168	26.8
00	100	119	2.3	151	34.9
L v TC mean		*132*		*160*	

At Condobolin, mean gross margins per hectare decreased from Far to Near climate, with greater variation occurring in the Near climate grouping as indicated by the larger standard errors of mean (Table 53). For both climate groupings, the best gross margin occurred for the LRC00TRC100 pasture combination ($184/ha for Far climate, $170 for Near climate). For the Far climate the worst gross margin occurred for the L75TC25 ($157/ha), and L100TC00 for the Near climate ($112/ha). For Near climate, L v TC pasture comparison, increasing the proportion of TC increased gross margin. For the RC v TC pasture comparison for both climate groupings, gross margin decreased when the proportion of TC was increased to 50%. Further increases in the proportion of TC increased gross margin but not quite to the same levels as RC100TC00. For the other pasture comparisons, 25% tropical reduced gross margin, but this increased with increasing proportion of tropical pasture. This was not due to changes in the cost of supplementary feeding (Table 54). At this proportion, the number of lambs sold was lower due to the lower condition score of the ewes in March (pre-joining) and April (joining) leading to lower conception rates (Supplementary information Table 6 and 7).

The mean cost of supplementary feeding at Condobolin from the Far to Near climate groupings increased, with greater variation for the Near climate (Table 54). For both climate groupings, LRC00TC100 required the least supplementary feeding, while RC100TC00 in the Far climate, and L100TC00 in the Near climate required the most supplementary feed. The cost of supplementary feed generally decreased as the proportion of tropical pasture (TRC or TC) increased, except for LRC v TRC comparison for Far climate where the cost of feed did not change.

Table 53. Condobolin mean gross margins per hectare ($/ha) and standard error of mean (se) for each pasture comparison for the Far and Near climate groupings.

Pasture comparison and proportion (%)		Far climate gross margin ($/ha)		Near climate gross margin ($/ha)	
LRC	**TRC**	**Mean**	**se**	**Mean**	**se**
100	00	177	12.2	150	38.9
75	25	171	12.7	143	34.7
50	50	180	16.6	153	35.6
25	75	176	12.1	164	35.6
00	100	184	13.7	170	35.5
RC	**TC**	**Mean**	**se**	**Mean**	**se**
100	00	182	9.3	162	28.5
75	25	173	5.9	143	26.6
50	50	169	6.8	144	32.4
25	75	179	12.7	157	39.8
00	100	178	14.0	160	32.9
L	**TC**	**Mean**	**se**	**Mean**	**se**
100	00	159	14.3	112	25.6
75	25	157	11.2	115	32.5
50	50	160	15.0	131	31.6
25	75	158	16.3	147	36.1
00	100	177	12.8	160	36.6

Table 54. Condobolin mean cost of supplementary feed per hectare ($/ha) and standard error of mean (se) for each pasture comparison for the Far and Near climate groupings. Overall pasture comparison means are presented in italics.

Pasture comparison and proportion (%)		Far climate feed cost ($/ha)		Near climate feed cost ($/ha)	
LRC	**TRC**	**Mean**	**se**	**Mean**	**se**
100	00	119	3.4	136	25.2
75	25	117	8.0	136	26.7
50	50	117	7.6	132	25.5
25	75	121	4.8	128	26.4
00	100	116	5.4	123	26.8
LRC v TRC mean		*118*		*131*	
RC	**TC**	**Mean**	**se**	**Mean**	**se**
100	00	142	3.0	153	22.2
75	25	137	0.1	154	21.6
50	50	132	1.7	147	26.4
25	75	125	7.0	138	25.0
00	100	120	6.4	130	26.2
RC v TC mean		*131*		*144*	
L	**TC**	**Mean**	**se**	**Mean**	**se**
100	00	130	5.8	159	18.5
75	25	124	5.9	149	24.7
50	50	129	7.2	146	25.3
25	75	132	8.6	137	24.3
00	100	119	6.6	130	27.9
L v TC mean		*127*		*144*	

At Wagga Wagga mean gross margins per hectare decreased from Far to Near climate, with greater variation in gross margins occurring in the Near climate grouping for LRC v TRC and RC v TC pasture comparisons. For the L v TC pasture comparison, variability was similar between Far and Near climate (Table 55). The best gross margin occurred for the LRC100TRC00 for the Far climate ($374/ha), and LRC00TRC100 for the Near climate ($320/ha). The worst gross margin occurred for RC75TC25 for Far climate ($281/ha), and RC50TC50 for Near climate ($253/ha). For RC v TC pasture comparison, increasing the proportion of TC increased the gross margin for both climate groupings. For the other pasture comparisons for both climate groupings, gross margins decreased when the proportion of tropical pasture was increased to 50%. Further increases in the proportion of TC increased gross margin to values above 0% tropical pasture, except for Far climate LRC v TRC pasture comparison which did not exceed 0% tropical pasture. This was due to changes in the cost of supplementary feeding (Table 56).

The mean cost of supplementary feed per hectare at Wagga Wagga from the Far to Near climate groupings increased, with increasing variation for the Near climate for LRC v TRC and RC v TC pasture comparisons (Table 56). For both climate groupings, RC100TC00 required the most supplementary feed, while LRC100TRC00 in the Far climate, and LRC00TRC100 in the Near climate required the least supplementary feed. The cost of supplementary feed decreased when the proportion of tropical pasture was increased for the RC v TC pasture comparison for both climate groupings. For the Far climate increasing the proportion of tropical pasture to 75% for LRC v TRC and L v TC increased the feed cost, with 100% tropical pasture having similar feed cost to the 0% tropical pasture. For the Near climate, feed costs were stable with a reduction at 100% tropical pasture.

Table 55. Wagga Wagga mean gross margins per hectare ($/ha) and standard error of mean (se) for each pasture comparison for the Far and Near climate groupings.

Pasture comparison and proportion (%)		Far climate gross margin ($/ha)		Near climate gross margin ($/ha)	
LRC	**TRC**	**Mean**	**se**	**Mean**	**se**
100	00	374	23.9	313	35.1
75	25	354	18.8	307	25.4
50	50	333	13.4	302	28.9
25	75	335	6.4	310	21.5
00	100	358	17.0	320	25.9
RC	**TC**	**Mean**	**se**	**Mean**	**se**
100	00	289	2.0	255	12.8
75	25	281	3.0	259	13.3
50	50	294	1.4	253	20.0
25	75	330	25.8	289	23.8
00	100	341	33.6	303	27.0
L	**TC**	**Mean**	**se**	**Mean**	**se**
100	00	344	37.8	288	25.0
75	25	319	37.3	281	26.7
50	50	311	28.6	274	22.4
25	75	311	16.8	286	25.4
00	100	350	24.8	300	27.7

Table 56. Wagga Wagga mean cost of supplementary feed per hectare ($/ha) and standard error of mean (se) for each pasture comparison for the Far and Near climate groupings. Overall pasture comparison means are presented in italics.

Pasture comparison and proportion (%)		Far climate feed cost ($/ha)		Near climate feed cost ($/ha)	
LRC	**TRC**	**Mean**	**se**	**Mean**	**se**
100	00	119	11.3	163	19.4
75	25	124	6.5	157	15.3
50	50	141	5.4	168	19.0
25	75	141	2.7	162	14.7
00	100	120	5.3	155	17.7
LRC v TRC mean		*129*		*161*	
RC	**TC**	**Mean**	**se**	**Mean**	**se**
100	00	183	10.7	211	10.5
75	25	175	1.0	199	14.12
50	50	166	6.3	198	19.8
25	75	141	10.2	175	15.5
00	100	127	15.8	161	14.6
RC v TC mean		*158*		*189*	
L	**TC**	**Mean**	**se**	**Mean**	**se**
100	00	130	19.7	174	14.0
75	25	142	22.4	174	16.78
50	50	148	10.7	176	15.4
25	75	159	4.8	176	15.1
00	100	122	10.4	162	18.4
L v TC mean		*140*		*172*	

At Leeton mean gross margins per hectare remained similar (a change of $2-7/ha) from Far to Near climate, and in contrast to the other four sites, variation was less in the Near climate grouping (Table 57). The best gross margin occurred for the LRC00TRC100 for both climate groupings ($182/ha for Far climate, $175/ha for Near climate). The worst gross margin occurred for L100TC for both climate groupings ($120/ha for far climate, $122/ha for Near climate). For L v TC pasture comparison, increasing the proportion of TC increased the gross margin for both climate groupings. For the LRC v TRC pasture comparison, gross margin declined when TRC was 25%, similarly at 50% TC decreased gross margins was lowest in the RC v TC pasture comparison. Further increases in the proportion of TC and TRC increased gross margin to values above 0% tropical pasture, except for Near climate RC v TC pasture comparison which did not exceed 0% tropical. This was due to changes in the cost of supplementary feeding (Table 58).

The mean cost of supplementary feeding at Leeton from the Far to Near climate groupings increased, with decreasing variation for the Near climate (Table 58). For both climate groupings, LRC00TRC100 required the least supplementary feeding, while RC100TC00 in the Far climate, and L100TC00 in the Near climate required the most supplementary feed. Increasing the proportion of tropical pasture, resulted in a decrease in the cost of supplementary feeding for all pasture comparisons for both climate groupings.

Table 57. Leeton mean gross margins per hectare ($/ha) and standard error of mean (se) for each pasture comparison for the Far and Near climate groupings.

Pasture comparison and proportion (%)		Far climate gross margin ($/ha)		Near climate gross margin ($/ha)	
LRC	**TRC**	**Mean**	**se**	**Mean**	**se**
100	00	167	40.4	165	7.7
75	25	161	39.6	158	10.3
50	50	168	42.2	160	16.1
25	75	175	46.1	168	12.5
00	100	182	48.5	175	12.7
RC	**TC**	**Mean**	**se**	**Mean**	**se**
100	00	161	33.2	163	3.6
75	25	154	32.1	151	2.1
50	50	153	34.8	151	7.8
25	75	163	45.4	158	12.0
00	100	167	46.3	162	15.0
L	**TC**	**Mean**	**se**	**Mean**	**se**
100	00	120	42.8	122	20.9
75	25	137	46.3	129	15.7
50	50	145	47.3	139	12.1
25	75	152	45.4	146	8.3
00	100	167	50.2	163	10.3

Table 58. Leeton mean cost of supplementary feed per hectare ($/ha) and standard error of mean (se) for each pasture comparison for the Far and Near climate groupings. Overall pasture comparison means are presented in italics.

Pasture comparison and proportion (%)		Far climate feed cost ($/ha)		Near climate feed cost ($/ha)	
LRC	**TRC**	**Mean**	**se**	**Mean**	**se**
100	00	116	26.3	120	4.1
75	25	115	29.2	121	6.0
50	50	110	29.3	119	8.3
25	75	108	29.1	118	7.8
00	100	105	29.4	112	6.4
LRC v TRC mean		*111*		*118*	
RC	**TC**	**Mean**	**se**	**Mean**	**Se**
100	00	140	22.0	143	3.5
75	25	135	23.5	143	1.6
50	50	127	24.0	133	3.8
25	75	119	29.7	128	2.4
00	100	110	31.3	119	4.2
RC v TC mean		*126*		*133*	
L	**TC**	**Mean**	**se**	**Mean**	**Se**
100	00	137	28.6	144	9.9
75	25	125	29.7	138	10.2
50	50	125	30.0	134	6.4
25	75	119	29.5	128	4.7
00	100	111	30.6	121	5.3
L v TC mean		*123*		*133*	

5.2.3 Capacity of farming systems to cope with increasing frequency of extreme events predicted with future climate scenarios

We were able to show the effect of incorporating tropical pastures into farming systems under conditions of increasing temperatures and variable rainfall using our climate comparisons based on historical data. The time frames encompass extreme conditions, for example drought (2017-2020).

Recently, issues have been identified relating to the relevance of future climate rainfall, which strongly drives the outcomes for each scenario. While future climate models can predict warmer temperatures, annual rainfall total and distribution must be assigned average, above or below average. To encompass all of these rainfall groupings we would need to run the models with three climatic datasets for each of the five sites and 15 pasture comparisons. This was beyond the timeframe of this study. Instead, we can use a reference site approach to determine the impact of future climate using the data from the existing sites (https://www.climatechangeinaustralia.gov.au/en/projections-tools/climate-analogues/analogues-explorer/). For example, under the RCP 4.5 emissions scenario (Representative Concentration Pathway where by 2100 CO_2 levels reach approximately 650 ppm CO_2-equivalent), the Cowra site in 2050 would be represented by the Tamworth results. This highlights the continuing trend in declining profitability and increasing value of tropical grasses mixes with a productive winter annual species in the production system. For the same 2050 climate scenario, Wagga could represent somewhere between Condobolin and Cowra, while Condobolin would be on the wetter end of scenarios for Leeton.

5.3 Confirming potential production and persistence of tropical species in southern NSW

5.3.1 Environmental conditions

Monthly averages for rainfall, maximum and minimum temperature are shown in Table 59–Table 60. Conditions at the sites were contrasting during the study. In 2018 annual rainfall was ~41% below average, annual maximum temperature was 1.6˚C above average, while the minimum temperature was approximately average. All sites received even less rainfall in 2019 (59% below average) and were warmer with maximum and minimum temperatures 1.9 and ~1˚C above the annual average respectively. By contrast, rainfall in 2020 was slightly above average (7%) and significantly above average in 2021 (34%). The annual average temperatures at all sites were approximately average in 2020 and 2021.

5.3.2 Establishment

Establishment plant densities varied between sites (Table 62) with the irrigated sites (Condobolin, Cowra and Orange) having higher plant populations than those which were not. Panic grass cv. Megamax059 had higher plant densities than other tropical grass cultivars at most sites ($P < 0.001$), with the exception of Orange. Desmanthus plant densities were generally lower at sites which experienced lower maximum temperatures during summer 2018 (Cowra, Orange) than those with higher monthly maximum temperatures (Condobolin, Goolgowi; Table 60), except Glen Innes.

In general, the temperate cultivars established with higher plant populations than the tropical cultivars ($P < 0.001$).

Table 59. Monthly rainfall (mm) totals recorded at or near field evaluation sites along with long-term average (LTA). Recordings are presented for the period from the year of sowing to May 2022 at each site.

Site	Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Condobolin	2018	28.6	8.4	1.0	2.4	15.5	29.7	1.5	3.8	8.5	29.9	83.0	11.8	224.1
	2019	14.3	37.4	15.9	0.2	17.4	19.1	19.6	5.3	5.5	1.6	12.9	6.1	155.3
	2020	10.5	104.4	113.7	136.8	6.2	41.0	50.1	65.0	49.8	47.1	38.1	23.2	685.9
	2021	149.9	79.6	143.8	0.2	21.8	75.9	55.6	23.5	33.8	41.1	150.3	32.7	808.2
	2022	148.9	13.4	21.2	80.0	102.8								
	LTA	*48.9*	*43.8*	*42.7*	*31.8*	*35.3*	*33.2*	*35.5*	*33.3*	*31.9*	*46.5*	*41.6*	*40.5*	*461.8*
Cowra	2018	28.6	48.1	4.6	12.3	29.7	39.1	6.1	25.8	13.1	50.6	70.1	62.2	390.3
	2019	63.3	18.4	59.0	0.7	26.8	53.6	12.1	20.3	12.0	6.1	22.3	8.1	302.7
	2020	42.4	27.1	86.8	133.1	37.0	52.5	92.9	67.5	47.1	111.4	49.9	31.1	778.8
	2021	58.3	109.4	162.6	0.9	44.8	92.2	81.7	79.3	76.8	74.9	206.7	27.4	1015.0
	2022	181.7	20.7	26.1	112.9	76.5								
	LTA	*58.8*	*47.7*	*49.2*	*43.0*	*46.1*	*52.5*	*51.8*	*51.7*	*50.8*	*57.0*	*54.7*	*57.3*	*624.5*
Glen Innes	2018	60.3	114.3	15.0	11.8	4.2	3.2	65.0	41.8	59.5	64.8	74.4	75.0	589.3
	2019	58.6	3.4	109.2	7.9	12.1	13.3	6.2	10.8	8.0	27.7	38.6	43.6	339.4
	2020	89.7	147.4	62.6	81.2	58.4	45.2	50.3	57.4	21.2	72.2	22.2	174.2	882.0
	2021	75.6	74.4	202.9	34.3	52.4	106.1	178.6	82.0	36.5	97.8	224.1	118.1	1282.8
	2022	103.4	122.8	175.4	29.4									
	LTA	*105.3*	*92.9*	*73.1*	*40.7*	*47.9*	*52.4*	*55.9*	*48.6*	*53.6*	*75.1*	*90.8*	*109.4*	*841.5*
Goolgowi	2018													
	2019	10.8	12.6	11.8	50.5	42.0	22.7	15.4	8.1	6.2	1.4	38.7	5.8	226.0
	2020	14.9	61.7	67.3	116.9	8.0	20.6	22.2	46.9	41.2	57.3	20.9	3.7	481.6
	2021	90.3	10.6	36.8	0.0	15.2	85.0	25.9	15.8	78.7	22.2	81.4	8.4	470.3
	2022	103.6	5.8	55.9	39.6	64.0								
	LTA	*29.2*	*27.0*	*38.3*	*31.9*	*32.7*	*30.8*	*28.7*	*32.3*	*30.5*	*39.0*	*30.6*	*28.2*	*379.2*
Guyra	2018													
	2019													
	2020	168.4	163.8	83.0	60.0	44.0	62.0	53.8	47.4	36.0	70.0	14.0	188.4	990.8
	2021	43.4	104.0	221.0	17.6	38.0	102.4	132.8	107.6	39.2	42.0	207.4	123.6	1179.0
	2022	111.0	121.6	156.8	39.6	76.6								
	LTA	*113.6*	*92.7*	*73.7*	*47.9*	*49.9*	*61.2*	*58.6*	*53.5*	*56.3*	*79.6*	*87.5*	*101.0*	*876.7*
Orange	2018	97.6	48.0	33.4	4.8	45.8	52.8	17.2	49.0	64.4	44.8	98.8	64.2	620.8
	2019	67.6	46.0	27.4	17.8	82.5	30.8	32.2	47.5	56.8	18.0	24.6	17.4	468.6
	2020	68.8	61.8	128.4	138	84.4	61.8	68.4	116.2	48.8	102.2	35.4	114.8	1029
	2021	57.6	153.0	216	12.8	37.6	154.1	183.0	98.4	70.0	55.6	307.0	71.9	1417
	2022	124.0	37.4	33.6	136.5	96.3								
	LTA	*86.7*	*74.6*	*66.8*	*53.7*	*67.8*	*73.9*	*89.2*	*93.8*	*78.6*	*78.0*	*79.0*	*79.9*	*919.6*
Yanco	2018	24.2	1.0	4.2	2.0	23.2	29.2	5.8	8.8	12.4	7.4	57.6	22.6	198.2
	2019	10.6	28.4	14.8	33.4	34	37.4	28.8	13.2	13.2	7.0	41.2	4.9	266.9
	2020	41.0	29.6	99.4	113.4	13.6	24.2	17.0	32.2	21.4	63.8	8.0	12.2	475.8
	2021	73.8	6.2	122	0.2	17.4	65.0	27.2	10.7	52.2	23.4	148.2	2.5	548.8
	2022	60.6	2.0	26.8	62.0	67.4								
	LTA	*31.8*	*31.9*	*36.8*	*32.3*	*38.1*	*37.0*	*35.9*	*37.7*	*38.0*	*39.0*	*34.6*	*32.5*	*426.9*
Wagga	2018													
	2019													
	2020	17.6	24.3	84.8	86.6	21.5	61.2	21.8	73.8	54.1	84.6	47.3	70.4	648.0
	2021	82.4	88.2	106.9	1.8	32.3	73.0	54.8	27.4	42.0	32.8	197.8	17.8	757.2
	2022	163.9	15.8	44.2	80.8	67.2								
	LTA	*41.6*	*39.4*	*40.6*	*45.5*	*55.1*	*48.5*	*55.6*	*54.0*	*54.2*	*60.6*	*42.8*	*40.7*	*578.6*

Table 60. Monthly mean maximum daily temperature (˚C) recorded at or near field evaluation sites. along with long-term average (LTA). Observations are presented for the period from the year of sowing to May 2022 at each site.

Site	Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Condobolin	2018	36.3	34.3	32.3	29.9	20.4	16.3	16.7	18.2	22.1	27.1	27.8	33.9
	2019	39.8	33.3	29.8	27.2	20.3	17.1	16.4	17.4	22.9	28.0	29.4	35.7
	2020	37.6	30.6	27.3	22.1	18.4	16.1	15	15.7	21.7	26.3	31.8	30.4
	2021	34.4	31.0	27.5	24.5	19.7	15.7	14.6	17.3	20.8	23.3	25.5	31.2
	2022	32.6	31.8	29.9	24.6	18.8							
	LTA	*34.1*	*32.8*	*29.5*	*24.7*	*19.6*	*15.8*	*15.1*	*16.9*	*20.7*	*25.2*	*28.8*	*31.8*
Cowra	2018	34.6	32.6	30.9	28.4	19.0	15.2	15.2	15.9	20.8	25.6	27.1	32.9
	2019	37.9	32.5	28.5	25.8	18.9	15.6	15.4	16.1	21.5	26.9	29.1	34.5
	2020	35.7	30.9	26.7	21.4	17.3	15.1	14.7	14.3	20.1	24.3	29.5	30.4
	2021	31.9	30.2	26.0	23.0	18.5	14.4	13.3	16.1	18.6	21.4	22.9	28.9
	2022	30.3	29.9	28.3	23.5	18.2							
	LTA	*32.2*	*31.4*	*28.1*	*23.6*	*18.6*	*14.7*	*13.7*	*15.5*	*18.6*	*22.7*	*26.7*	*30.2*
Glen Innes	2018	28.8	26.3	25.2	23	17.9	14.6	14.8	15.4	18.5	21.4	24.2	27.5
	2019	30.6	28.0	25.8	21.4	17.2	14.8	15.3	16.3	20.9	24.1	26.9	30.2
	2020	29.3	24.5	22.9	20.8	15.4	14.6	13.6	14.1	15.6	16.3	22.7	23.8
	2021	25.3	25.7	22.7	19.2	16.8	12.7	12.2	15.1	17.5	20.3	20.3	24.7
	2022	25.5	23.2	22.7	20.2	16.1							
	LTA	*25.7*	*24.9*	*23.2*	*20.1*	*16.4*	*13.2*	*12.7*	*14.2*	*17.3*	*20.3*	*22.6*	*24.6*
Goolgowi	2018												
	2019	39.4	33.6	30.5	26.4	19.3	16.4	15.8	16.9	22.2	27.8	28.7	35.1
	2020	35.5	31.2	27.6	22.1	17.9	16.0	15.6	16.2	22.8	25.6	32.5	31.3
	2021	32.9	31.6	27.3	24.5	20.4	15.5	15.0	17.8	21.1	23.3	25.3	31.7
	2022	33.2	31.8	29.6	24.7	18.7							
	LTA	*33.2*	*32.3*	*28.8*	*24.1*	*19.2*	*15.5*	*14.6*	*16.6*	*20.1*	*24.3*	*28.2*	*31.1*
Guyra	2018												
	2019												
	2020	27.2	22.3	20.0	18.5	13.0	12.0	10.8	12.0	16.3	19.6	23.9	22.5
	2021	23	22.2	20.0	16.8	14.4	10.4	10.2	13.2	15.6	18.3	18.7	22.0
	2022	23.3	20.3	19.9	17.8	14.3							
	LTA	*24.5*	*23.5*	*21.7*	*18.3*	*14.1*	*11.1*	*10.2*	*11.9*	*15.4*	*18.8*	*21.5*	*23.8*
Orange	2018	29.0	27.0	24.9	23.1	15.1	11.1	11.1	11.7	15.3	20.3	21.8	25.6
	2019	32.2	27.4	24.6	21.1	14.6	12.2	11.6	12.3	16.3	22.3	24.6	27.6
	2020	30.1	25.0	21.2	17.1	13.3	11.1	11.3	10.7	15.7	19.1	23.1	24.1
	2021	26.8	24.2	20.9	17.8	14.4	11.0	9.3	11.9	14.9	17.5	18.9	24.6
	2022	25.1	23.9	22.7	18.2	13.5							
	LTA	*26.7*	*25.8*	*22.8*	*18.6*	*14.2*	*10.7*	*9.6*	*11.1*	*14.3*	*18.1*	*21.4*	*24.7*
Wagga	2018												
	2019												
	2020	34.5	31.2	26.7	20.7	16.8	14.2	13.6	13.9	19.4	22.9	29.8	29.3
	2021	31.5	29.3	25.8	22.5	18.8	14.1	13.0	15.8	18.2	21.3	23.3	30.0
	2022	31.3	30.7	28.9	23.0	17.9	12.7						
	LTA	*31.1*	*30.5*	*27.2*	*22.2*	*17.0*	*13.7*	*12.5*	*14.4*	*17.4*	*21.1*	*25.2*	*29.2*
Yanco	2018	35.8	33.8	30.9	28.8	19.4	15.5	15.7	16.8	20.9	26.5	27.5	31.5
	2019	39.1	32.6	29.3	25.8	18.6	15.2	14.7	15.8	21.3	27.3	27.5	22.3
	2020	34.5	31	27.1	21.6	17.5	15.0	14.7	15.4	21.7	25.6	32.4	31.4
	2021	32.7	31.3	26.8	23.8	20.1	15.0	13.8	17.2	20	22.7	24.8	30.9
	2022	32.1	31.5	29.5	24.0	18.6							
	LTA	*34.1*	*32.4*	*28.9*	*24.3*	*19.0*	*15.2*	*14.5*	*16.3*	*20.5*	*24.9*	*28.8*	*30.8*

Table 61. Monthly mean minimum daily temperature (˚C) recorded at or near field evaluation sites, along with long-term average (LTA). Observations are presented for the period from the year of sowing to May 2022 at each site.

Site	Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Condobolin	2018	20.1	18.1	14.8	13.3	5.6	3.9	1.3	2.4	5.5	12	14.9	19.9
	2019	25.4	19.0	17.0	12.8	8.3	4.0	4.8	3.6	6.6	11.8	14.4	18.7
	2020	21.4	19.6	15.2	10.8	5.3	4.0	2.8	3.2	6.4	10.1	14.2	14.0
	2021	17.9	16.3	11.9	7.0	5.2	4.7	4	3.5	4.9	7.3	13.5	15
	2022	18.9	16.3	15.9	11.3	7.7							
	LTA	*18.5*	*18.2*	*14.9*	*10.0*	*6.5*	*3.9*	*2.8*	*3.5*	*5.8*	*9.6*	*13.2*	*15.9*
Cowra	2018	17.6	16.0	13.4	11.3	4.7	3.3	0.1	1.3	3.4	8.8	12.7	16.4
	2019	21.7	16.7	15.1	10.4	5.6	3.1	2.7	0.8	4.0	8.3	12.4	15.4
	2020	19.3	18.4	14	10.1	5.2	4.0	3.1	3.5	5.1	8.8	12.2	13.8
	2021	15.3	15.1	12.8	5.4	4.9	3.9	3.7	3.3	4.3	7.0	12.2	13.1
	2022	16.9	14.5	14.7	10.2	7.2							
	LTA	*17.3*	*16.2*	*13.6*	*8.8*	*4.8*	*3.6*	*2.4*	*2.4*	*4.0*	*7.2*	*11.6*	*14.5*
Glen Innes	2018	12.8	13.4	12.9	9.3	3.3	1.6	0.8	-0.3	4.6	9.1	9.6	12.6
	2019	15.0	13.0	13.2	8.7	4.2	2.4	1.3	1.7	3.8	7.3	9.7	13.2
	2020	14.2	13.6	10.8	7.4	3.7	1.9	1.6	2.0	5.1	8.1	9.9	13.5
	2021	12.6	12.9	11.9	5.5	3.3	2.3	2.1	2.0	3.8	7.7	11.2	12.0
	2022	14.3	12.3	11.8	9.4	7.7							
	LTA	*13.5*	*13.3*	*11.6*	*8.0*	*4.5*	*1.9*	*0.8*	*1.3*	*4.1*	*7.3*	*9.9*	*12.2*
Goolgowi	2018												
	2019	23.0	18.0	16.1	12.7	7.5	4.2	4.6	2.4	6.0	10.8	13.2	17.6
	2020	18.4	18.2	14.8	10.6	5.6	4.2	2.7	3.7	7.8	11.3	15.5	14.8
	2021	17.9	16.9	13.5	8.3	6.3	5.7	4.2	4.4	6.1	8.7	13.5	15.3
	2022	20.1	17.1	15.9	12.2	7.7							
	LTA	*17.4*	*17.4*	*14.3*	*10.3*	*7.0*	*4.5*	*3.5*	*3.8*	*5.9*	*9.2*	*12.8*	*15.4*
Guyra	2018												
	2019												
	2020	15.3	13.4	10.4	7.3	3.4	1.4	1.4	1.1	4.3	7.3	9.2	12.1
	2021	11.2	11.8	10.9	5.4	3.3	1.7	1.3	1.7	3.1	6.0	9.4	10.6
	2022	12.3	11	10.7	7.8	5.7							
	LTA	*10.8*	*10.9*	*9.2*	*5.6*	*2.4*	*0.3*	*-0.6*	*0.1*	*2.4*	*5.4*	*7.6*	*9.9*
Orange	2018	14.8	11.9	10.6	9.4	4.1	2.5	1.1	1.4	3.9	7.7	9.6	12.6
	2019	18.4	12.7	11.8	7.9	4.7	1.9	2.4	0.7	3.6	7.1	9.3	11.3
	2020	15.4	12.8	10.6	8.5	3.4	2.5	1.5	1.5	5.3	8.2	9.7	11.2
	2021	13	11.7	10.2	5.5	4.1	2.3	1.7	2.0	3.1	5.5	9.8	11.6
	2022	14.3	12.4	11.8	8.4	5.0							
	LTA	*13.5*	*13.1*	*10.8*	*7.3*	*4.6*	*2.6*	*1.5*	*2.0*	*4.2*	*6.7*	*9.2*	*11.3*
Wagga	2018												
	2019												
	2020	17.5	18.0	14.2	9.3	4.5	3.7	2.7	3.6	6.2	9.8	13.0	12.9
	2021	15.9	15.2	12.1	6.0	4.7	4.2	3.5	2.9	4.7	6.8	11.5	13.2
	2022	18.2	15.1	15.2	11.0	6.8							
	LTA	*16.4*	*16.9*	*14.1*	*10.1*	*6.8*	*4.3*	*3.3*	*4.3*	*6.0*	*8.5*	*11.1*	*14.2*
Yanco	2018	20.4	18.9	15.6	13.5	7.6	5.2	4.4	5	7	12.2	14.7	18.1
	2019	23.5	18.2	16.4	13.9	8.4	5.0	5.3	3.3	7	11.3	13.7	10.5
	2020	18.2	18.2	14.9	11.1	6.6	5.4	4.0	4.8	8.4	11.5	15.2	14.6
	2021	17.6	16.7	13.6	9.6	7.4	6.3	5.4	5.5	7.3	9.2	13.1	15.3
	2022	19.7	17.0	16.0	12.4	8.8							
	LTA	*19.0*	*18.3*	*15.4*	*11.8*	*7.7*	*5.7*	*4.9*	*5.2*	*7.6*	*10.6*	*14.3*	*16.1*

Table 62. Sowing rates (kg/ha germinable seed) and mean establishment (plants/m^2) of entries sown at each evaluation site^

Entry ID*	Common name	Cultivar (or line)	Sowing rate (kg/ha)	Establishment plant density (plants/m^2)					
				Condobolin	Cowra	Glen Innes	Goolgowi	Guyra	Orange
1	Bahia grass	Pensacola	2.0	35	36	5	2		104
2	Digit grass	Premier	5.0	49	105	12	1	50	54
3	Kikuyu	Whittet	2.0	40	40	7	1	13	35
4	Makarikari grass	Bambatsi	2.0	52	59	37	1	38	59
5	Panic grass	Megamax 059	4.5	196	142	48	6	109	85
6		Gatton	1.75	46	108	28	2	62	101
7	Paspalum	Common	4.0	15	32	21	1	73	79
8	Rhodes grass	Callide	1.5	34	70	12	11	40	22
9		Katambora	1.0	28	38	12	5	65	6
10		Reclaimer	0.75	8	41	8	5		15
11	Desmanthus	JCU Blend	3.0	12	3	12	30		9
12		Marc	3.0	8	4	32	6		5
13	Cocksfoot	Currie	5.0		95				
14		Kasbah	5.0	85			55		
15		Porto	5.0						117
16	Phalaris	Holdfast	5.0		143	50			115
17		Horizon	5.0				93		
18	Tall fescue	Hummer	12.0		203	43			
19		Temora	12.0		215				
20	Veldt Grass	Mission	4.0				119		
21	Lucerne	SARDI Grazer	8.0	9	105	30	51		
22		Pegasus	8.0						116
23		Aurora	8.0						
24	Tedera	Lanza	10.0	18					
	l.s.d (P = 0.05)			31.3	32.6	10.9	14.9	18.5	36.9

*Entry id used to indicate entry in Frequency/Herbage mass regression figure

^Establishment counts unable to be assessed at Yanco and Wagga Wagga sites

5.3.3 Persistence and herbage production

The change in frequency between the initial assessment in year one and the final assessment in autumn 2022 varied between sites (Table 63). The average change in frequency ranged from an increase in most tropical grass species at Condobolin (average change +22%) to a decline at Wagga Wagga (average change -21%).

Kikuyu was the most persistent tropical species across sites (average +28%) noting that it established poorly at three of the eight sites. By contrast, panic grass cv. Megamax 059 showed poor persistence across all sites (average -20%), except for Goolgowi where frequency was static. Panic grass cv. Gatton had better persistence at Cowra and Goolgowi, however frequency declined at all other sites (average -27%). Rhodes grass cultivars had high persistence at the Condobolin site (especially cv. Reclaimer), Yanco and Wagga Wagga, but declined at most other sites (Cowra, Glen Innes and Orange sites). Digit grass cv. Premier had good persistence at most sites, however, frequency declined at the Yanco and Wagga sites (37% and 64% respectively) ($P < 0.05$). Plant frequency of bahia grass generally increased at sites where it established well (average +41%). Frequency scores for desmanthus declined across all sites (average -15%); the decline occurred within the first 12 months of sowing.

Among the temperate grass species, plant frequency was generally maintained (cocksfoot cultivars) or increased (average 25%). The exception was the drier/warmer Goolgowi site where plant frequency of all temperate grasses and lucerne declined (average -40% and -28% respectively). This contrasted with the tropical grasses at that site whose plant frequency increased (~17%, $P < 0.05$).

Table 63. Back transformed and square root transformed (in parenthesis) change in frequency scores from the first and last measurement at each site for tropical and temperate species. Entries with a positive increase in frequency are indicated in bold.

Common name	Cultivar (or line)	Condobolin	Cowra	Glen Innes	Goolgowi	Guyra	Orange	Yanco	Wagga Wagga
Bahia grass	Pensacola	**76.3** (5850)	**64.7** (423)	**10.0** (182)	-1.5 (4)		**55.3** (3142)	**1.3** (3)	-40.7 (7029)
Digit grass	Premier	**32.0** (1049)	**23.3** (546)	0.0 (168)	**20.0** (407)	-3.0 (8)	**30.7** (984)	-37.0 (1878)	-64.7 (4225)
Kikuyu	Whittet	**75.3** (5759)	**67.0** (4734)	**7.0** (228)	-0.33 (0)	**20.0** (433)	**24.0** (681)	0.0 (0)	**33.7** (1647)
Makarikari grass	Bambatsi	**35.0** (1466)	18.0 (474)	8.0 (165)	**9.17** (95)	-21 (464)	-19.3 (413)	-34.0 (1270)	-47.0 (2382)
Panic grass	Megamax 059	-9.3 (298)	-46.3 (2196)	-23.0 (538)	0.0 (10)	-27 (874)	-44 (1947)	0.0 (0)	-17.7 (2810)
	Gatton	-5.3 (266)	**10.3** (160)	-10.0 (178)	**17.2** (308)	-26 (704)	-52.7 (2813)	-32.0 (1037)	-40. 7(1655)
Paspalum	Common	**38.3** (1662)	**12.0** (392)	**16.0** (278)	0.0 (0)	**24** (698)	**3.0** (255)	-1.3 (5)	-26.3 (1988)
Rhodes grass	Reclaimer	**74.0** (5548)	**29.7** (1100)	-15.0 (263)	-4.0 (19)		-72.3 (5330)	-15.0 (225)	-4.7 (38)
	Katambora	**22.0** (1713)	-20.7 (1007)	-23.0 (591)	-3.33 (41)	-24 (617)	-50.3 (2710)	-15.0 (375)	-3.0 (98)
	Callide	**4.3** (2153)	-14.3 (1022)	-13.0 (211)	-7.83 (75)	-25.0 (634)	-59.0 (3506)	-0.7 (1)	**0.3** (0)
Desmanthus	JCU Blend	-33.0 (29)		-4.0 (21)	-21.6 (502)		-5.3 (40)	-7.0 (147)	
	Marc						-4.3 (25)	0.0 (0)	
Cocksfoot	Currie		-2.0 (13)						
	Kasbah	-2.7 (55)			-30.5 (931)				
	Porto						**50.7** (2583)		
Phalaris	Holdfast		**12.7** (162)	**45.0** (2049)			**56.3** (3179)		
	Horizon				-40.7 (1682)			0.0 (0)	
Tall fescue	Hummer		**2.3** (68)	**56.0** (3427)					
	Temora		**5.7** (76)						
Veldt Grass	Mission				-49.2 (2444)				
Lucerne	SARDI Grazer	**10.7** (143)	-1.0 (33)	**18.0** (385)	-28.7 (822)				
	Pegasus						**8.0** (139)		
	Aurora							-3.3 (33)	
Tedera	Lanza	-7.0 (54)						**0.3** (0)	
l.s.d (*5%*)		(2075.3)	(1614.8)	(598.7)	(370.4)		(1354.6)	(909.2)	(2144)

There was a positive correlation between herbage production and plant frequency at all sites ($P \leq 0.01$, Fig. 19). The average site mean for dry matter production across entries was highest at Cowra (2547 kg/ha) and Orange (2319 kg/ha); 2.5-fold greater than the average production at other sites.

The temperate grass cultivars were consistently ranked in the top five entries at the cooler/wetter sites (Cowra, Glen Innes, Guyra and Orange). This was indicative of the shorter seasonal production of tropical grasses, which had no production over late autumn and early spring at these sites. Among the tropical species, paspalum was ranked consistently in the top five entries at the Tableland sites (Glen Innes, Guyra and Orange), while digit grass and Makarikari grass performed consistently well across all four cooler sites (i.e., Cowra, Glen Innes, Guyra and Orange).

At the warmer/drier sites (Condobolin, Goolgowi, Yanco and Wagga) Rhodes grass cultivars were consistently ranked within (or just outside) the top five species. Panic grass cv. Gatton performed well at Goolgowi and Yanco. None of the temperate species were ranked in the top five producing cultivars at any of the drier/warmer sites. At these sites the tropical species had a longer growing season, from earlier in spring until further into autumn than at the cooler/wetter sites. Desmanthus were consistently ranked lowest for frequency and production at all sites.

1.1.1 Forage mineral concentration

Mineral concentrations for each tropical and temperate cultivar were averaged across assessments and the three sites to provide a representation of their value over the evaluation period. These values were compared with the high requirements for a 50 kg lamb growing 250 g/day and a pregnant ewe (Table 64). All forages had sufficient concentrations of Ca, Mg, P and Cl to meet the high demands of these sheep classes. Sulphur concentrations were also above the requirements for all forages except digit grass. Sodium concentrations of bahia grass, digit grass and kikuyu, also tall fescue cv. Temora and lucerne cv. SARDI Grazer were also below the requirements for these classes of sheep. Interestingly the Na concentration of lucerne cv. Pegasus was 83% higher than the published requirement.

Key mineral ratios indicated that Ca and Mg levels were below the threshold for the tetany index (<2.2) and K:(Na + Mg) ratio (<6) for all forage species respectively. On average the DCAD (<12) was twice the sheep requirement for all cultivars, except lucerne cv. Pegasus which was 33% below the threshold.

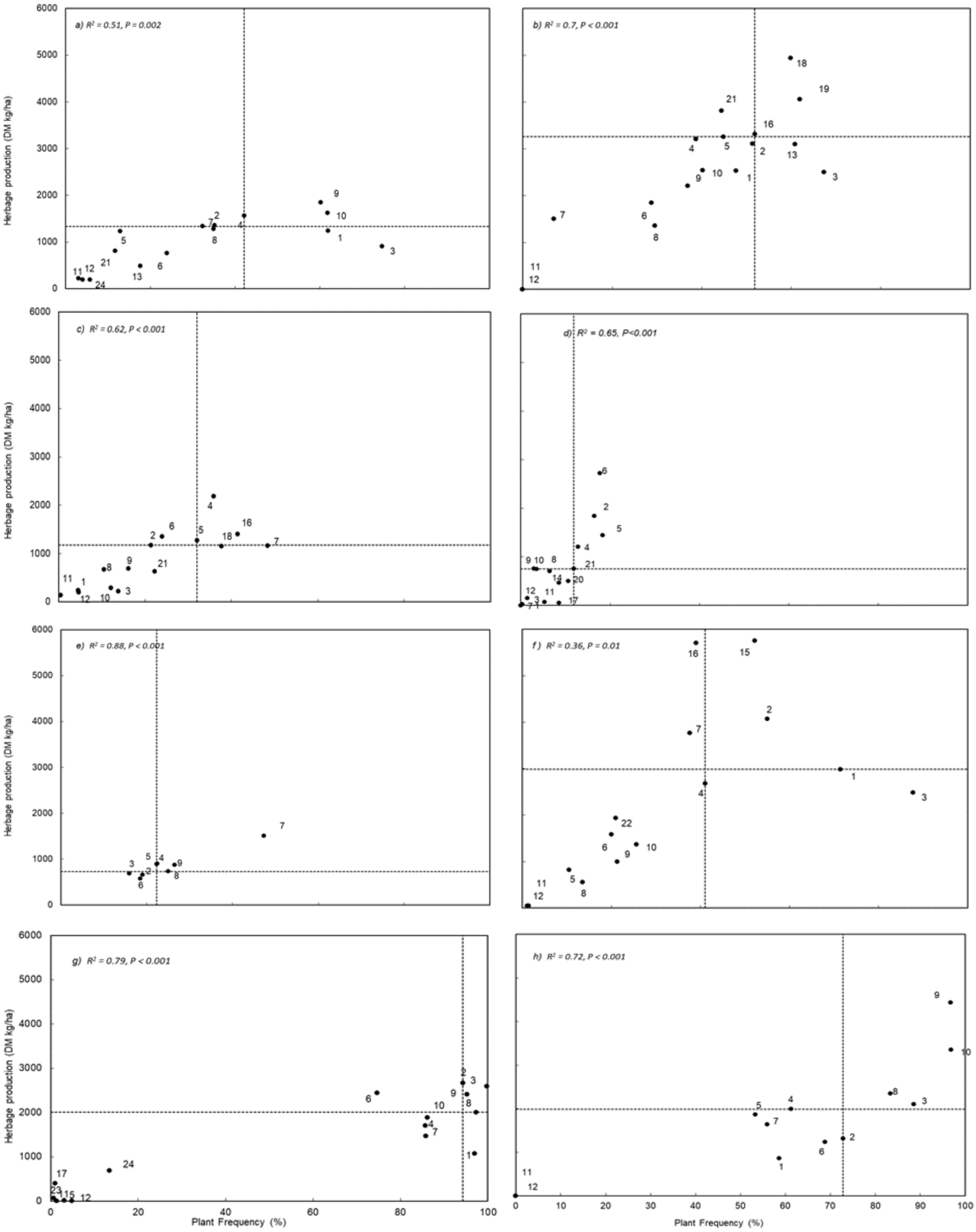


Fig. 19. Relationship between average plant frequency (%) and average herbage production per assessment (kg DM/ha) for entries at a) Condobolin, b) Cowra, c) Glen Innes, d) Goolgowi, e) Guyra, f) Orange, g) Yanco and h) Wagga Wagga. Numbers for each point correspond to the cultivar IDs given in Table 62. Dotted lines indicate the top five performers for plant frequency (vertical line) and herbage production (horizontal line) across all assessment times.

Table 64. Average dietary concentration of calcium (Ca), magnesium (Mg), phosphorous (P), potassium (K), sodium (Na), sulfur (S) and chloride (Cl) for cultivar entries at Condobolin, Cowra and Orange, plus key mineral indices which reflect the risk of mineral imbalance (DCAD, dietary cation-anion difference). Figures in bold are outside required limits.

Pasture species and cultivar	Ca (%)[A]	Mg (%)[A]	P (%)[A]	K (%)[A]	Na (%)[A]	S (%)[A]	Cl (%)[A]	Ca:P (%)[A]	DCAD (meq/100g DM)[B]	Tetany index[C]	K:(Na+Mg) ratio[D]
Lamb requirement	>0.28	>0.09	>0.24	<3	>0.06	>0.18	>0.04	1.2	<12	<2.2	<6
Pregnant ewe requirement	>0.4	>0.09	>0.2	<3	>0.9	>0.2	>0.1	1.2	<12	<2.2	<6
Bahia grass cv. Pensacola	0.59	0.27	0.25	1.44	**0.01**	0.26	0.26	2.44	**13.77**	0.81	1.91
Digit grass cv. Premier	0.49	0.39	0.28	2.32	**0.03**	**0.17**	0.70	1.83	**33.04**	1.44	2.53
Kikuyu cv. Whittet	0.47	0.34	0.30	2.76	**0.02**	0.21	0.99	1.76	**34.25**	1.53	2.71
Makarikari grass cv. Bambatsi	0.35	0.19	0.24	2.44	0.38	0.18	0.58	1.57	**37.78**	1.56	1.64
Panic grass cv. Gatton	0.67	0.31	0.35	2.32	0.29	0.19	0.61	2.13	**45.72**	1.19	2.08
Panic grass cv. Megamax059	0.53	0.29	0.28	1.78	0.37	0.20	0.64	2.24	**47.97**	1.31	1.81
Common paspalum	0.59	0.24	0.26	1.27	0.07	0.34	0.37	2.27	**17.23**	1.09	2.51
Rhodes grass cv. Callide	0.58	0.14	0.36	2.24	0.53	0.34	0.81	1.81	**36.48**	1.00	1.79
Rhodes grass cv. Katambora	0.52	0.12	0.25	1.67	0.72	0.27	0.94	2.32	**35.21**	1.43	1.13
Rhodes grass cv. Reclaimer	0.57	0.13	0.32	1.66	0.69	0.32	0.73	2.05	**31.93**	1.25	1.16
Cocksfoot cv. Currie	0.53	0.20	0.37	2.30	0.06	0.25	0.60	1.58	**28.79**	1.15	3.21
Cocksfoot cv. Porto	0.65	0.25	0.36	1.34	0.40	0.30	0.28	2.02	**25.26**	1.41	0.95
Tall fescue cv. Hummer	0.43	0.25	0.31	1.51	0.48	0.34	0.46	1.65	**25.20**	0.69	2.74
Tall fescue cv. Temora	0.47	0.28	0.29	2.52	**0.02**	0.27	0.74	1.56	**28.05**	1.47	2.64
Phalaris cv. Holdfast	0.45	0.17	0.23	1.81	0.08	0.26	0.67	2.21	**14.81**	1.23	1.21
Lucerne cv. Pegasus	1.95	0.32	0.32	1.13	0.11	0.30	0.24	6.63	8.14	0.24	0.97
Lucerne cv. SARDI Grazer	1.56	0.21	0.27	2.23	**0.02**	0.35	0.48	6.19	**22.80**	0.61	3.13
l.s.d (5%)	*0.067*	*0.116*	*0.072*	*0.454*	*0.11*	*0.032*	*0.081*	*0.549*	*8.89*	*0.303*	*0.538*

[A] Requirement derived from National Research Council (2007)

[B] Estimated from Takagi and Block (1991)

[C] Kemp and t' Hart (1957)

[D] (Dove *et al.* 2016)

5.4 Modelling emergence of tropical grasses in NSW

Emergence frequency varied with location and management practice applied (Table 1). Emergence occurred the highest proportion of years at Tamworth (≥94%), the proportion increasing with management practices that increased ground cover the most successful management practice (emergence 100% of years). Condobolin and Cowra had similar emergence frequencies ranging 71–87% with different management practices and time period. Emergence ranged 36–48% of years at Wagga Wagga declining to only 16–48% of years at Leeton. Emergence frequency declined slightly in the near past (1989/90 to 2019/20) compared to the far past (1957/58 to 1987/88) at all sites, except Leeton. At this site emergence frequency increased from 16–19% of years in the far past to 36–48% of years in near past (Table 65).

The management treatments imposed had varying effects on emergence. The presence of winter weeds had an inconsistent effect while utilising ground cover generally improved emergence at all locations and time periods. Utilising ground cover also tended to provide opportunities for successful pasture emergence earlier in the season (Fig. 20).

Table 65. Successful tropical pasture first emergence (expressed as a percentage (%) of years) for Tamworth, Condobolin, Cowra, Leeton and Wagga Wagga for two time periods (far past and near past) and three management comparisons (baseline, winter weed incursion and ground cover).

Location	Far past			Near past		
	Baseline	Weed incursion	Ground cover	Baseline	Weed incursion	Ground cover
Tamworth	94	97	100	94	94	94
Condobolin	87	81	87	77	71	87
Cowra	74	71	84	71	71	74
Wagga Wagga	42	42	48	36	42	45
Leeton	16	19	19	45	48	48

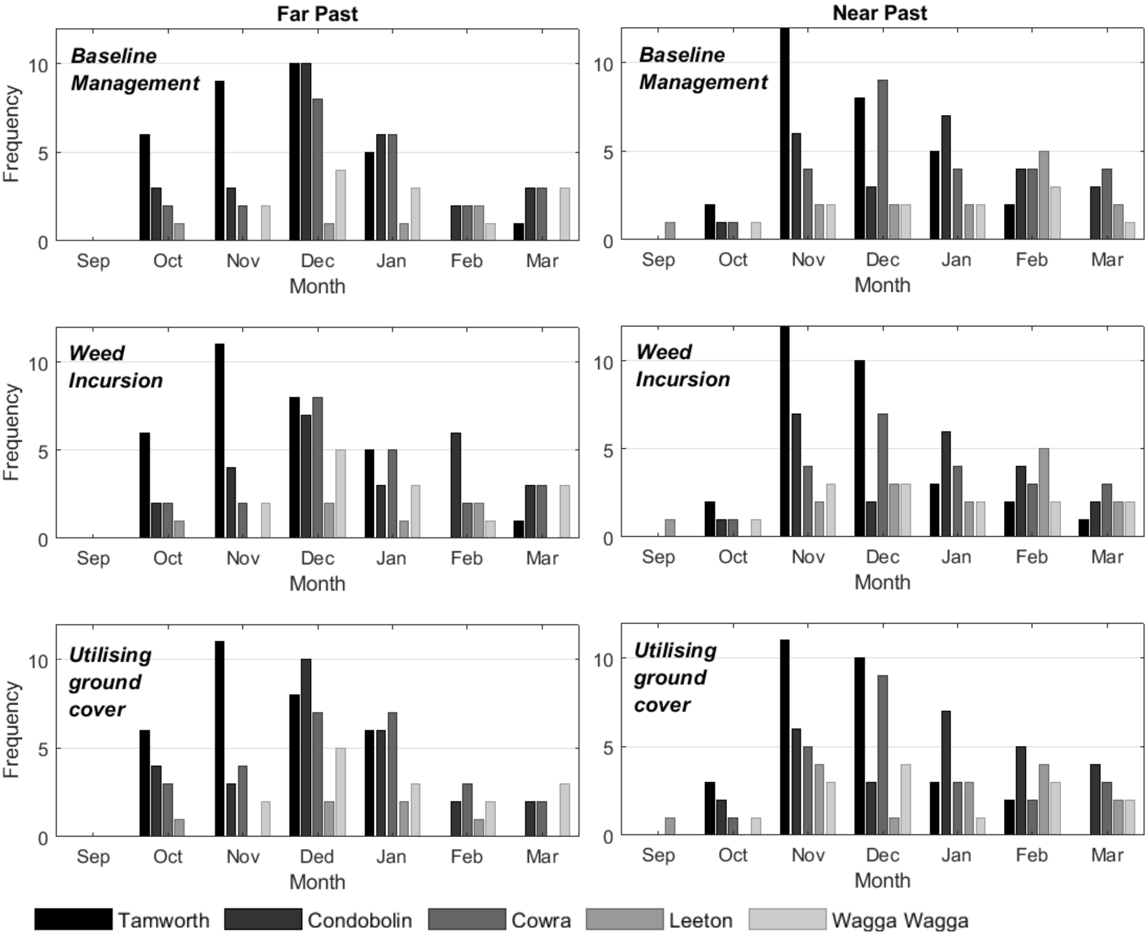


Fig. 20. Monthly frequency of first emergence of a tropical pasture at Tamworth, Condobolin, Cowra, Leeton and Wagga Wagga for two time periods (1957–1988 and 1989–2020) and three management treatments (baseline management (bare fallow), weed incursion and utilising ground cover).

Soil water holding capacity had a significant effect on tropical grass emergence at Leeton. Successful emergence occurred in more years on the brown Chromosol with the higher water holding capacity than the red Chromosol (Table 66). Additionally, emergence rates on the brown Chromosol were 81% of years over the far past and 97% of years over the near past period.

Table 66. Tropical pasture emergence rates (expressed as a percentage of years) at Leeton, comparing two soil types (Red and Brown Chromosol) over two time periods (far past and near past).

Soil Type	Far past (1957/58–1987/88)	Near past (1989/90–2019/20)
Red Chromosol	16	45
Brown Chromosol	81	97

The number of emergence events that occurred per year was examined to understand the opportunity for multiple establishment events (Table 67). On average the number of emergence events/year ranged from 3.3–3.5 events/year at Tamworth to 1.3–1.8 events/year at Leeton. However, when the years without an emergence event were excluded, the number of events increased to 2.0–2.9 events/year, except for Tamworth, which increased to 3.4–3.7 (data not presented). The average number of days when emergence was possible each year was highest at Wagga (6.2–8.4 days/year), followed by Tamworth (5.3–5.7 days/year) and Leeton (3.6–7.6 days/year). Cowra (2.5–2.8 days/year) had the lowest number of emergence days/year (Table 67). This was due to establishment events being longer at Wagga (3.1–4.5 days) and Leeton (2.8–4.3 days) compared to the other three sites (all 1.4–1.7 days). Weather conditions would have affected event length, but soil type and moisture holding capacity would have had an effect also.

Table 67. The average number of emergence events per year, the average number of days of emergence per year and average emergence event length for Tamworth, Condobolin, Cowra, Leeton and Wagga Wagga for two time periods (1957–1988 and 1989–2020) under baseline management (bare fallow). The establishment conditions were based on the threshold triggers but excluded the modelled growth component as growth had commenced during subsequent events.

Location	Period	Emergence (events/year)	Emergence period (days/year)	Emergence event length (days)
Tamworth	Far	3.5	5.7	1.6
	Near	3.3	5.3	1.6
Condobolin	Far	2.5	3.7	1.5
	Near	2.1	3.2	1.5
Cowra	Far	2.0	2.8	1.4
	Near	1.5	2.5	1.7
Wagga	Far	2.0	6.2	3.1
	Near	1.9	8.4	4.5
Leeton	Far	1.3	3.6	2.8
	Near	1.8	7.6	4.3

5.5 Quantifying seedling emergence response of tropical perennial pasture species to temperature

1.4.1 Temperatures during the experiment

The mean minimum and maximum air temperatures for the 14-day period of the experiment each month are presented in Fig. 21. Mean maximum temperatures occurred at all sites in December–January, except Wagga Wagga which recorded its highest mean maximum temperature in February. The lowest mean minimum air temperature at all sites was recorded in August, except for Trangie which occurred in July. Mean soil temperatures for the 14-day assessment period each month followed a similar trend to air temperatures and were generally within 1–2°C of each other, soil temperatures lagging slightly behind air temperatures.

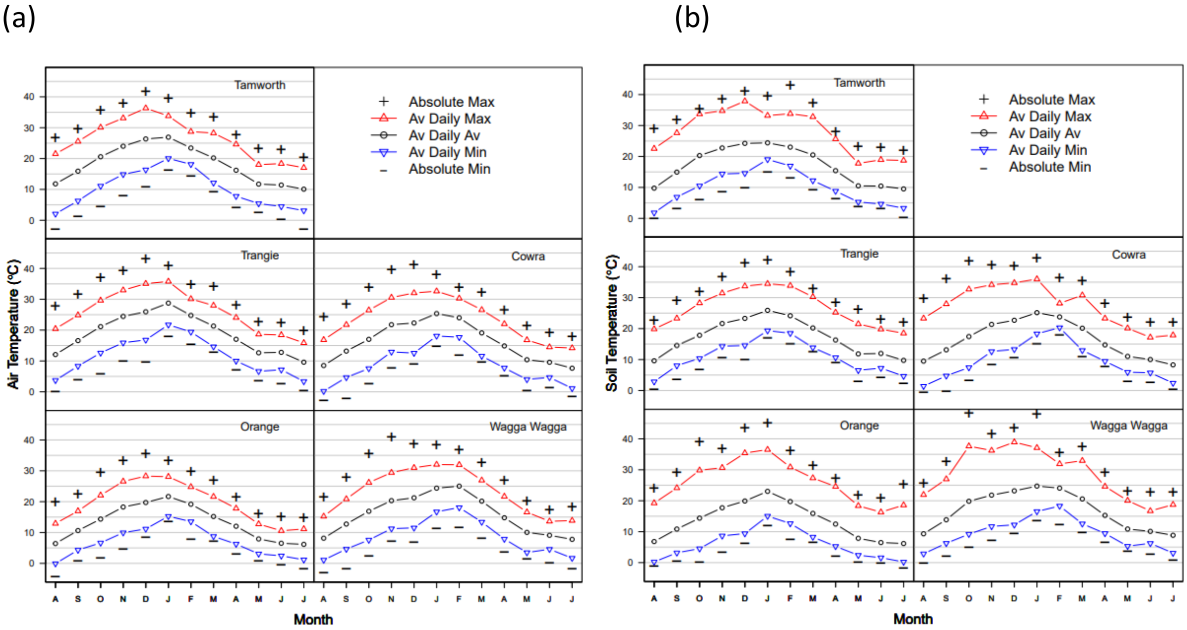


Fig. 21. Minimum, maximum, average, also absolute minimum and maximum (a) air temperature (°C) and (b) soil temperature (°C) at 10 mm over the 14 days for each month the experiment was conducted from August (A) to July (J).

5.5.2 Emergence response surfaces

Response surface plots of seedling emergence over the 14 days post sowing are presented in Fig. 22 and Fig. 23. Katambora Rhodes grass had the widest emergence window of the four core grasses emerging over the greatest number of months of the year at all sites (Fig. 22), while Bambatsi and Gatton panic generally had the smallest emergence window, emerging over the fewest months of the year. Of the five sites, seedling emergence was highest and occurred over greater period of the year at Tamworth, and emergence lowest at the Cowra and Wagga sites and over the least number of months at the Orange and Cowra sites.

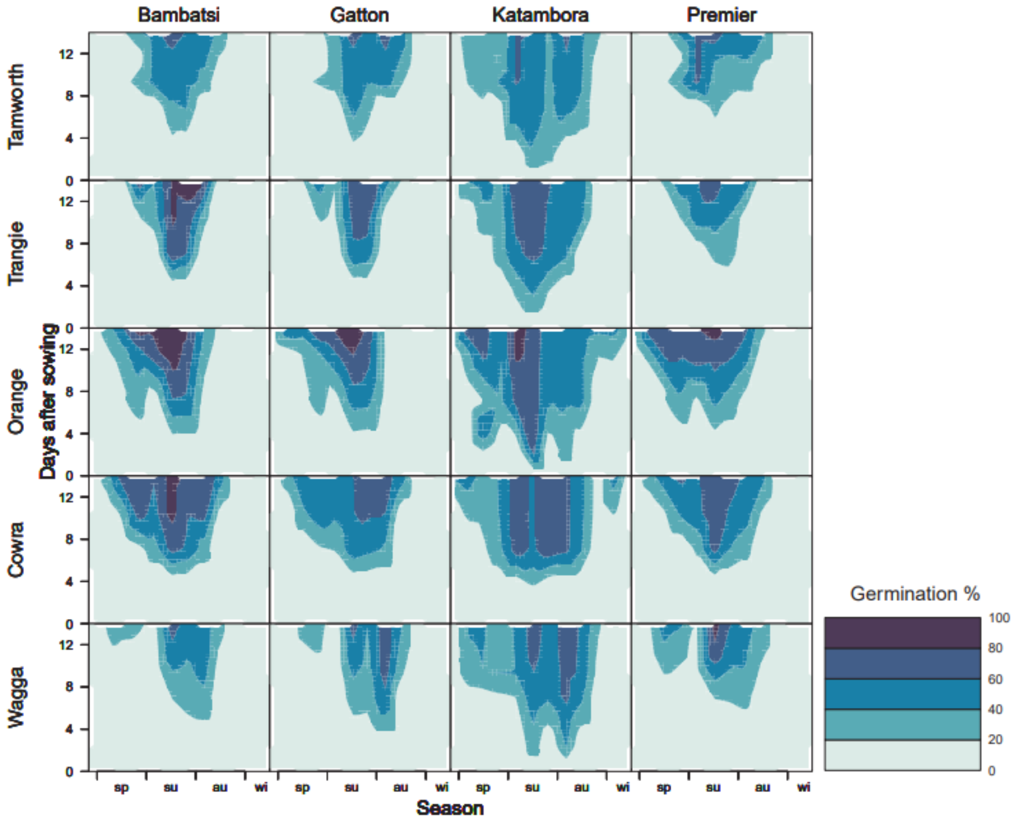


Fig. 22. Plots of average cumulative seedling emergence (%) assessed four times over 14 days for the 12 months of the year from August to July for (a) Bambatsi panic, Gatton panic grass, Katambora Rhodes grass, and Premier digit grass at five sites: Tamworth, Trangie, Orange, Cowra and Wagga Wagga. Emergence of each species was adjusted to maximum achieved across all sites. X-axis labels are spring (sp, September–November), summer (su, December–February), autumn (au, March–May), and winter (wi, June–August).

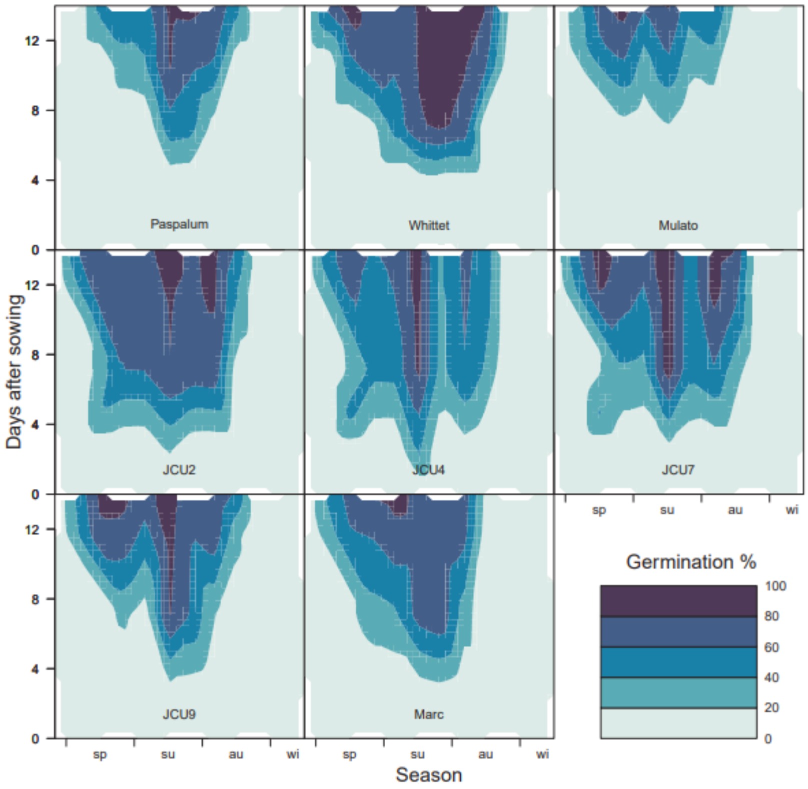


Fig. 23. Plots of average cumulative seedling emergence (%) assessed four times over 14 days for the 12 months of the year from August to July for common paspalum and Whittet kikuyu at Trangie, also *Urochloa* hybrid cv. Mulato II and desmanthus cultivars JCU2, JCU4, JCU7, JCU9 and Marc at Tamworth. Emergence of each species was adjusted to maximum achieved across all sites. X-axis labels are spring (sp, September–November), summer (su, December–February), autumn (au, March–May), and winter (wi, June–August).

5.5.3 Emergence response to temperature

The smoothed response of seedling emergence to soil temperature after 10 days for each species is shown in Fig. 24. There was no seedling emergence of Rhodes grass when average soil temperatures were ≤11 and ≤12°C in warming and cooling soils respectively. Emergence of digit grass was approximately linear in both warming and cooling soils with nil emergence when temperatures were ≤14°C. There was no emergence of Bambatsi panic seedlings when soil temperatures were <12 and ≤15°C in warming and cooling soils respectively. The rate of emergence increased as soil temperature increased and declined approximately linearly as soil temperatures declined. There was no emergence of panic seedlings when soil temperatures were <14 and 15°C in warming and colling soils respectively. The change in slope when soil temperatures were 18–20°C corresponded with highly variable emergence across the sites.

Due to the fewer number data points for kikuyu, paspalum, *Urochloa* hybrid and desmanthus, emergence responses for these species were not as instructive. Their responses to temperature are shown in Fig. 24.

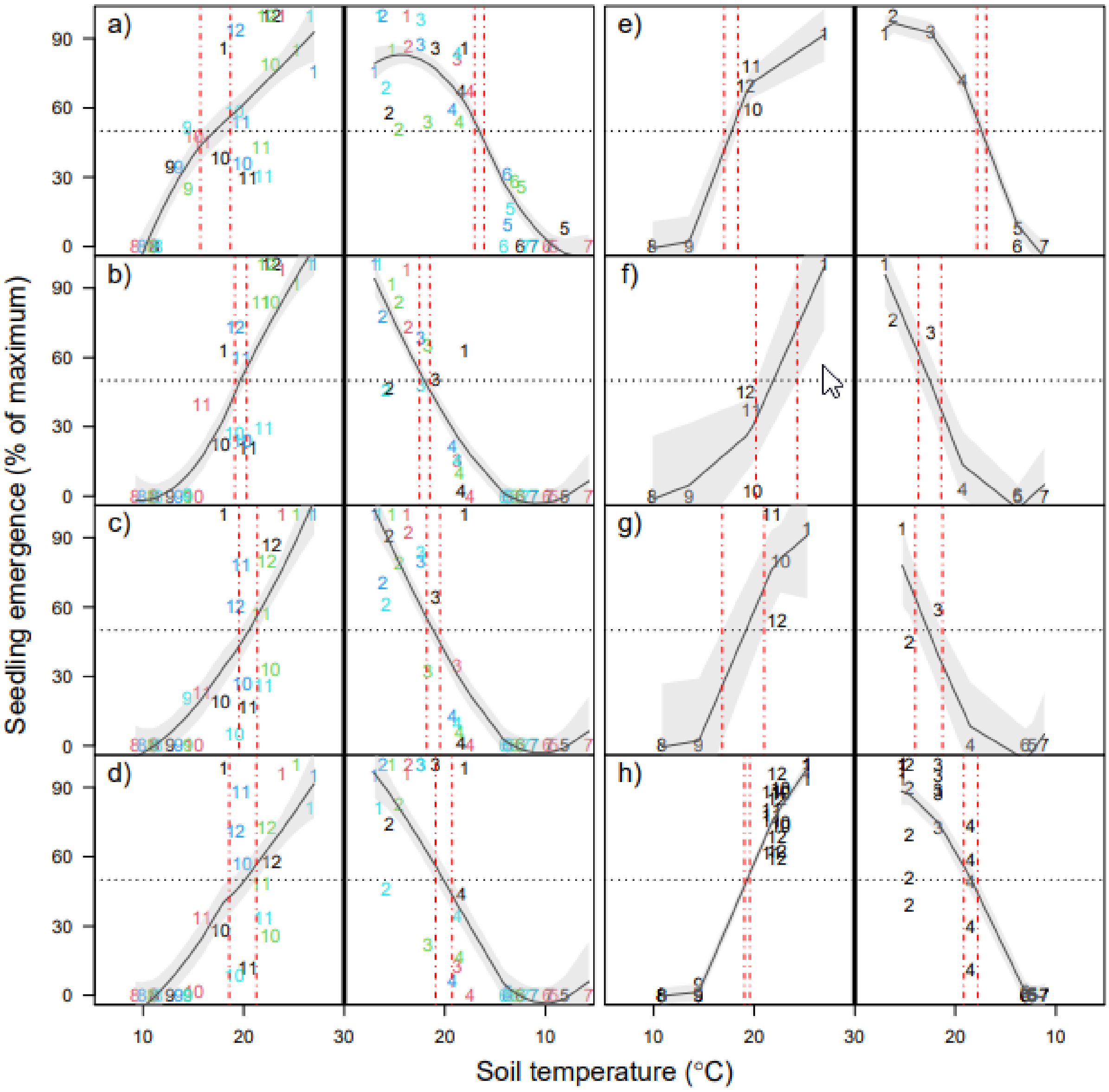


Fig. 24. Smoothed seedling emergence response to soil temperature for 12 months (August–January as soil temperatures increased (left panel of each subfigure) and January–July (right panel) as temperatures decreased for (a) Rhodes grass, (b) digit grass, (c), Bambatsi panic (d) panic, (e) kikuyu, (f) paspalum, (g) *Urochloa* hydrid and (h) desmanthus. Sites for pooled figures (a-d): Cowra (⬛), Orange (🟥), Tamworth (🟩), Trangie (🟦) and Wagga Wagga (🟦). Numbers on each figure indicate the month of the year, i.e., 1, January to 12, December. Emergence was 10 days after sowing and adjusted to a proportion of the maximum achieved at all sites over the 12 months of the study. Soil temperatures are average of first 3 days after sowing. The grey shaded areas represent the standard error of the mean. The black dotted horizontal line represents 50% seedling emergence while the red lines indicate the upper and lower temperature ± standard error to achieve 50% maximum emergence.

5.5.4 Soil temperatures to achieve 50% maximum seedling emergence

Average soil temperatures to achieve 50% of maximum seedling emergence for each species in warming and cooling soils are shown in Table 68. Together these temperatures provide an indicative 'window' for effective emergence. This window was widest for Rhodes grass, then kikuyu and narrowest for paspalum. Desmanthus, digit grass and the panics were intermediate.

Table 68. Predicted soil temperatures (°C) for 50% of maximum emergence for the pasture species tested in warming and cooling soils.

Entry	Warming soil temperature (°C)	Cooling soil temperature (°C)
Rhodes grass	17.1±1.5	16.6±0.5
Digit grass	19.7±0.6	22.0±0.5
Bambatsi panic	20.5±0.9	21.2±0.7
Panic	20.1±1.4	20.1±0.8
Kikuyu[1]	17.8±0.7	17.4±0.5
Paspalum[1]	21.9±2.1	22.5±1.1
Urochloa hybrid[1]	19.2±1.8	22.7±1.3
Desmanthus[12]	19.3±0.3	18.5±0.7

[1] Values are based on emergence at one site

[2] Values for the five cultivars are combined

Using our temperatures and average monthly air temperatures from 1990-2022 (https://climateapp.net.au/) we estimated when grasses could be sown at each site. For example, mean temperatures reach 20°C recommended for digit grass, panic and Bambatsi panic in November at Tamworth and Trangie, December at Cowra and Wagga, and January at Orange (Table 69). These temperatures were reached at Tamworth and Trangie earlier than the other sites, i.e., in September–October and therefore sowing in these locations could commence in early spring. Temperatures were slowest to rise at Orange with adequate temperatures for sowing achieved about two months after Tamworth and Trangie.

4.0 Tropical perennial grass seedling establishment and persistence in Central West NSW

4.0.1 Rainfall and temperature

The annual rainfall during 2018 (263 mm) and 2019 (172 mm) were well below the long-term average (496 mm) and within the lowest 10% (decile 1) recorded since 1923. Both minimum and maximum temperatures were above the long-term averages (Fig. 25).

Table 69. Months with corresponding temperature for 50% of maximum emergence based on long-term average mean air temperature data (1990–2022, https://climateapp.net.au/) for the species tested at each location in warming (August–January) and cooling soils (January–July).

Pasture species	Warming-cooling soil temperatures (°C)	Location				
		Tamworth	Trangie	Orange	Cowra	Wagga
Rhodes grass	17-17	Oct-Apr	Early Oct-Late Apr	Early Dec-Feb	Late Oct-Early Apr	Late Oct-Early Apr
Kikuyu	18-17	Oct-Apr	Oct-Late Apr	Dec-Feb	Early Nov-Early Apr	Early Nov-Early Apr
Desmanthus	19-19	Nov-Late Mar	Late Oct-Apr	Late Dec-Feb	Nov-Late Mar	Nov-Late Mar
Urochloa hybrid	19-23	Nov-late Feb	Early Nov-Mar	Jan	Nov-Late Feb	Nov-Late Feb
Panic	20-20	Nov-late Mar	Early Nov-Early Apr	Jan	Late Nov-Late Mar	Late Nov-Late Mar
Bambatsi panic	20-21	Nov-late Mar	Early Nov-Late Mar	Jan	Late Nov-Mar	Late Nov-Mar
Digit grass	20-22	Nov-Mar	Early Nov-Late Mar	Jan	Late Nov-Early Mar	Late Nov-Early Mar
Paspalum	22-23	Dec-late Feb	Late Nov-Mar	Jan	Dec-late Feb	Dec-late Feb

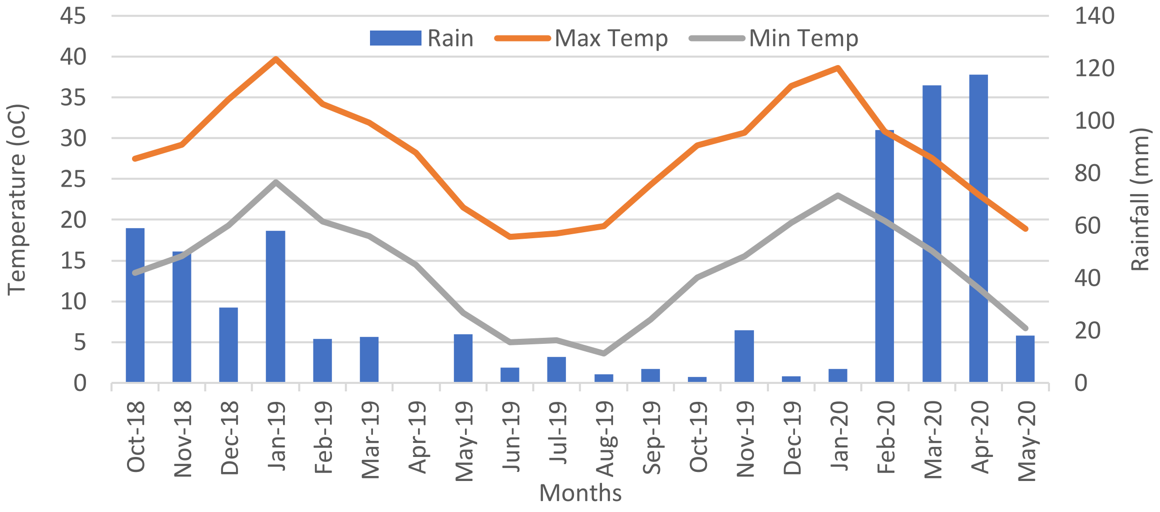


Fig. 25. Mean maximum and minimum temperatures (°C) and monthly rainfall (mm) at the experimental site, October 2018-May 2020.

4.0.2 Establishment

In general, all species established well when sown in spring and autumn; seedling densities higher than those sown in summer ($P < 0.05$) (Table 70). There was no effect of stored soil moisture on the number of seedlings which emerged ($P > 0.05$, main effect). Panic, Makarikari grass and digit grass had higher establishment plant densities than Rhodes grass at all sowing times ($P < 0.05$) and both stored soil moisture levels. In most cases, Gatton panic also had higher establishment plant densities than kikuyu and paspalum.

Table 70. Plant density (plants/m^2) of six tropical grasses sown in three seasons into soils with either high or low stored soil moisture levels. Numbers followed by the same letter are not significantly different (P = 0.05).

	High stored soil moisture			Low stored soil moisture		
Species	Spring	Summer	Autumn	Spring	Summer	Autumn
Makarikari grass	37	20	28	29	6	38
Digit grass	33	14	46	26	6	39
Gatton Panic	46	6	51	41	4	50
Kikuyu	25	1	29	29	1	26
Paspalum	27	2	25	15	1	16
Rhodes grass	14	2	10	9	1	29
l.s.d. (P = 0.05)			14.1			

4.0.3 Plant persistence

There were insufficient plants from the summer sowing time to predict seedling persistence, so these data were not included in the analysis. Predicted mean survival (%) of the six grasses in December 2019, 14 months and 9 months after sowing are shown in Table 71. Averaged over all grasses, plant survival was highest for those established in spring with HSSM and lowest for those established with LLSM. Average plant survival of those established in autumn were not affected by stored soil moisture.

In the HSSM plots, >90% of the tagged Makarikari grass, digit grass, panic and kikuyu plants established in spring had persisted. Paspalum and Rhodes grass plants also had high survival (>80%). In contrast, plant survival in the LSSM conditions was <60% for all grasses except Makarikari grass and Gatton panic. Of the plants which established in autumn, kikuyu had the highest survival (>94%) of the grasses in both stored soil moisture treatments. Makarikari grass, paspalum and Rhodes grass also had similar survival under both LSSM and HSSM (average >80%). Interestingly, autumn sown panic had 40% survival in the LSSM treatment, almost half of those sown in spring.

Table 71. Survival (%) of tagged plants of each species in December 2019 under contrasting stored soil moisture levels. The spring and autumn sown plants were 14 months and 9 months old respectively.

Grass	Spring				Autumn			
	LSSM		HSSM		LSSM		HSSM	
	Mean	se	Mean	se	Mean	se	Mean	se
Makarikari grass	87	14.6	99	-	75	13.1	81	13.5
Digit grass	57	12.9	93	-	86	15.9	70	12.9
Panic	75	12.9	94	-	40	11.2	69	13.2
Kikuyu	39	12.5	93	-	94	-	99	-
Paspalum	47	12.2	87	15.3	87	15.4	87	15.0
Rhodes grass	55	14.4	81	13.2	87	15.2	81	13.4
Average	*60*		*91*		*78*		*81*	

4.0.4 Herbage mass

By winter 2019 after all treatments had established, the grasses sown in spring had the highest production with little difference between the summer and autumn sown grasses. Among those sown in spring, Makarikari grass and panic had the highest herbage mass production, and paspalum the least (P < 0.05, Table 72a). All grasses sown with HSSM had higher production than those with LSSM, some up to 4 times higher (e.g., Rhodes grass). Among the summer sown treatments, Makarikari grass was the most productive grass sown with both HSSM and LSSM conditions. However, when sown in autumn, kikuyu was the most productive (P < 0.05). Despite there being no significant differences in establishment plant densities due to the level of stored soil moisture, grasses that established with HSSM generally had significantly higher herbage production than those established with LSSM at each sowing time (Table 72a).

Due to drought conditions, autumn 2020 (8 months after the initial herbage assessment) was the next opportunity to assess production. Average herbage production of the grasses was highest for those sown in spring (5326 kg DM/ha), followed by those sown in autumn (4591 kg DM/ha). At all sowing times, grasses sown with HSSM had approximately twice the production of those sown with LSSM. Within the spring HSSM treatment, panic and Makarikari grass had the highest herbage production and paspalum the least (P < 0.05)(Table 72b). Makarikari grass sown in summer with HSSM had higher production than the other species except panic sown with HSSM. There was no significant difference between any of the grasses sown in summer with LSSM. Paspalum sown in autumn with LSSM produced the least herbage, significantly less than Makarikari grass, Rhodes grass and kikuyu sown with HSSM.

Table 72. Herbage mass production (kg DM/ha) in (a) winter 2019 (18 July 2019) and (b) autumn 2020 (25 March 2020). Data for the winter 2019 assessment have been backtransformed. Values within a column followed by the same letter are not significant different (P = 0.05). For the autumn 2020 assessment, the least significant difference (l.s.d; P = 0.05) provided is for comparison of means within a column.

	High stored soil moisture			Low stored soil moisture		
Species	Spring	Summer	Autumn	Spring	Summer	Autumn
			(a) Winter 2019			
Makarikari grass	5091 a	542 a	34 c	1586 ab	137 a	28 a
Digit grass	1548 b	233 ab	225 bc	994 bc	76 a	38 a
Panic	4227 a	380 a	387 ab	2037 a	57 a	19 a
Kikuyu	1694 b	56 b	830 a	569 cd	0 a	191 a
Paspalum	619 c	142 ab	91 bc	182 d	2 a	43 a
Rhodes grass	4476 a	230 ab	132 bc	1135 abc	0 a	110 a
			(b) Autumn 2020			
Makarikari grass	9865	8117	7689	4979	2454	3481
Digit grass	6013	4265	5442	4375	3091	4230
Panic	10578	5799	6405	6370	1814	2164
Kikuyu	7297	3379	6869	2665	640	1988
Paspalum	2375	1027	3552	247	1631	991
Rhodes grass	6049	2630	6976	3093	2309	5300
l.s.d. (P = 0.05)			2395.0			

4.1 Impact of cover on tropical perennial grass establishment

Rainfall during the period this experiment was conducted was above average; 2021 rainfall being 58% higher than the long-term average (i.e., 784 cf. 496 mm). Temperatures were generally similar to the long-term average (Fig. 26).

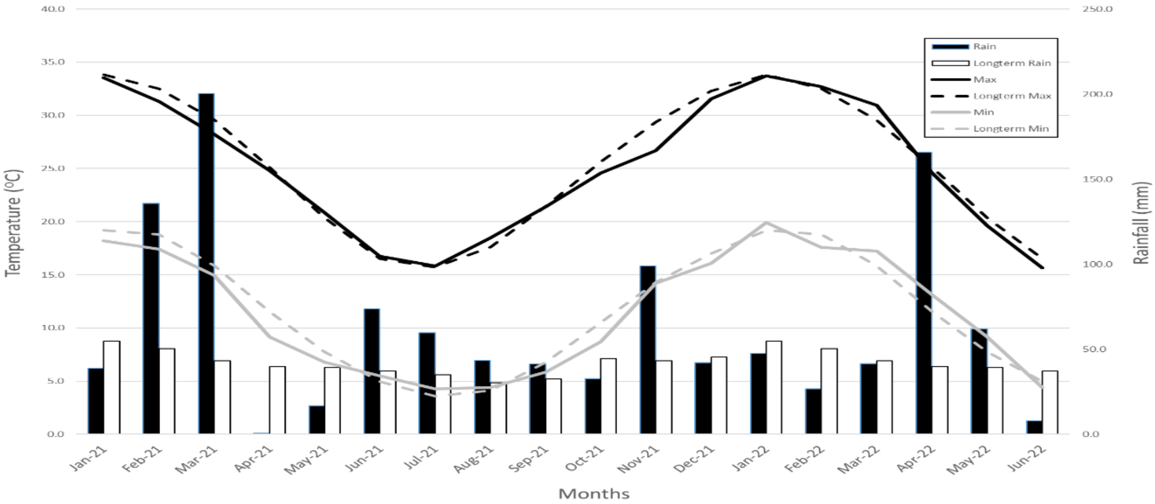


Fig. 26. Mean maximum and minimum temperatures (°C) and monthly rainfall (mm) at the experimental site, January 2021-June 2022 and the long-term average.

Bambatsi panic had established 5 weeks after sowing on the 102 mm rainfall plus the 30 mm irrigation applied. Seedling density averaged 30 plants/m^2 with no effect of either tillage or cover type (Table 73). There was no additional seedling emergence following the 107 mm received December 2021–February 2022.

Table 73. Bambatsi panic seedling densities (plants/m^2) at two tillage and three grazing treatment combinations on 2 December 2021 and 16 February 2022. Least significant difference (P = 0.05) is shown for comparison of means within a count date.

Tillage treatment	Grazing treatment		
	Bare	Grazed	Un-grazed
2 December 2021			
No Tillage	42	53	32
Tillage	52	45	48
lsd (P = 0.05)		21.8	
16 February 2022			
No Tillage	51	47	35
Tillage	44	38	54
lsd (P = 0.05)		23.6	

4.2 Water use and production of tropical and temperate species in Central West NSW

4.2.1 Growing season rainfall and temperature

During both the 2020-21 and 2021-2022 growing seasons, August-May rainfall was well above average (Fig. 27a). During the non-growing period between the two growing seasons (i.e., June–July), total rainfall was below average; 45% of the long-term average (32 v. 71 mm).

During spring of the 2020-21 growing season, monthly maximum temperatures were average to above average (Fig. 27b). However, from December 2020, temperatures were below average due to the higher rainfall (Fig. 27b). Temperatures throughout most of the 2021-22 growing season were also below average (Fig. 27b). Cumulative GDD (Fig. 27c) show the milder start to the 2021-22 growing season compared to 2020-21.

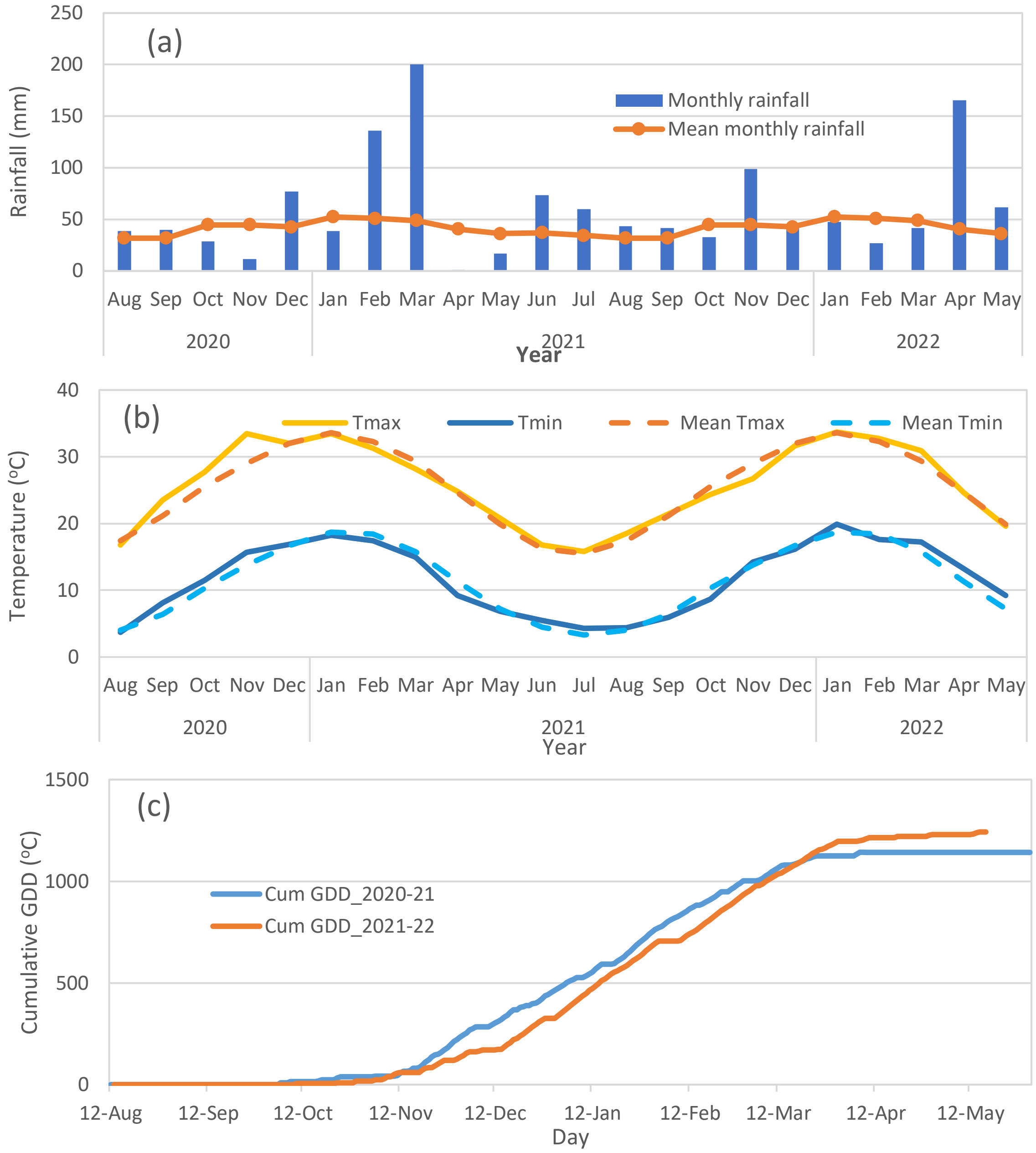


Fig. 27. Monthly and long-term average (a) rainfall (mm) and (b) temperatures (^{o}C) August 2020–May 2022, also (c) GDD for growing seasons 2020-21 and 2021-22.

4.2.2 Soil water dynamics and use efficiency

Soil water extraction

Soil water content was consistent among the treatments at the start of the 2020-21 growing season (August 2020), all treatments drying to 1.8 m depth by the end of the growing season (Fig. 28). Maximum extracted water for the treatments were similar (87-91 mm), with the largest proportion of soil water extracted from the upper profile (0.1–0.7 m, Fig. 28, Table 74).

The 2021-22 growing season was different as the soil profile had started to refill due to late season rainfall and was wetter in May than the start of the season in all treatments. However, there had been significant soil moisture extraction until 5 April 2022 (Fig. 28). The MEWs for the three perennial grasses (77-92 mm) were greater than for both lucerne and Sudan grass (39 and 65 mm, respectively) with the majority extracted from the upper profile (0.1–0.7 m, Fig. 28).

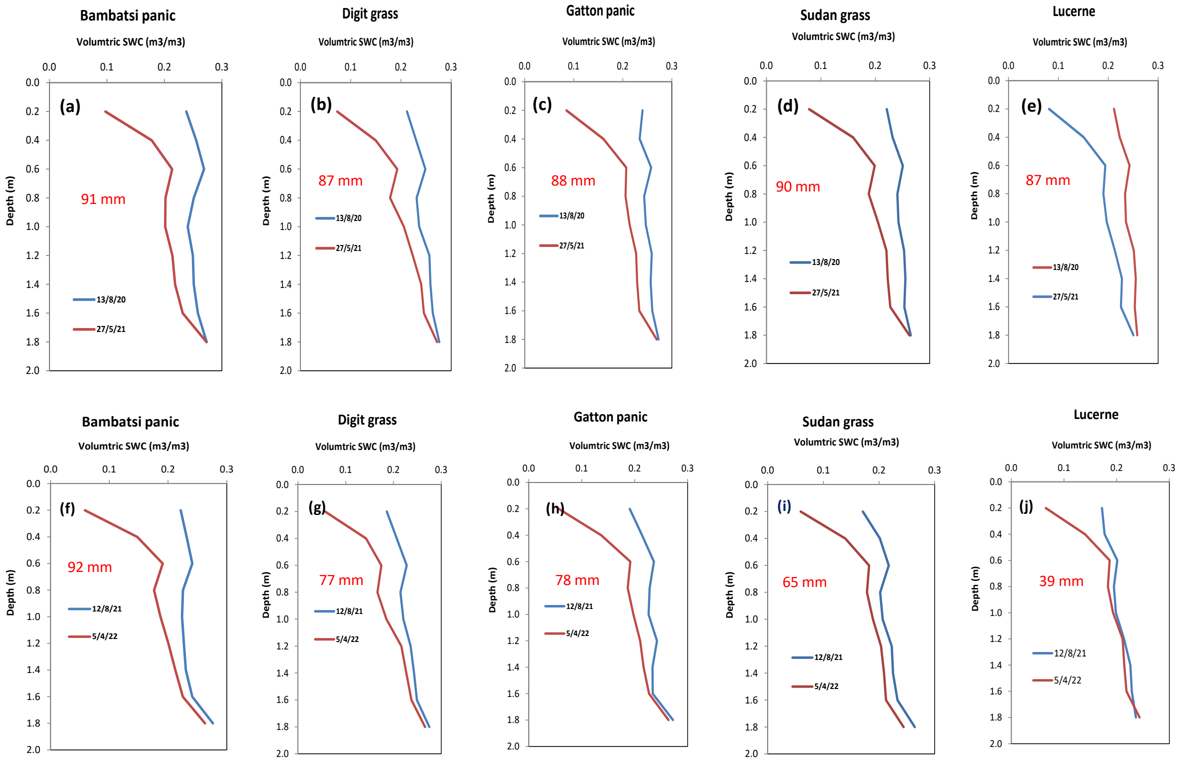


Fig. 28. Pattern of soil water extraction during the (a-e) 2020-21 and (f-j) 2021-22 growing seasons. Dates for the 2020-21 season were: 13 August 2020–27 May 2021; and 2021-22 season: 12 August 21–05 April 22.

Table 74. Mean values of soil profile maximum and minimum stored soil water (SSW, mm) during the growing season, and maximum extractable water (MEW, mm) for different soil profile layers (upper 0.1-0.7 m, middle 0.7-1.3 m, lower 0.7-1.9 m), (2020-21: 13 August 2020–27 May 2021; 2021-22: 12 August 2021–04 April 2022).

Year	Treatments	Maximum SSW (mm)	Minimum SSW (mm)	Maximum extractable water (mm)			
				0.1-0.3 m	0.7-1.3 m	1.3-1.9 m	0.1-1.9 m
2020-21	Bambatsi panic	457	366	55	25	12	91
	Digit grass	443	356	55	23	8	87
	Gatton panic	454	366	56	21	12	88
	Sudan grass	443	353	53	24	12	90
	Lucerne	433	346	50	24	13	87
2021-22	Bambatsi panic	424	332	60	22	10	92
	Digit grass	412	334	49	21	7	77
	Gatton panic	416	338	51	20	6	78
	Sudan grass	389	323	42	12	11	65
	Lucerne	370	331	32	4	3	39

Rainfall refill efficiency

Stored soil water is accumulated under tropical pasture species during winter when they are not actively growing. During 2021, The tropical perennial grasses accumulated 49-58 mm, Sudan grass 36 mm and lucerne 24 mm (Fig. 29). Bambatsi panic had the highest rainfall refill efficiency, capturing 43% of the rainfall. The perennial grasses (37-43%) had higher refill efficiencies the Sudan grass (27%) and lucerne (18%) (Table 75).

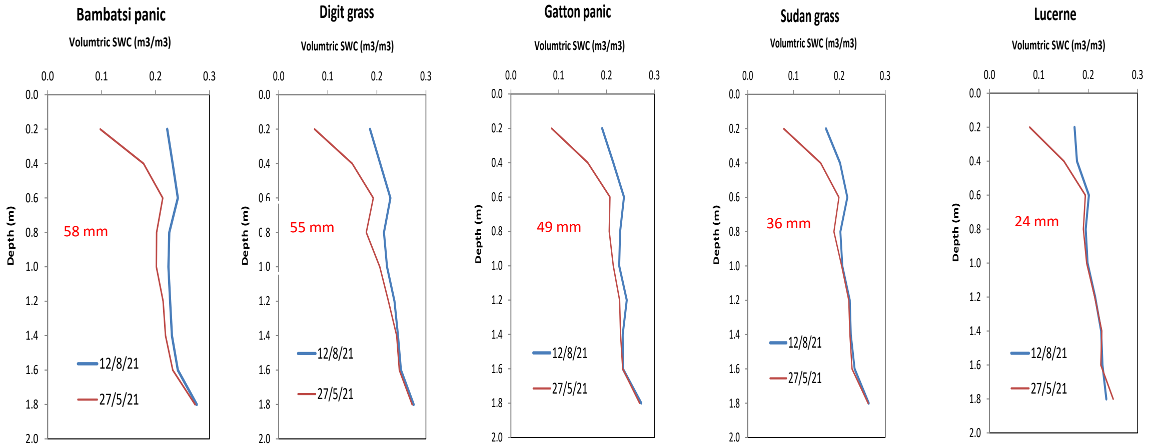


Fig. 29. Soil water refill patterns observed in season 2020-21 (May to August).

Table 75. Changes in stored soil water (SSW, mm) for different soil layers between the 2020-21 and 2021-22 growing seasons, from autumn (28 May 2021, start of the refill period) to spring (12 August 2021, end of the refill period).

Treatments	SSW (mm)		Change in SSW (mm)				Rainfall (mm)	Rainfall efficiency (%)
	May 2021	August 2021	0.1-0.7 m	0.7-1.3 m	1.3-1.9 m	0.1-1.9 m		
Bambatsi panic	366	424	41	12	5	58	135	43
Digit grass	356	412	41	13	2	55	135	41
Gatton panic	366	416	38	10	2	49	135	37
Sudan grass	353	389	31	4	2	36	135	27
Lucerne	346	370	25	1	-2	24	135	18

4.2.3 Herbage production and water use efficiency

During the 2020-21 growing season, herbage production ranged from 20762 (Bambatsi panic) to 8390 kg DM/ha (lucerne). Cumulative herbage production is shown in Fig. 30a and highlights the low spring growth of Gatton panic compared to the other grasses high higher growth of Bambatsi panic during summer (Fig. 30a). Sudan grass was included in herbage assessments from December and produced 18494 kg DM/ha by the end of the growing season which was less than Bambatsi panic but higher than digit grass and Gatton panic.

Productivity in the 2021-22 season strongly contrasted with the previous year. Lucerne was the most productive (11740 kg DM/ha) and the perennial grasses the least (3745–5491 kg DM/ha) (Fig. 30b).

This was due to good growth of lucerne in October while the perennial grasses were inactive, and milder temperatures (Fig. 27).

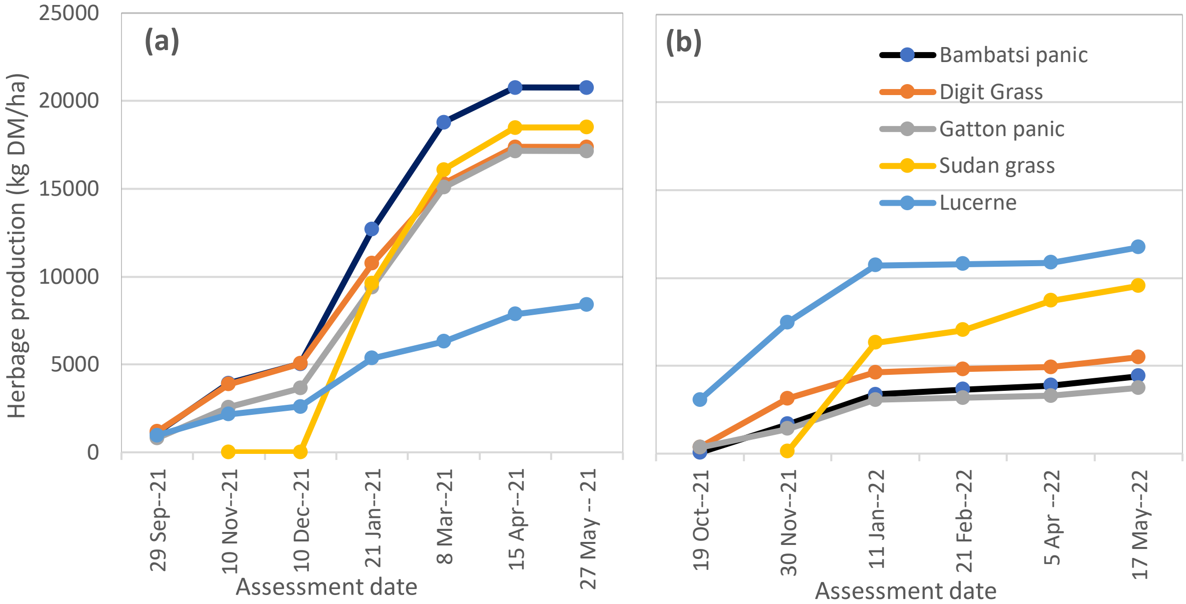


Fig. 30. Cumulative herbage production (kg DM/ha) of treatments during the (a) 2020-21 and (b) 2021-22 growing seasons.

During the 2020-21 growing season, the treatments had similar total water use (675-679 mm) (Table 76), but water use efficiencies varied from 31 kg DM/ha/mm for Bambatsi panic to 12 kg DM/ha/mm for lucerne with the other species intermediate (25-27 kg DM/ha/mm) (Fig. 31). During the 2021-22 growing season, total water use was lower ranging from 577 (lucerne) to 603 (Sudan grass). Despite this the high herbage production of lucerne mean it had the highest WUE (26 kg DM/ha/mm) of the treatments with the tropical perennial grasses having WUE values ≤10 kg DM/ha/mm (Table 76).

4.0 Tropical perennial grass seedling establishment and persistence in Central West NSW

4.0.1 Rainfall and temperature

The annual rainfall during 2018 (263 mm) and 2019 (172 mm) were well below the long-term average (496 mm) and within the lowest 10% (decile 1) recorded since 1923. Both minimum and maximum temperatures were above the long-term averages (Fig. 25).

4.0.2 Plant frequency

Plant frequency of perennial grasses were consistently greater than lucerne, although values for all perennial species increased throughout the experiment (Fig. 31). Sudan grass assessed at the end of each growing season had values similar to lucerne.

Table 76. Herbage production (kg DM/ha) and components of the water balance used to calculate water use efficiency (WUE, kg DM/ha/mm) for treatments during the growing seasons 2020-21 and 2021-22. Water balance components are rainfall (mm), profile stored soil water (0.1–1.9 m, SSW, mm) at the start (August) and end (May) of the growing season, total water used (mm) and water use efficiency.

Season	Treatments	Herbage production (kg DM/ha)	Rainfall (mm)	Start SSW (mm)	End SSW (mm)	Total water use (mm)	WUE (kg DM/ ha/mm)
2020-21	Bambatsi panic	20762	588	457	366	679	31
	Digit grass	17383	588	443	356	675	26
	Gatton panic	17148	588	454	366	676	25
	Sudan grass	18494	588	443	353	678	27
	Lucerne	8390	588	433	346	675	12
2021-22	Bambatsi panic	4402	602	424	428	598	8
	Digit grass	5491	602	412	430	584	10
	Gatton panic	3745	602	416	423	595	6
	Sudan grass	9550	602	389	388	603	16
	Lucerne	11740	602	370	395	577	22

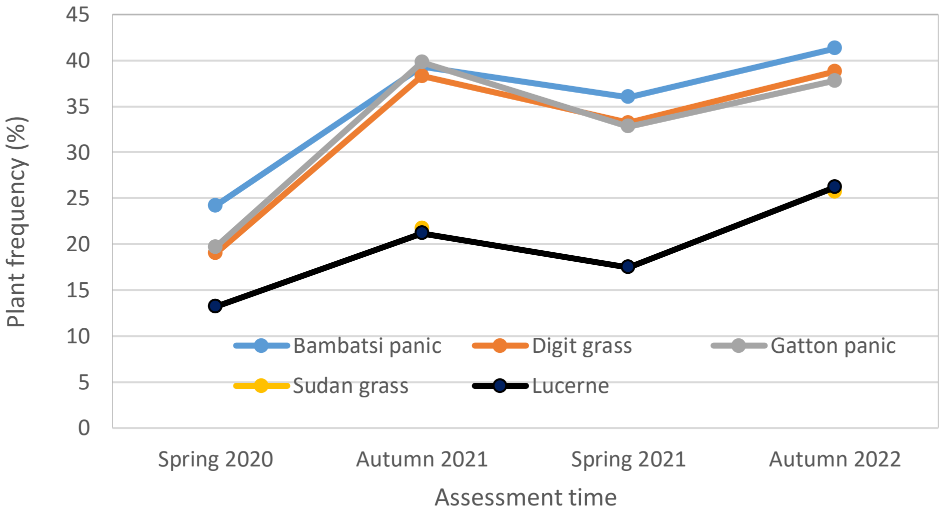


Fig. 31. Plant frequency for each treatment during the 2020-21 and 2021-22 seasons.

4.1 Herbicides for control of broadleaf weeds in desmanthus pastures

1.8.1 Experiment 1 – Pre-pasture emergent

There was no effect of imazethapyr applied pre-emergent on desmanthus seedling plant densities assessed 3 weeks after sowing (average 75 plants/m^2, Fig. 32). Trifluralin had no effect on seedling density at half rate, however density declined at the standard and double rates; plant densities at the double rate being 45% of the control ($P < 0.05$). There were significant reductions in plant density at all rates of both S-metolachlor and pyroxasulfone compared to the control. At the double rate pyroxasulfone plant density was 5% of the control ($P < 0.05$).

Seedling herbage mass assessed 6 weeks after sowing reflected significant damage by all herbicides ($P < 0.05$, Table 77a), including imazethapyr which had good seedling establishment 3 weeks prior to the assessment. Imazethapyr and trifluralin resulted in the least effect on seedling growth while pyroxasulfone had the greatest effect. S-metolachlor was intermediate. There was no interaction with herbicide rate as the plants responded similarly for all rates; seedling herbage mass declining with increasing herbicide rate ($P < 0.05$).

The effect of the herbicides was still evident at the herbage mass assessment conducted at the end of the growing season with significant main effects and herbicide-rate interaction (Table 77b). Herbicides which had the least effect on desmanthus plants were ranked: trifluralin>imazethapyr>S-metolachlor and pyroxasulfone ($P < 0.05$). Damage increased with increasing rate of active ingredient (main effect, $P < 0.05$), but there was no effect of 0.5 rates of trifluralin and imazethapyr ($P < 0.05$). This suggests that plots sprayed with imazethapyr may have had a delayed effect and some emerged seedlings may have died after the plant count conducted 3 weeks after sowing.

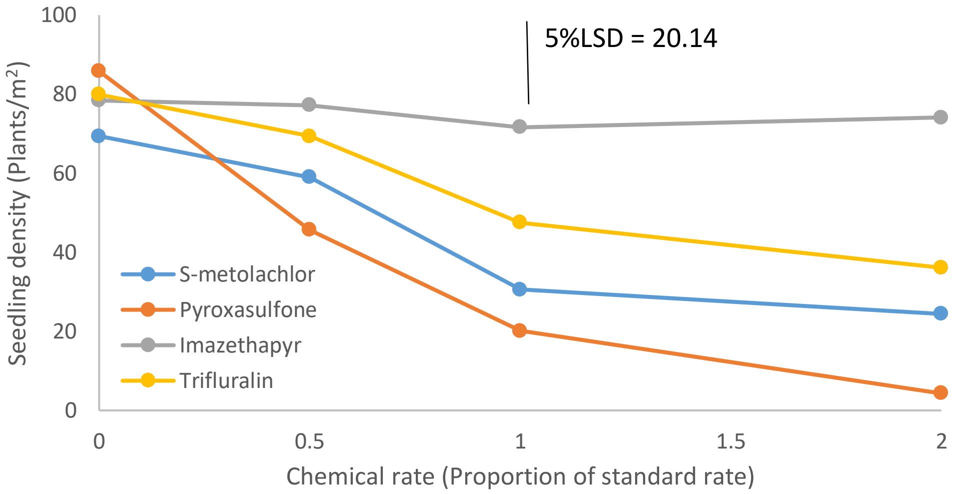


Fig. 32. Seedling density (plants/m^2) of desmanthus 3 weeks after sowing and treatment with pre-emergent herbicide. LSD ($P = 0.05$) is shown.

The effects of the pre-emergent herbicides were still evident the following growing season (November 2016, 8 months after application), especially those sprayed with S-metolachlor and pyroxasulfone (Table 77c). At standard rates of these two herbicides, desmanthus production was ~25% of the control. In contrast, the productivity of desmanthus sprayed with imazethapyr and trifluralin at standard rates was 70-75% of the control ($P < 0.05$).

Table 77. Herbage mass (kg DM/ha) of desmanthus on (a) 29 March 2016, (b) 10 May 2016 and (c) 17 November 2016 sprayed pre-emergent with herbicides at four rates (0, 0.5x, 1x and 2x). Values with the same lowercase letter within an assessment date are not significantly different (herbicide x rate interaction, $P = 0.05$). Within each assessment, average herbicide and rate values with the same uppercase letter are not significantly different (main effect, $P = 0.05$).

	Rate (proportion of standard rate)				
Herbicide	0	0.5x	1x	2x	*Average*
			(a) 29 March 2016		
S-metolachlor	53.6	30.4	18.0	14.3	*29.1 B*
Pyroxasulfone	56.5	25.5	17.5	4.4	*26.0 C*
Imazethapyr	50.7	46.2	33.8	18.3	*37.3 A*
Trifluralin	59.4	45.0	38.1	25.5	*42.0 A*
Average	*55.1 A*	*36.8 B*	*26.9 C*	*15.6 D*	
			(b) 10 May 2016[1]		
S-metolachlor	1957 a	916 cd	280 e	47 fg	*602 C*
Pyroxasulfone	2049 a	1227 bc	231 e	2 g	*589 C*
Imazethapyr	1616 ab	1499 ab	978 cd	197 ef	*965 B*
Trifluralin	1848 a	1684 ab	978 cd	613 d	*1211 A*
Average	*1864 A*	*1315 B*	*548 C*	*139 D*	
			(c) 17 November 2016[1]		
S-metolachlor	2144 abc	1788 bcd	571 f	32 g	*872 B*
Pyroxasulfone	2374 a	1750 cd	549 f	10 g	*858 B*
Imazethapyr	2146 abc	2067 abcd	1615 d	678 f	*1560 A*
Trifluralin	2209 ab	2137 abc	1609 d	1123 e	*1740 A*
Average	*2217 A*	*1932 A*	*1018 B*	*292 B*	

[1] Herbage mass values have been backtransformed

1.8.2 Experiment 2 – Seedling pasture

MCPA, 2,4-D amine and fluroken caused significant damage to desmanthus seedlings following application ($P < 0.05$, Fig. 33). The damage caused by fluroken was severe (phytotoxicity score >8) and the majority of seedlings died. Seedlings sprayed with 2,4-D amine and MCPA showed moderately high to heavy damage 7 DAA (phytotoxicity score >5) with damage continuing to 28 DAA ($P < 0.05$). Seedlings sprayed with the half rate of both herbicides made some recovery over the 4 weeks following application but continued to have significantly more damage than the control 28 DAA ($P < 0.05$).

Both bromoxynil and flumetsulam caused only minor distortion of the plant growing points (phytotoxicity scores ≤3) to desmanthus seedlings. Damage caused by the double rate of bromoxynil was significantly greater than the control ($P < 0.05$) until 28 DAA when there was no effect. One week after application (7 DAA), flumetsulam at all rates caused significant damage to the seedling desmanthus ($P < 0.05$). Damage declined over the 4 weeks to be minor compared to the control by 28 DAA.

Herbage production in April (53 DAA) showed the contrasting effect of the herbicides on desmanthus seedling growth. MCPA and 2,4-D amine had the greatest effect, especially at the standard and double rates (productivity 25-50% of the control) ($P < 0.05$). In contrast, flumetsulam had no effect and bromoxynil a small effect on herbage production (66% of the control, Fig. 34).

Both MCPA and 2,4-D amine delayed flowering of the establishing desmanthus plants. This was particularly evident at the standard and double rates ($P < 0.05$, data not shown). Bromoxynil had nil/slight effect on flowering at all rates tested while flumetsulam was intermediate ($P < 0.05$, data not shown).

The proportion of seed pods that had matured at the end of the growing season was highly variable. Plants sprayed with flumetsulam had the highest proportion of mature pods (66%) similar to bromoxynil and MCPA (51-56%) while plants sprayed with 2,4-D amine had the lowest proportion (35%) ($P < 0.05$). There was no effect of any herbicide rate, except for the double rate of 2,4-D amine where plants had a lower proportion of mature pod than the control and 0.5 rate ($P < 0.05$).

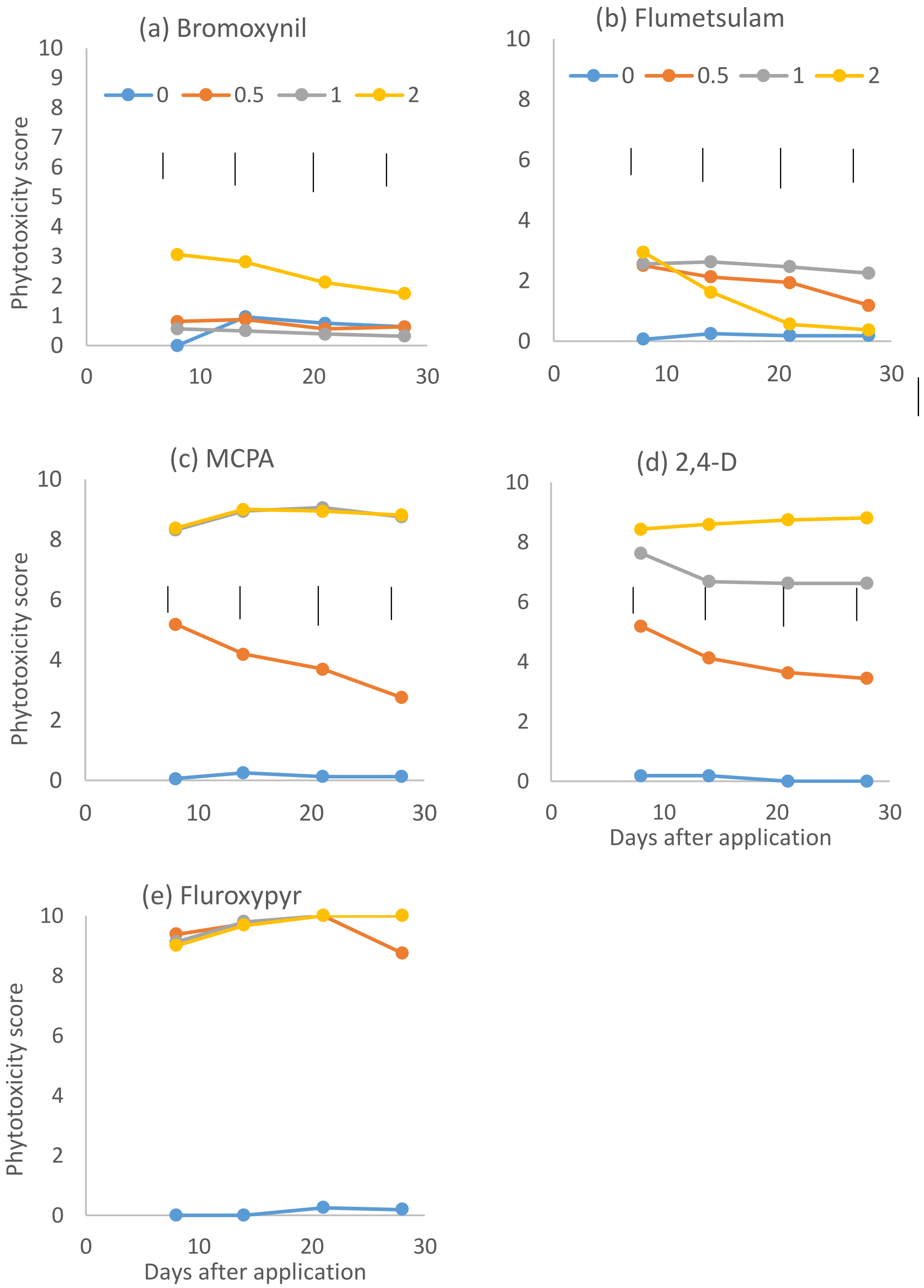


Fig. 33. Phytotoxicity score to assess desmanthus plant damage over 4 week period following treatment with (a) bromoxynil, (b) flumetsulam, (c) MCPA, (d) 2,4-D amine, (e) fluroxypyr, at four rates (details are provided in Table 15). Score 0 = nil damage and score 10 = plant death. LSD for comparison within an assessment date are shown (P = 0.05).

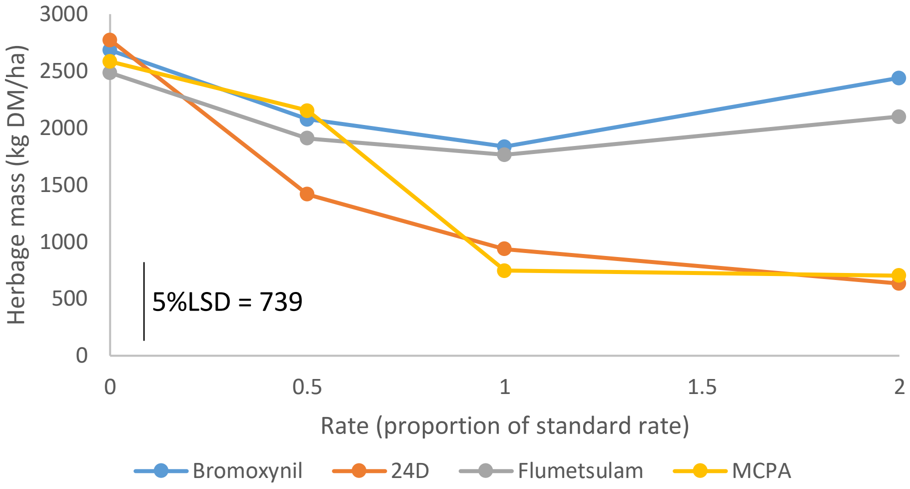


Fig. 34. Herbage production (kg DM/ha) of establishing desmanthus, 53 days after application of four herbicides. Fluroxypyr was not included in the analysis as all plants had died.

1.8.3 Experiment 3 – Established pasture

The greatest plant damage to mature plants of desmanthus during the 4 weeks following herbicide application was inflicted by 2,4-DB, isoxaflutole and paraquat (Fig. 35).

2,4-DB resulted in significant damage to mature plants of desmanthus during the 4 weeks following herbicide application with plant stems twisting and growing points distorted (Fig. 35, $P < 0.05$). By 7 DAA, damage was significant at all rates applied compared to the control (phytotoxicity scores average 7 cf. 0.5 for control) and damage to the plants generally increased over the 4 weeks phototoxicity was assessed ($P < 0.05$). At the final phytotoxicity assessment (29 DAA) plants sprayed with all rates of 2,4-DB were still showing the greatest damage ($P < 0.05$, Fig. 35).

Initial (7 DAA) plant damage resulting from all rates of isoxaflutole application was moderate compared to the control (phytotoxicity score 5-6, $P < 0.05$). Over the following weeks as plants continued to grow, the extent of foliage bleaching due to the herbicide declined as the plants continued to grow, except for the double rate which resulted in maximum damage 14 DAA (Fig. 35). By 29 DAA, plants sprayed with a half rate of isoxaflutole had fully recovered.

Imazethapyr and terbuthylazine did not cause physical damage to desmanthus plants at any rate. Bromoxynil was similar, except the double rate which retarded growth 7 DAA ($P < 0.05$), but plants had recovered by 14 DAA to be similar to the control (Fig. 35).

At the first assessment 7 DAA paraquat had the greatest effect with phytotoxicity scores 8-9.5 at all rates compared to the control. By 14 DAA, plants were recovering and phytotoxicity scores fell as the plants produced new leaf. Peak brownout caused by paraquat application ranged 91-98% and occurred 7 DAA at the standard and double rates. Peak brownout was slower for the 0.5 rate occurring 14 DAA. The plants produced new growth quickly which did not show any phytotoxic effects of the herbicide 29 DAA (Fig. 35).

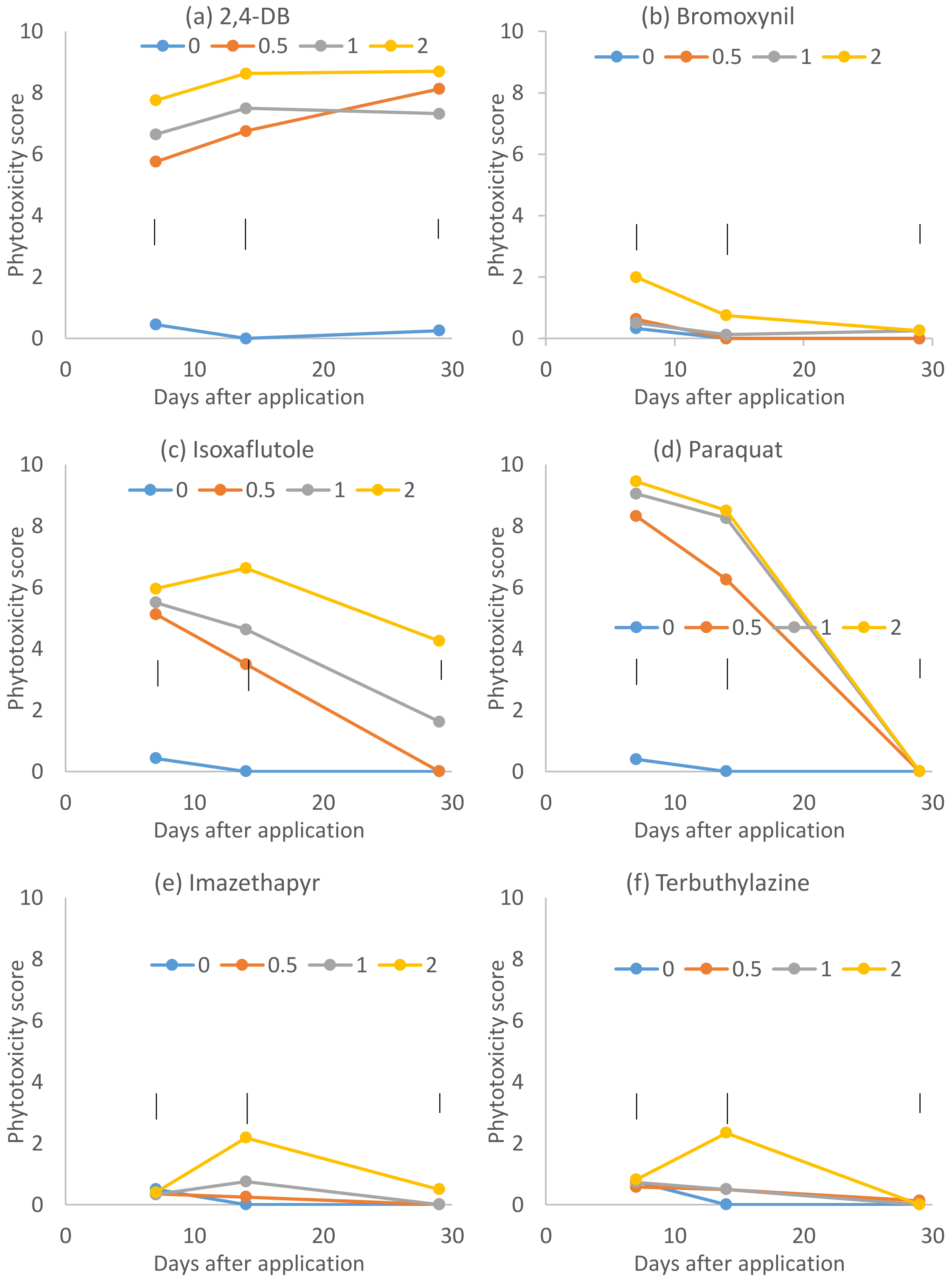


Fig. 35. Phytotoxicity score to assess desmanthus plant damage following treatment with (a) 2,4-DB, (b) bromoxynil, (c) isoxaflutole, (d) paraquat, (e) imazethapyr and (f) terbuthylazine at four rates (details are provided in Table 16). Score 0 = nil damage and score 10 = plant death.

Herbage mass assessed 4 weeks after treatments had been applied reflected the phytotoxicity assessment with all rates of 2,4-DB and paraquat reducing herbage mass by an average 38 and 26% compared to the control, respectively ($P < 0.05$, Fig. 36). There was no effect of bromoxynil, imazethapyr and terbuthylazine on desmanthus production. Isoxaflutole reduced herbage production at the standard and double rates by 9 and 21% respectively ($P < 0.05$).

There was no effect of any of the herbicides on desmanthus regrowth after cutting assessed 11 and 16 weeks after the treatments had been applied. This indicating that there were no long-lasting effects of any of the herbicides applied (data not shown).

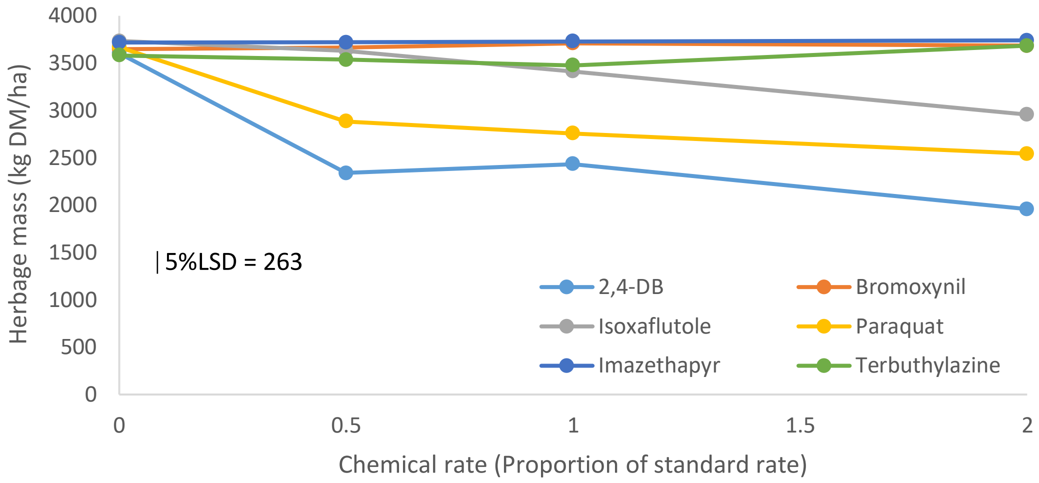


Fig. 36. Desmanthus herbage production (kg DM/ha) in December 2017, 4 weeks after application of six herbicides at four rates.

4.2 Quality of ensiled tropical perennial grasses

Full details of the results are provided in Piltz et al. (2022). In summary, the silages in both experiments were generally well preserved based on the NH_3-N content, low levels of VFAs and olfactory assessment and Experiment 2 showed that bacterial inoculants improved fermentation characteristics. It is important to note that our results were due to the rapid and effective wilts achieved, which was due to the low yields and high temperatures.

Focussing on experiment 2, pasture composition of digit grass when it was cut for ensiling is shown in Table 78 and Table 79. Wilting had no effect on the characteristics presented in Table 78, while WSC increased and neutral and acid detergent insoluble CP content decreased (Table 79).

Table 78. Composition of Premier digit grass at mowing and ensiling (Source: Piltz et al. 2022).

Digestible organic matter (DM basis) (g/kg)	606.7
Neutral detergent fibre (g/kg DM)	645.0
Acid detergent fibre (g/kg DM)	315.0
Starch (g/kg DM)	21.7
Crude protein (g/kg DM)	138.7
Non-protein nitrogen (g CP/kg DM)	138.7
True protein (g CP/kg DM)	117.0

No effect of wilting on these parameters.

Table 79. Composition of Premier digit grass at Tamworth Agricultural Institute at the time of cutting (W0) and after two wilting periods (W1 and W2) (Source: Piltz et al. 2022).

Component	Length of wilt			P value
	W0	W1	W2	
Dry matter content (g/kg)	223	365	447	NA
Water soluble carbohydrate (g/kg DM)	43.5^{a}	58.0^{b}	65.0^{c}	0.003
Neutral detergent insoluble protein (g CP/kg DM)	81.5^{b}	81.0^{b}	69.5^{a}	0.046
Acid detergent insoluble protein (g CP/kg DM)	11.0^{b}	10.5^{b}	9.0^{a}	0.033

Values in the same row with different superscript letters are significantly different ($p < 0.05$).
NA: not analysed

Composition of the silages are shown in Table 80. Addition of an inoculant reduced ($P < 0.05$) both pH and NH_3-N compared to the Control at both DM contents (W1 and W2) and physical forms (chopped and unchopped), clearly showing the effect of improved fermentation.

The level of VFA for all silages (Table 80) was consistent with well-preserved, wilted silages. Acetic acid represented 94.2–98.4% of the total VFA measured. Acetic acid levels were higher ($P < 0.05$) in the W1 compared to the W2 silages, and higher for the 1174 compared to the Control and Classic silages. Levels of D-lactate, L-lactate and total lactic acid varied ($P < 0.001$) between silages and inoculant (Table 80).

Table 80. Effect of dry matter content (Wilt), physical form (Form) and inoculant on the composition1 of silages produced from Premier digit grass (Source: Piltz et al. 2022).

Wilt[1]	Form	Inoculant	DM[2] (g/kg)	CP (g/kg DM)	pH	NH$_3$-N[2] (% of total N)	Lactic acid (g/kg DM)			Volatile fatty acid (g/kg DM)					
							D-lactate	L-lactate	Total	Acetic	Iso-butyric	Valeric	Iso-valeric	Hexanoic	Total
W1	Chopped	Nil	317.3^{a}	145.1^{c}	5.4^{d}	8.3^{f}	8.8^{ab}	8.8^{b}	17.5^{bc}	6.1^{f}	0.016^{d}	0.003^{b}	0.070^{e}	0.021^{d}	6.3^{d}
W1	Chopped	1174	341.7^{b}	140.8^{bc}	4.4^{ab}	5.0^{d}	34.8^{e}	16.0^{c}	50.6^{f}	10.0^{g}	0.009^{c}	0.002^{ab}	0.034^{bcd}	0.015^{c}	10.2^{f}
W1	Chopped	Classic	339.3^{b}	141.9^{bc}	4.3^{a}	4.3^{b}	29.0^{de}	24.4^{d}	53.3^{f}	7.1^{f}	0.003^{a}	0.003^{b}	0.021^{a}	0.006^{a}	7.9^{e}
W2	Chopped	Nil	450.3^{de}	136.3^{ab}	5.9^{e}	5.0^{d}	2.9^{a}	2.3^{a}	5.1^{ab}	1.3^{a}	0.008^{bc}	0.002^{ab}	0.044^{d}	0.022^{d}	1.4^{a}
W2	Chopped	1174	409.7^{c}	132.8^{a}	4.3^{a}	4.0^{a}	35.3^{e}	9.8^{b}	45.1^{ef}	5.7^{e}	0.004^{ab}	0.002^{ab}	0.033^{bc}	0.013^{b}	5.2^{c}
W2	Chopped	Classic	433.7^{d}	136.0^{ab}	4.3^{a}	4.0^{a}	22.5^{cd}	28.0^{d}	50.5^{f}	3.0^{c}	0.004^{ab}	0.003^{b}	0.034^{bcd}	0.006^{a}	3.1^{b}
W2	Unchopped	Nil	411.7^{c}	130.5^{a}	6.0^{e}	5.7^{e}	1.5^{a}	1.0^{a}	2.5^{a}	1.7^{ab}	0.010^{c}	0.002^{ab}	0.042^{cd}	0.021^{d}	1.8^{a}
W2	Unchopped	1174	455.5^{e}	134.4^{a}	4.5^{bc}	4.0^{a}	23.8^{cd}	6.8^{b}	30.6^{cd}	4.3^{d}	0.003^{a}	0.001^{a}	0.029^{ab}	0.012^{b}	4.5^{c}
W2	Unchopped	Classic	442.0^{d}	130.4^{a}	4.6^{c}	4.7^{c}	17.4^{bc}	19.3^{c}	36.7^{de}	2.6^{bc}	0.016^{d}	0.003^{b}	0.070^{e}	0.021^{d}	2.7^{b}
	p value		<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.012	<0.001	<0.001	<0.001

1. Wilted to a nominal dry matter (DM) content of 350 (W1) or 500 (W2) g/kg.
2. DM: oven dry matter; NH$_3$-N: ammonia nitrogen as a % of total N.

Values in the same column with different superscript letters are significantly different ($P < 0.05$).

5.11 Understanding nitrogen fertility in tropical perennial pastures

5.11.1 Seasonal conditions

Rainfall during the 10-years of the experiment was highly variable (Fig. 37). Seven months received >150 mm, while 30 months had <20 mm. Rolling 12-month total rainfall values helped to illustrate several distinct trends over the 10-years. For the first 2-years from sowing, rainfall was in a drying trend, with rolling 12-month totals below the long-term average annual of 654 mm. The period from December 2014 to September 2017 was mostly a wet period, where rolling totals were mostly above the annual average, apart from February–July 2016. From October 2017, the rolling 12-month total showed a strong drying trend into extreme drought, reaching a low of 261 mm for the 12-months to December 2019. The remainder of the experiment experienced a wetting trend, with the rolling 12-month total peaking at 1116 mm for the 12-months to November 2021.

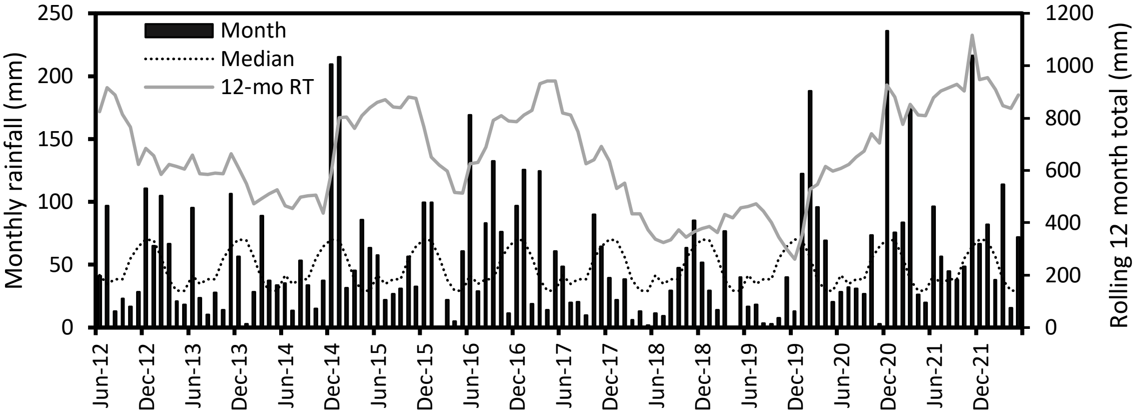


Fig. 37. Monthly rainfall (mm) at Tamworth Agricultural Institute over a 10-year period from June 2012 to May 2022. Bars show monthly totals compared with the median values (dotted), while the rolling 12-month total (12-mo RT, grey line) gives perspective to the average annual rainfall of 654 mm.

5.11.2 Herbage production

In years 1–5, herbage mass was sampled on 26 occasions between April 2013 and April 2017. After the first growing season, herbage mass of treatments with applied N outperformed those with nil N (Fig. 38a). Total herbage production over years 1–5 from the nil N treatments (i.e., treatments 1–3, Table 1) averaged 35.0 t DM/ha. The 100 N and 200 N treatments produced 49.0 and 54.2 t DM/ha, representing 143 and 158% of nil N, respectively.

In years 1–5, all treatments with nil N were similar, but production from treatments with applied N became significantly higher as soon as spring 2013 (Fig. 38a). With applied fertiliser, cumulative production from the 200 N treatment became significantly greater than 100 N by autumn 2014 and remained so for the duration of the study.

In the second phase of the study, years 6–10, herbage mass was sampled on 24 occasions (Fig. 38b). With the return of improved seasonal conditions from February 2020, herbage accumulation sharply increased over the three subsequent growing seasons (2019–20, 2020–21 and 2021–22). Total herbage production over years 6–10 from the nil N treatment was 19.3 t DM/ha, while production ranged from 42.9 to 58.1 t DM/ha with fertiliser. Interestingly, production from the two treatments with 100 kg N/ha was similar, 43.9 v. 42.9 t DM/ha, for the continuous (100 N) and changed regimes (nil N/100 N), respectively. However, the continuous 200 N treatment significantly outperformed the changed regime (nil N/200 N) with 58.1 v. 53.3 t DM/ha.

During the second phase of the experiment, the contrasts in production between the nil N and the plus N fertiliser treatments were more pronounced. Herbage production from the nil N treatment significantly lagged the others. Production from the 100 N treatments was 227 and 222% of nil N, for the continuous and changed regimes, respectively. For the 200 N treatments, production was 301 and 276% of nil N, respectively, for the continuous and changed regimes.

Production through time from the nil N treatment demonstrated the initial ‘honeymoon’ production of a newly established tropical grass pasture. From establishment to the end of year 3 (May 2015), nil N averaged 8.1 t DM/ha/year. However, despite above average rainfall in the final three years, nil N averaged 4.8 t DM/ha/year. In contrast 200 N produced 16.1 t DM/ha/year during the final three years. Treatments with higher fertiliser rates were better able to match water availability and fertility to achieve higher levels of production.

One question tested with this experiment was whether adding fertiliser to a mature tropical grass stand could elevate production to levels comparable with a continuous regime. This appears to be true for a moderate rate of fertiliser, 100 N. Total production in the latter 5 years for 100 N and nil N/100 N were similar, c. 43.9 and 43.0 t DM/ha, respectively (Fig. 39). But, for the 200 N regimes, the continuous treatment significantly outperformed the changed regime, with 58.1 v. 53.3 t DM/ha, respectively. Furthermore, the continuous 200 N treatment diverged from the nil N/200 N treatments during 2020–21, capitalising on the high rainfall. Notably, the production from nil N/200 N significantly outperformed the nil N/100 N, diverging in the third year (2020–21) after the treatment changed (Fig. 38b).

5.11.1 Plant frequency and persistence

Plant frequency by the end of the first growing season 2012–13 reached 60% in all treatments (Fig. 39). Over the next two growing seasons, the frequency of all treatments increased to >80%. However, by the end of the 10 years, all treatments, regardless of fertiliser treatment, had reached a frequency of >95% (Fig. 3). Frequency of the nil N/200 N, 100 N and 200 N treatments demonstrated a similar behaviour with a significant decline during the drought years (2018–2020) but a rapid recovery by 2022.

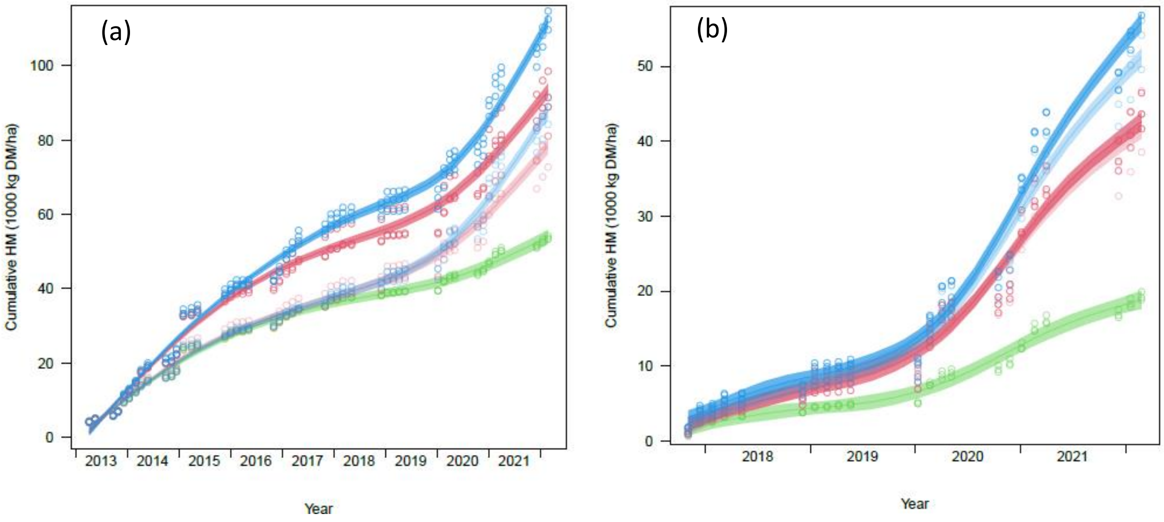


Fig. 38. Cumulative herbage production for (a) the whole experimental period (April 2013 to May 2022) and (b) in phase 2 of the experiment (November 2017 to May 2022) for treatments with annual applications of nil N (green), nil N/100 N (pink), nil N/200 N (light blue), 100 N (red), and 200 N (blue). Open circles indicate recorded herbage mass values for each treatment. The solid lines and shaded areas represent the predicted herbage production ± standard error of prediction respectively.

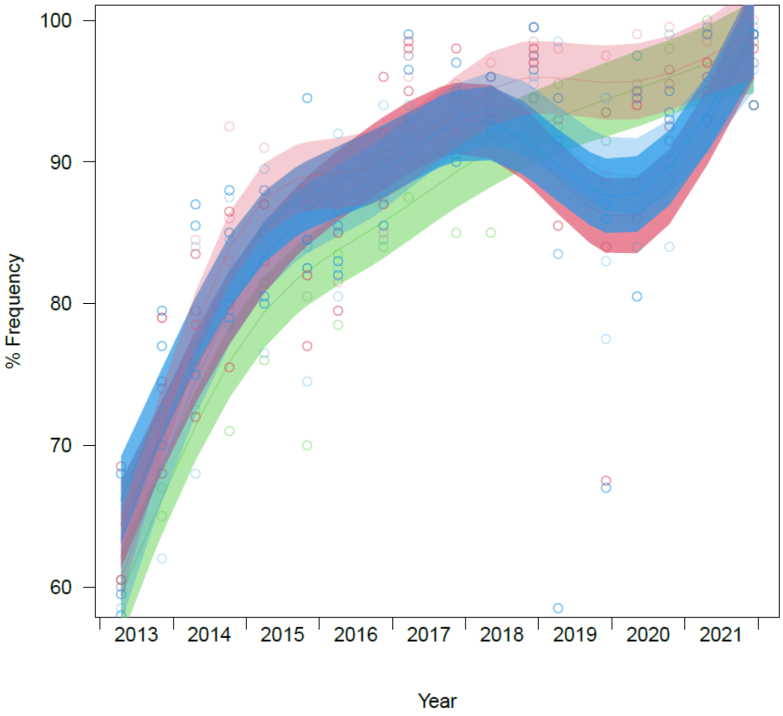


Fig. 39. Digit grass plant frequency from 2013–2022 for nitrogen treatments: nil N (green), nil N/100 N (pink), nil N/200 N (light blue), 100 N (red), and 200 N (blue). Open circles indicate recorded herbage mass values for each treatment. The solid lines and shaded areas represent the predicted herbage production ± standard error of prediction, respectively.

5.11.2 Soil C and N

From October 2012 to March 2022, soil cores were taken 20 times. Results of samples collected from the first 11 occasions are presented in Fig. 40.

Soil C and N were summarised into soil layers representing the upper (0–30 cm), middle (30–60 cm) and lower root zones (60–150 cm). Greatest changes in values were observed in the upper and middle root zones (Fig. 40). Total C and N declined during the first 2 years (sampling times 1–4) of the experiment before plateauing, while the C:N ratio gradually increased. Total N was noticeably higher in the upper root zone and decreased with soil depth. Also, the C:N ratio increased with soil depth; the ratio ranged from 12–17 for the upper root zone, 15–30 for middle root zone, to 35–60 for lower root zone (Fig. 40). Differences due to N treatments were not clear. Nitrate N data (not shown) were more variable, showing large changes in response to fertiliser application and rainfall events.

Due to laboratory issues we are still awaiting analyses of soil cores from the last 9 occasions. We are hoping to see the ongoing impact of the continuous and changed treatments on soil C and N in proportion to the rate of fertiliser N applied.

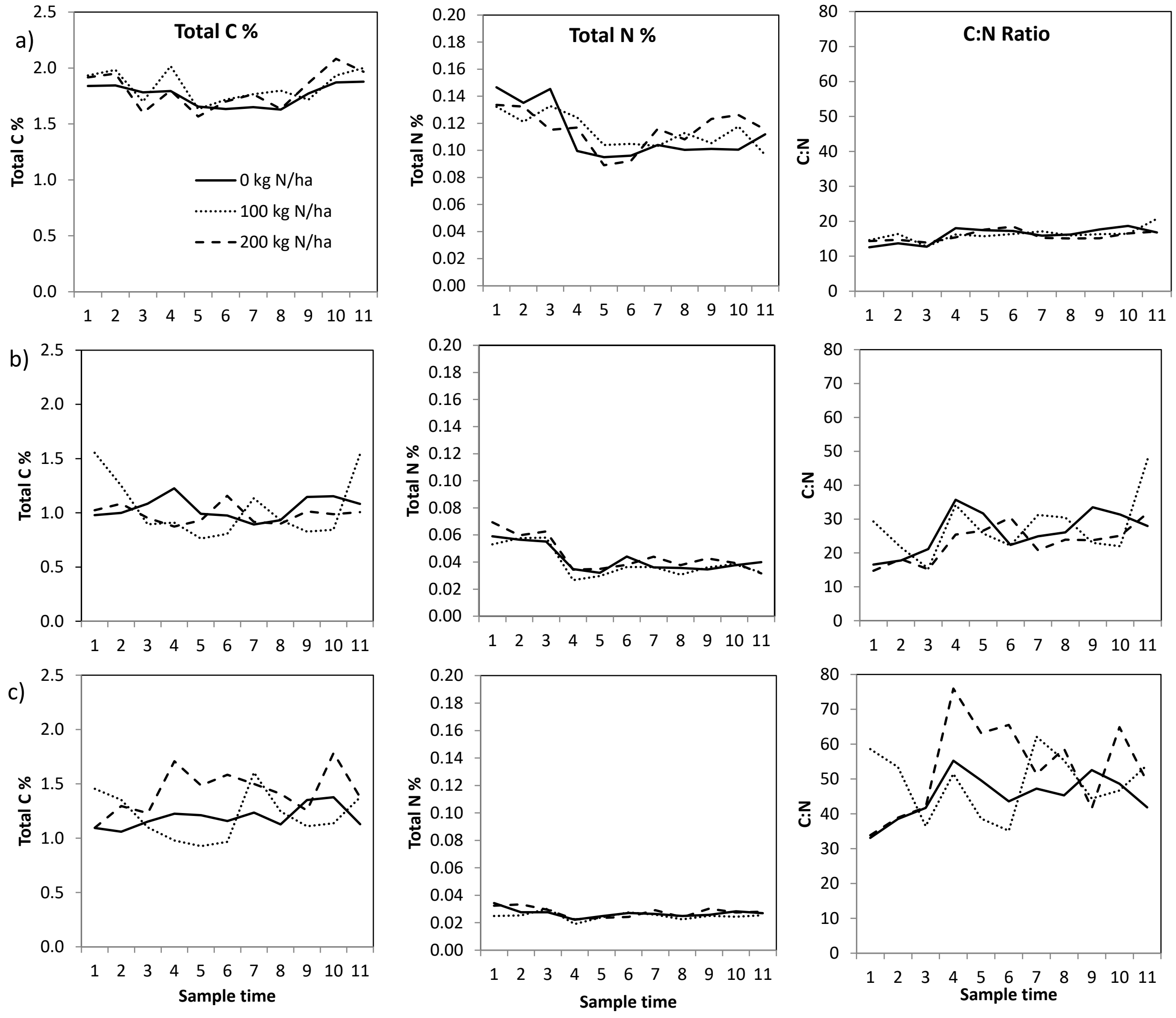


Fig. 40. **Soil total C (%), total N (%) and C:N ratio for a) upper (0–30 cm), middle (30–60 cm) and lower root-zones (60–150 cm) for the nil N (0 kg N/ha), 100 N (100 kg N/ha) and 200 N treatments (200 kg N/ha). Data are for 11 sample times from October 2012 to October 2017.**

5.11.3 Herbage nutritive value

All components of nutritive value assessed were highest quality, showing the least variation between the treatments at the first assessment following the drought (Fig. 41). Variation between the treatments generally increased with each subsequent assessment, but the treatments were consistently ordered from highest values for animal production to lowest: 200 N > nil N/200 N > 100 N > nil N/100 N > nil N.

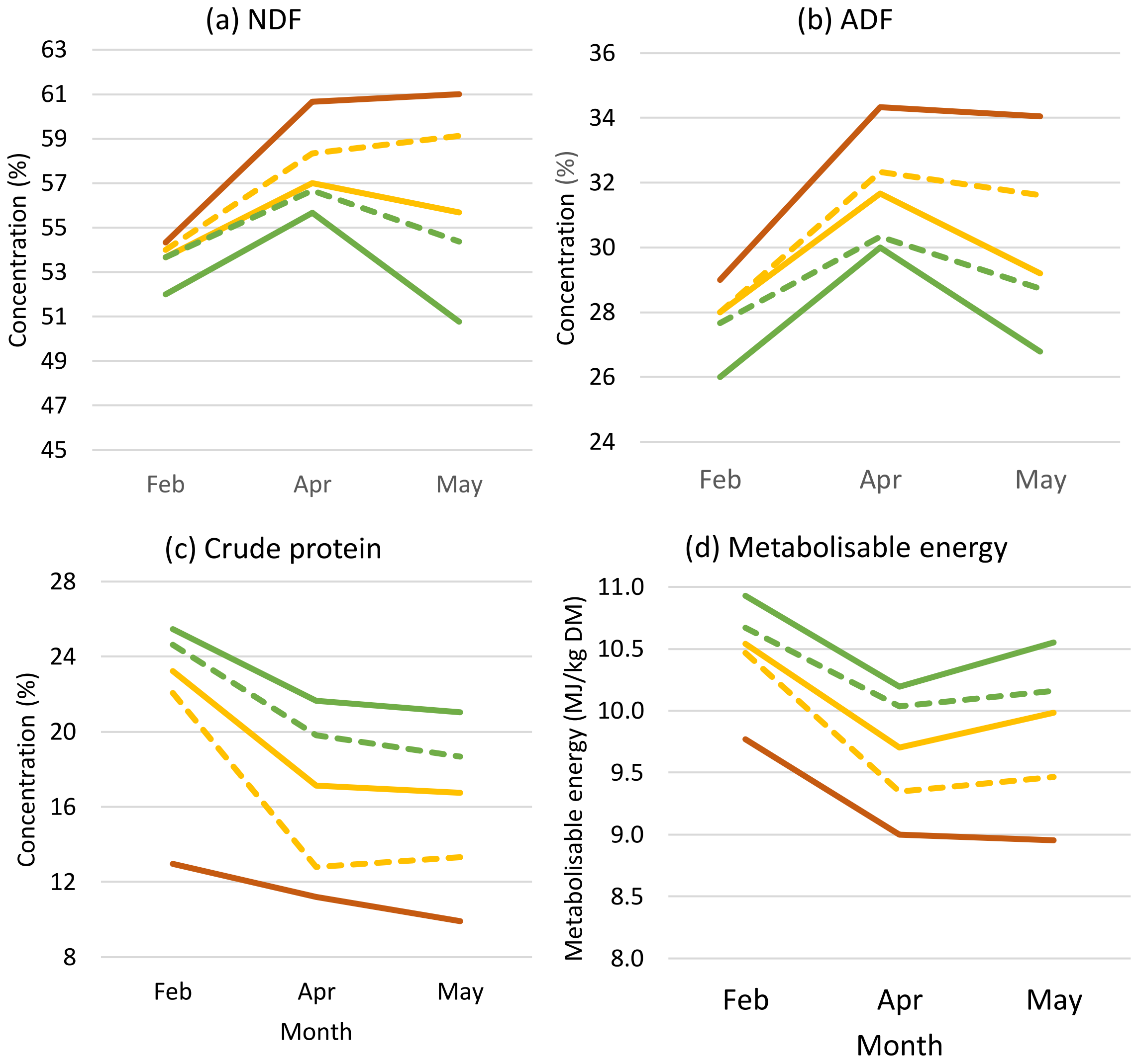


Fig. 41. (a) Neutral detergent (ADF), (b) acid detergent fibre (ADF), (c) crude protein and (d) metabolisable energy of digit grass forage in February, April and May 2020 following significant rainfall in January–February 2020 for the nil N (—), nil N/100 N (– –), nil N/200 N (– –), 100 N (—), and 200 N (—) treatments.

At the February assessment, the four treatments which received N were more than twice as productive (av 5.6 t DM/ha) as the unfertilised treatment (2.5 t DM/ha). Fibre content and ME of digit grass were similar for all treatments, but CP concentration was significantly higher in those fertilised with N (24 cf. 13%). By April, growth had slowed as temperatures declined. Despite this, productivity of the N fertilised plots ranged 2.6–4.1 t DM/ha; up to 3.5 times greater than the unfertilised plots (1.2 t DM/ha). Values for nutritive components for the treatments had diverged and reflected the N applied during the growing season. Interestingly, the treatments which were not fertilised until phase 2 of the experiment did not maintain the levels of those fertilised annually. By May, pasture growth had almost ceased (<1 t DM/ha), however, CP and ME levels of herbage in N fertilised treatments still exceeded the nil N treatment.

4.4 Hard seed breakdown patterns of temperate and tropical legumes in northern inland NSW

5.12.1 Tropical legumes

The initial hard seed values (*d*) ranged from 95% (fine stem stylo-NSW) to 6% (caatinga stylo cv. Unica) (Table 81). Fine stem stylo-NSW had significantly higher hard seed levels than the other legumes ($P < 0.05$), followed by desmanthus cv. Marc-NSW and SQ (87 and 86% respectively). Desmanthus cv. JCU2-SQ and NSW were ranked fourth and fifth (hard seed values of 85 and 79% respectively).

Desmanthus cv. Marc-SQ had the highest Weibull slope (*b*, $P < 0.05$), followed by desmanthus cv. Marc NSW ($P < 0.05$) (Table 81). The two desmanthus cv. JCU2 entries were similar to one another and ranked third and fourth ($P > 0.05$). These four entries also Caatinga stylo cv. Primar-NSW had Weibull slope values >1 indicating a slow initial rate of hard seed breakdown that increased with time (Table 81, Fig. 42). These five entries also had the highest *e* values indicating an extended breakdown pattern, especially the two desmanthus cv. Marc entries which had *e* values >1300 days. These values were significantly higher than those for the other three entries (650–836 days) showing a much slower hard seed break down of desmanthus cv. Marc compared with cv. JCU2. Predicted time for these entries to achieve 50% of their initial hard seed values averaged 1288 days for desmanthus cv. Marc (both entries) and 616 days for desmanthus cv. JCU2 (both NSW and SQ entries) and caatinga stylo cv. Primar-NSW.

Despite differences in initial hardseededness, all other entries in the experiment had Weibull slope values (*b*) < 1 and low inflection points (*e* < 171 days) indicating a rapid initial hard seed breakdown (Table 81, Fig. 42). Butterfly pea had the lowest inflection point of the entries tested (*e* = 26 days) indicating a highly rapid hard seed breakdown pattern compared to the other legume entries.

At the final assessment (15 October 2018, 1444 days), 47 months after the experiment commenced, only desmanthus cv. Marc (both entries) had notable levels of hard seed (av. 29%). All other entries had predicted hard seed values ≤7% (Table 81).

The legume entries seed increased in NSW generally had higher initial hard seed than those increased in Southern Queensland, the exception being desmanthus cv. JCU2, however differences between the locations was least for the two desmanthus cultivars. Desmanthus seed increased in Southern Queensland also tended to have higher Weibull slopes and inflection points for both cultivars than those increased in NSW, but the value of the parameters and over all pattern of breakdown was similar for both entries suggesting minimal practical difference in location of seed increase between NSW and Southern Queensland. The exception was finestem stylo, but this is likely due to a seed quality issue not a difference in hard seed level.

Weibull curves were fitted to the data for samplings 0-9 and described in a previous MLA project report. These fitted curves for each entry are shown as the orange lines on Fig. 42 while the red lines are the curves for the entire data set (S0-S11). There was little difference in the curves for most entries, the exceptions being the two desmanthus cvv. JCU2 entries and Marc SQ and caatinga stylo cv. Primar.

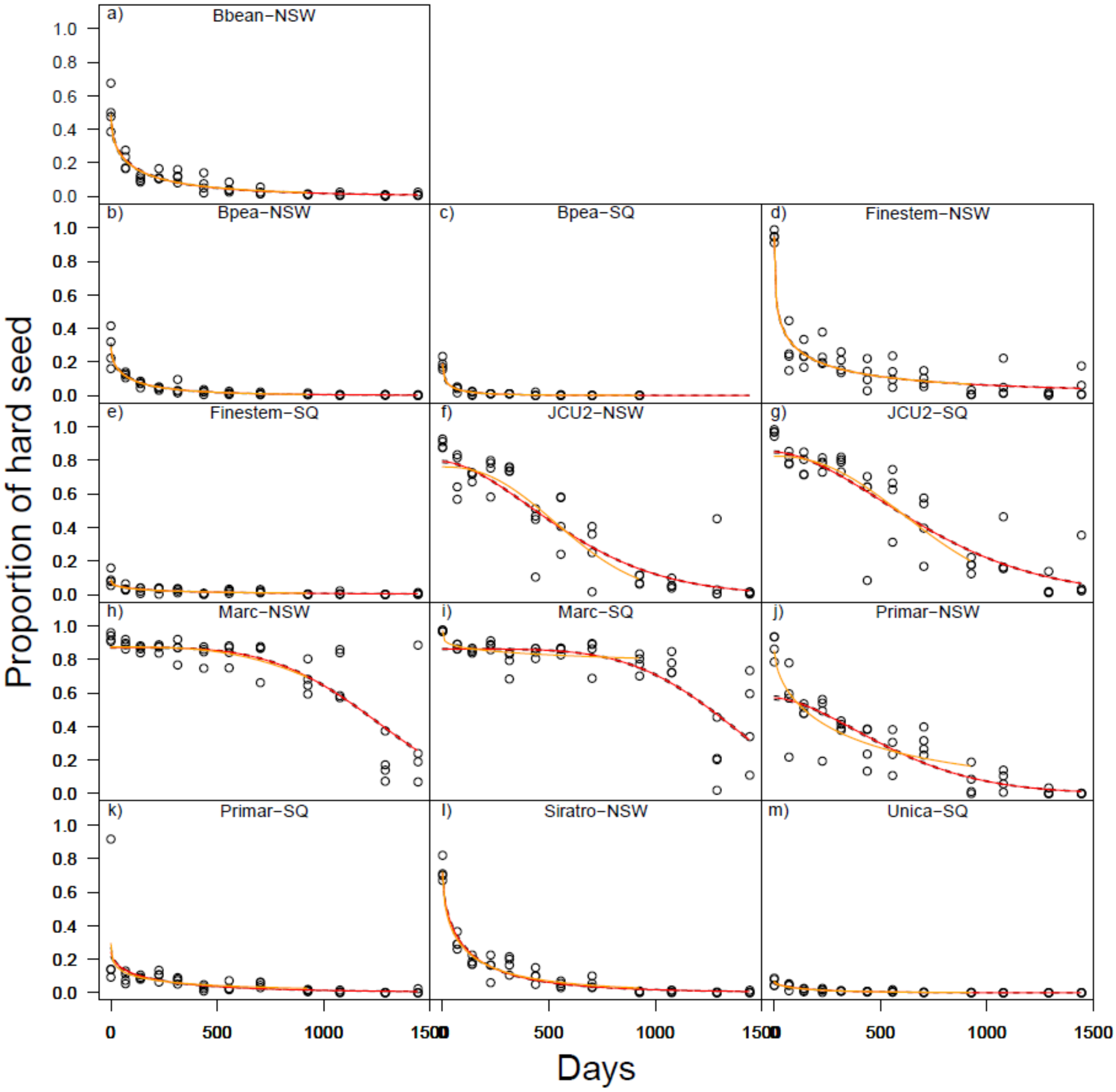


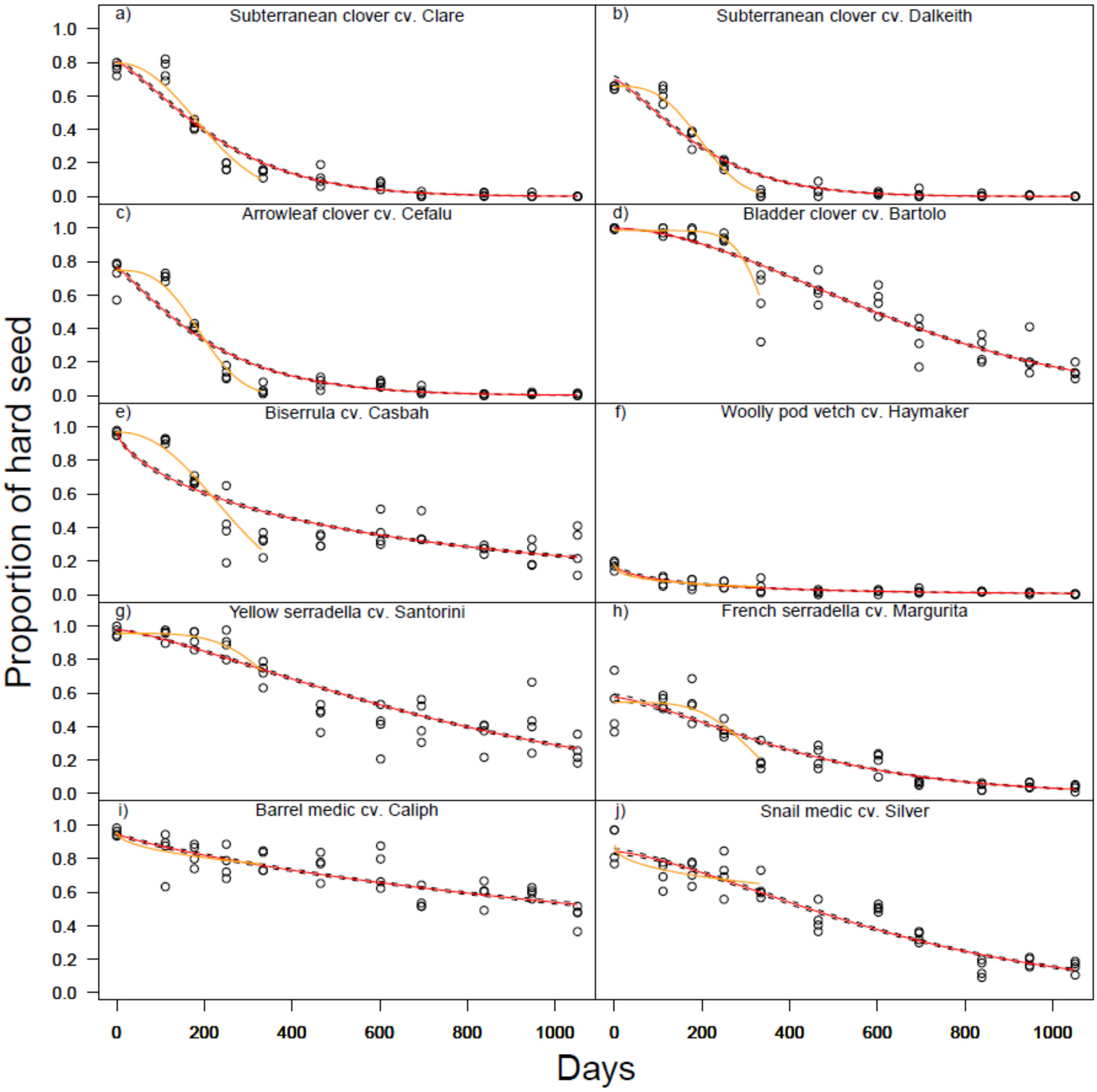
Fig. 42. Observed hard seed break down patterns of 13 tropical legumes at Tamworth, November 2014-October 2018: (a) burgundy bean-NSW, (b) butterfly pea-NSW, (c) butterfly pea-SQ, (d) fine stem stylo-NSW, (e) fine stem stylo-SQ, (f) desmanthus cv. JCU2-NSW, (g) desmanthus cv. JCU2-SQ, (h) desmanthus cv. Marc-NSW, (i) desmanthus cv. Marc-SQ, (j) caatinga stylo cv. Primar-NSW, (k) caatinga stylo cv. Primar-SQ, (l) siratro-NSW, and (m) caatinga stylo cv. Unica-SQ. Red solid and dashed lines represent the predicted hard seed ± standard error respectively. The orange lines represent the predicted hard seed breakdown pattern November 2014-May 2017.

Table 81. Estimates and standard errors (se) of the Weibull coefficients for parameters *b*, *d* and *e*, also the predicted hard seed (%) and standard error at the final assessment (15 October 2018, 1444 days) for each tropical legume, and the number of days to achieve 50% of initial hard seed (50%*d*).

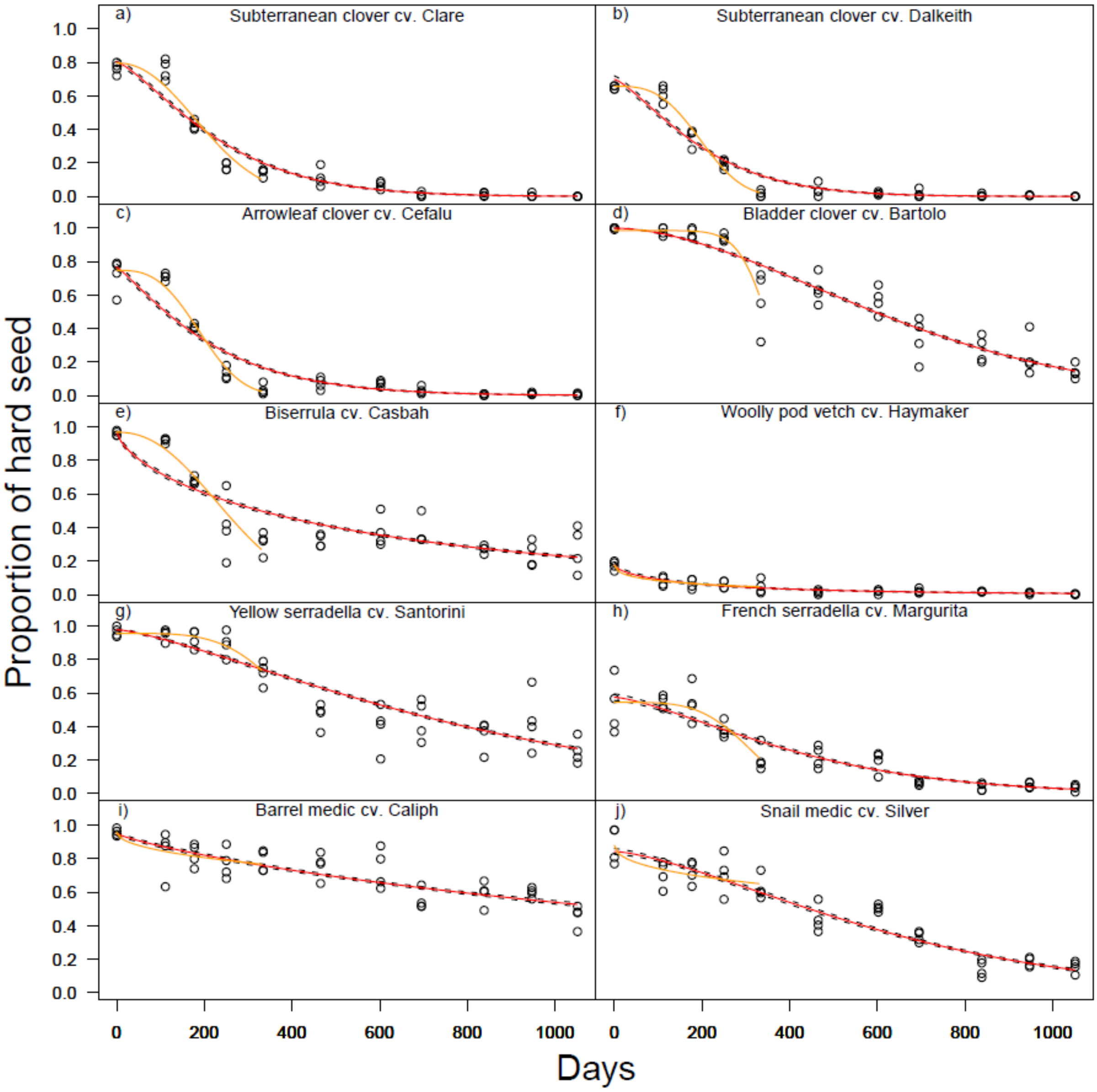
	b		d		e		Hard seed (%)		Days to 50%d
Cultivar	Estimate	SE	Estimate	SE	Estimate	SE	Estimate	SE	
Burgundy bean cv. B1-NSW	0.54	0.040	0.47	0.039	112	19.7	0.01	0.001	57
Butterfly pea cv. Milgarra-NSW	0.58	0.050	0.28	0.031	87	18.5	0.00	0.001	46
Butterfly pea cv. Milgarra-SQ	0.50	0.067	0.19	0.014	26	8.3	0.00	0.000	13
Fine stem stylo-NSW	0.36	0.011	0.95	0.012	61	4.3	0.04	0.002	22
Fine stem stylo-SQ	0.50	0.084	0.08	0.015	165	68.6	0.00	0.001	80
Desmanthus cv. JCU2-NSW	1.70	0.037	0.79	0.007	690	8.3	0.02	0.002	556
Desmanthus cv. JCU2-SQ	1.72	0.041	0.85	0.007	837	8.8	0.07	0.003	676
Desmanthus cv. Marc-NSW	3.84	0.128	0.87	0.003	1368	7.9	0.26	0.008	1243
Desmanthus cv. Marc-SQ	4.42	0.156	0.86	0.003	1447	9.1	0.32	0.009	1332
Caatinga stylo cv. Primar-NSW	1.67	0.074	0.57	0.012	651	15.5	0.01	0.002	522
Caatinga stylo cv. Primar-SQ	0.59	0.061	0.24	0.027	171	37.8	0.01	0.001	92
Siratro cv. Aztec-NSW	0.59	0.027	0.71	0.024	111	9.2	0.01	0.001	60
Caatinga stylo cv. Unica-SQ	0.76	0.102	0.06	0.010	149	36.7	0.00	0.000	92

5.12.2 **Temperate legumes**

Bladder clover, yellow serradella, biserrula and barrel medic had high initial predicted hardseed levels (*d*, ≥95%, P < 0.05) (Table 82). Woolly pod vetch had the lowest initial predicted hard seed value (17%) of the legumes tested (P < 0.05).



The majority of entries had Weibull slope (*b*) values > 1, indicating a hard seed breakdown rate that was initially slow then increased (Fig. 43), however the maximum value was only 1.78 (bladder clover, P < 0.05) (Table 82). Barrel medic, biserrula and woolly pod vetch had Weibull slopes <1, ranging from 0.84 (barrel medic) to 0.68 (biserrula)(P < 0.05). Barrel medic also the highest scale parameter value (*e* = 1969 days) of the temperate legumes. This value parameter in conjunction with the initial high hard seed value (*d* = 95%) and the Weibull slope with value of almost 1 defines the long and near linear breakdown pattern of this legume (Fig. 43). The predicted period for barrel medic to reach 50% initial hard seed value was ~3.5 years (50%*d* = 1274 days). This breakdown pattern contrasted with the two subterranean clovers which had higher Weibull slopes (*b* = 1.31) and a low scale value (*e* = 221–260 days) indicating a more rapid hard seed breakdown pattern (Table 82, Fig. 43). The subterranean clovers were predicted to achieve 50%*d* in less than 200 days (~6 months).



At the final assessment in May 2019, 35 months after the experiment commenced, barrel medic had the highest hard seed value (53%). Yellow serradella and biserrula were ranked second and third with 27 and 22% hard seed respectively. Bladder clover and snail medic averaged 15% hard seed while all of the other legumes had ≤3% hard seed (Table 82).

The initial analysis of these data used only 5 assessments (S0-S4) conducted over an 11-month period. Extending the data set to 11 assessments over 35 months, gave quite different Weibull slope and scale parameters. If the early stages of the breakdown pattern are of most interest, then the smaller data set was highly suitable, but these parameters were not suitable for predicting the longer term breakdown pattern. Similarly, the larger dataset tended to smooth the initial breakdown, masking much of the variation that did occur. This might have been overcome by using a different Weibull function. For example, a four-parameter Weibull curve would have allowed a second inflection point and may have provided a better fit for some species, however, interpretation of the parameters would be far more difficult.

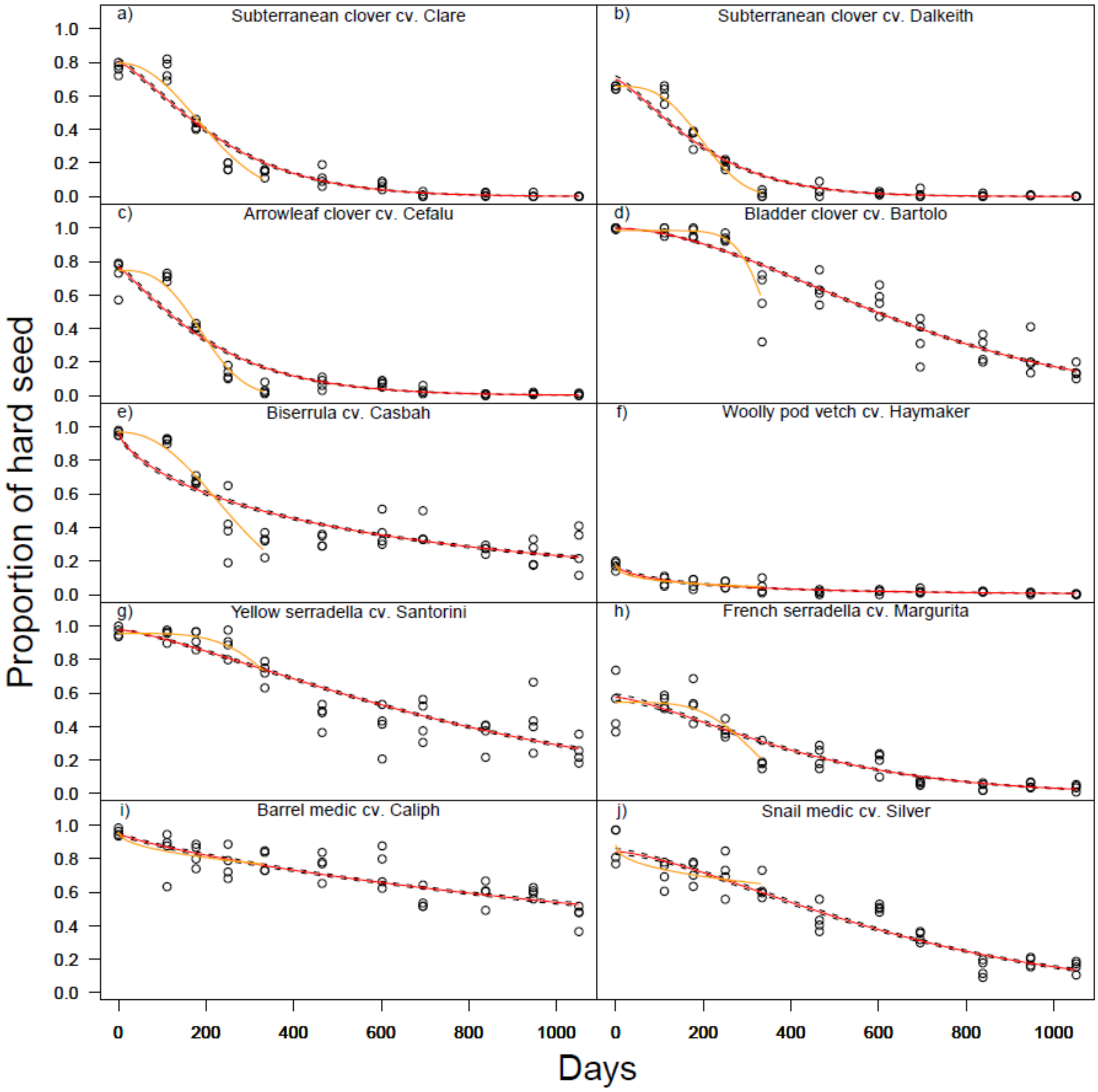


Fig. 43. Observed hard seed breakdown pattern of ten temperate legumes at Tamworth, November 2014-19: (a) subterranean clover cv. Clare, (b) subterranean clover cv. Dalkeith, (c) arrowleaf clover, (d) bladder clover, (e) biserrula, (f) woolly pod vetch, (g) yellow serradella, (h) French serradella, (i) barrel medic and (j) snail medic. Red solid and dashed lines represent the predicted hard seed ± standard error respectively. Orange line represents the predicted hard seed breakdown pattern November 2014-May 2017 reported in an earlier report.

Table 82. Estimates and standard error (se) of the Weibull coefficients for *b*, *d* and *e*, also the predicted hard seed (proportion) and standard error at the final assessment (May 2019, 1051 days) for each temperate legume and the number of days to achieve 50% of the initial hard seed level (i.e., 50%*d*).

	b		d		e		Hard seed (proportion)		Days to 50%*d*
Cultivar	Estimate	se	Estimate	se	Estimate	se	Estimate	se	
Subterranean clover cv. Clare	1.31	0.048	0.80	0.018	260	8.6	0.00	0.000	197
Subterranean clover cv. Dalkeith	1.31	0.054	0.70	0.020	222	8.6	0.00	0.000	168
Arrowleaf clover cv. Cefalu	1.16	0.043	0.77	0.019	232	8.9	0.00	0.001	169
Bladder clover cv. Bartolo	1.78	0.052	1.00	0.000	730	8.6	0.15	0.008	594
Biserrula cv. Casbah	0.69	0.032	0.97	0.008	599	18.5	0.22	0.008	352
Woolly pod vetch cv. Haymaker	0.68	0.092	0.17	0.019	188	40.9	0.01	0.002	109
Yellow serradella cv. Santorini	1.33	0.050	0.98	0.005	866	15.3	0.27	0.009	658
French serradella cv. Margurita	1.40	0.079	0.58	0.020	472	19.6	0.03	0.003	363
Barrel medic cv. Caliph	0.84	0.074	0.95	0.012	1969	152.9	0.53	0.011	1274
Snail medic cv. Silver	1.46	0.092	0.84	0.017	696	18.1	0.14	0.008	541

4.5 Competitive ability of tropical grasses and tropical legumes seedlings in mixes during establishment

5.13.1 Experiment 1 – *Desmanthus*-tropical grasses

At Harvest 1 (54 days after planting) the average grass components outyielded the legume components at all planting ratios (Fig. 44a). Mixtures containing Rhodes grass were the most advanced with greater productivity than the other grasses (average 16.6 cf. average 3.1 g/box). The legume component of all mixtures averaged less than 0.5 g/box at each planting ratio highlighting the extent that the tropical grasses outcompeted desmanthus.

At harvest 2 (35 days after regrowth) the grass components continued to outyield the legumes at all planting ratios (Fig. 44b). The contribution of the legume components to herbage mass for the legume:grass ratios 1:3, 1:1 and 3:1 were 7, 12 and 19% respectively. The model that described the species competitiveness all of the mixtures was k≠t with RYT<1. Indicating that the species were inhibiting each other and under yielding occurred (Fig. 44b). The tropical grass species had the higher crowding coefficient in all mixes except: desmanthus cv. Marc-digit grass; desmanthus cv. Marc-Rhodes grass; desmanthus cv. Ray-digit grass; and desmanthus cv. JCU4-buffel grass (data not shown).

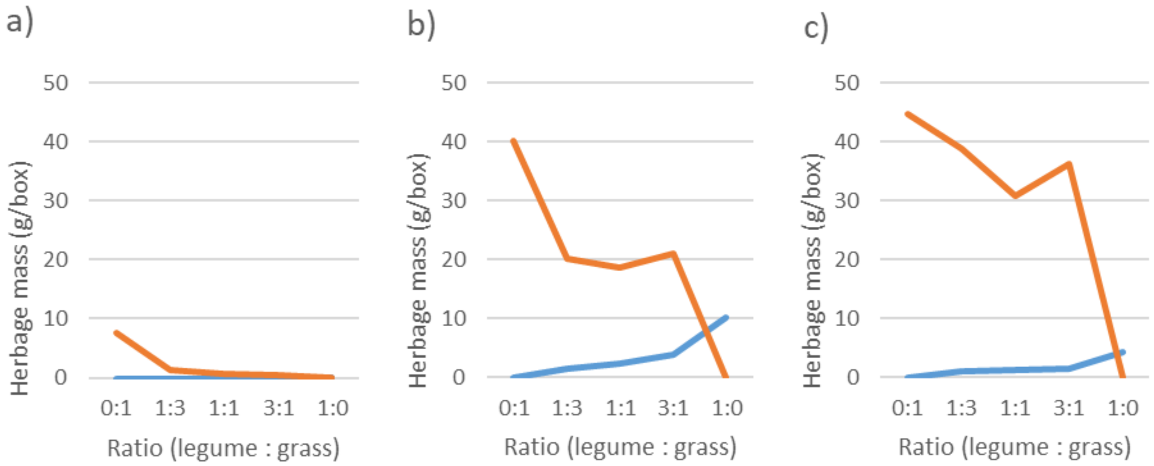


Fig. 44. Average legume (blue line) and grass (orange line) herbage mass (g/box) for harvest 1 (a), 2 (b) and 3 (c) for Experiment 1: *Desmanthus*-tropical grasses.

At harvest 3 (30 days after regrowth), the grass components continued to outyield the legume components at all planting ratios (Fig. 45c); the contribution of the legume components to total herbage mass for the mixes ranged from 2-5%. This indicated that there was some competition from desmanthus. The competitiveness between desmanthus and the tropical grasses for most of the mixtures was best described by the model k≠t with RYT<1, under-yielding with the tropical grasses in these mixtures having the higher crowding coefficients (Table 83). For the mixtures, desmanthus cv. JCU4-buffel grass and desmanthus cv. JCU4-panic grass, the best model to describe the species competitiveness was k=t≠1 with RYT=1, indicating that the two species were competing for the same resources. The tropical grass species in these mixtures had the higher crowding coefficients so the legume was being adversely affected. For the mixture desmanthus cv. JCU7-digit grass the species in the mixture were equally competitive (k = t = 1), with each species contributing to total herbage mass in direct proportion to its ratio in the mixture (Table 83). For the remaining mixtures at this harvest the competitiveness between desmanthus and the tropical grasses was best described by the model k≠t with RYT>1, over-yielding with the tropical grasses in these mixtures having the higher crowding coefficients (Table 83).

Table 83. Model, relative crowding coefficients for tropical legumes (kij) and tropical grasses (kji), their relative total yield (RTY), and interpretation of the model for each mixture at harvest 3 in Expt 1 calculated from species herbage mass (g/box).

Species mixture	Model	Kij	Kji	RYT	Interpretation
Desmanthus cv. Marc-Buffel	k≠t	0.300	3.054	0.916	Under-yielding
Desmanthus cv. Marc-Digit	k≠t	0.333	2.708	0.902	Under-yielding
Desmanthus cv. Marc-Panic	k≠t	0.333	1.734	0.577	Under-yielding
Desmanthus cv. Marc-Rhodes	k≠t	0.300	1.521	0.456	Under-yielding
Desmanthus cv. Ray-Buffel	k≠t	0.300	7.219	2.166	Over-yielding
Desmanthus cv. Ray-Digit	k≠t	1.400	9.625	13.475	Over-yielding
Desmanthus cv. Ray-Panic	k≠t	0.500	2.968	1.484	Over-yielding
Desmanthus cv. Ray-Rhodes	k≠t	0.167	1.063	0.178	Under-yielding
Desmanthus cv. JCU2-Buffel	k≠t	0.500	2.743	1.372	Over-yielding
Desmanthus cv. JCU2-Digit	k≠t	0.273	1.169	0.319	Under-yielding
Desmanthus cv. JCU2-Panic	k≠t	0.500	10.600	5.300	Over-yielding
Desmanthus cv. JCU2-Rhodes	k≠t	0.600	1.870	1.122	Over yielding
Desmanthus cv. JCU4- Buffel	k=t≠1	0.500	2.000	1.000	Competition
Desmanthus cv. JCU4-Digit	k≠t	0.222	1.556	0.345	Under-yielding
Desmanthus cv. JCU4- Panic	k=t≠1	0.231	4.428	1.023	Competition
Desmanthus cv. JCU4-Rhodes	k≠t	0.200	1.633	0.327	Under-yielding
Desmanthus cv. JCU7- Buffel	k≠t	0.444	2.875	1.277	Over-yielding
Desmanthus cv. JCU7-Digit	k=t=1	1.000	1.049	1.049	Equally competitive
Desmanthus cv. JCU7- Panic	k≠t	0.333	4.000	1.332	Over-yielding
Desmanthus cv. JCU7-Rhodes	k≠t	0.250	2.066	0.517	Under-yielding

5.13.2 Experiment 2 – *Stylosanthes*-tropical grasses

At Harvest 1 (52 days after planting) the average grass components were more advanced than the legume components at all planting ratios (Fig. 45a). At this harvest the grasses averaged >20 g/box across the planting ratios, while the legumes averaged <0.5 g/box. At harvest 2 (47 days after regrowth) the contribution of the legume components to herbage mass for the legume:grass ratios 1:3, 1:1 and 3:1 was still low in comparison to the grass components with a slight increase at the planting ratio of 3:1 (Fig. 45b).

At harvest 2 (47 days after regrowth) the model that best described the competitiveness between the stylo species and the tropical grasses for most mixtures was k≠t with RYT<1 (Table). This indicated that the species were inhibiting each other and under yielding occurred, but the tropical grasses in all mixtures had the higher crowding coefficients (Table). However, for the mixture shrubby stylo-buffel grass the best model to describe the species competitiveness was k=t≠1 with RYT=1, indicating that the two species were competing for the same resources. Buffel grass had the higher crowding coefficient indicating that shrubby stlo was being adversely affected.

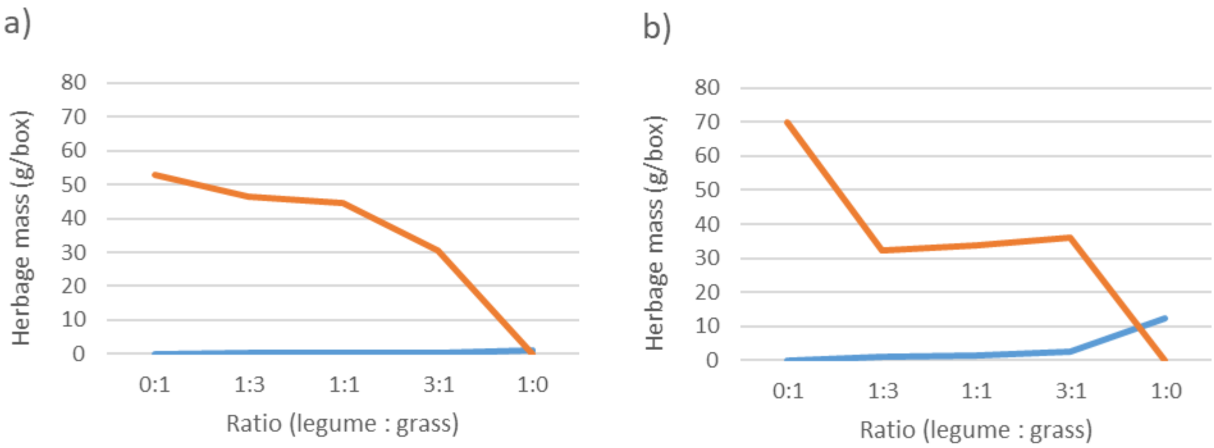


Fig. 45. Average legume (blue line) and grass (orange line) herbage mass (g/box) for harvest 1 (a) and 2 (b) for Experiment 2: *Stylosanthes*-tropical grasses.

Table 4. Model, relative crowding coefficients for tropical legumes (kij) and tropical grasses (kji), their relative total yield (RTY), and interpretation of the model for each mixture at harvest 2 in Expt 2 calculated from species herbage mass (g/box).

Mixture (species i and j)	Model	Kij	Kji	RYT	Interpretation
Caatinga stylo-Buffel	k≠t	0.008	0.338	0.003	Under-yielding
Caatinga stylo-Digit	k≠t	0.350	0.453	0.159	Under-yielding
Caatinga stylo-Panic	k≠t	0.011	1.681	0.018	Under-yielding
Caatinga stylo-Rhodes	k≠t	0.001	0.901	0.090	Under-yielding
Caribbean stylo-Buffel	k≠t	0.120	0.326	0.039	Under-yielding
Caribbean stylo-Digit	k≠t	0.020	1.212	0.024	Under-yielding
Caribbean stylo-Panic	k≠t	0.048	1.190	0.057	Under-yielding
Caribbean Stylo-Rhodes	k≠t	0.008	0.985	0.008	Under-yielding
Common stylo-Buffel	k≠t	0.085	1.013	0.086	Under-yielding
Common stylo-Digit	k≠t	0.065	2.476	0.161	Under-yielding
Common stylo-Panic	k≠t	0.033	1.522	0.050	Under-yielding
Common stylo-Rhodes	k≠t	0.001	1.930	0.002	Under-yielding
Fine stem stylo-Buffel	k≠t	0.003	1.114	0.003	Under-yielding
Fine stem stylo-Digit	k≠t	0.005	0.488	0.002	Under-yielding
Fine stem stylo-Panic	k≠t	0.010	0.786	0.008	Under-yielding
Fine stem stylo-Rhodes	k≠t	0.002	1.340	0.003	Under-yielding
Shrubby stylo-Buffel	k=t≠1	0.692	1.489	1.030	Competition
Shrubby stylo-Digit	k≠t	0.125	0.939	0.117	Under-yielding
Shrubby stylo-Panic	k≠t	0.750	0.793	0.595	Under-yielding
Shrubby stylo-Rhodes	k≠t	0.002	0.680	0.001	Under-yielding

4.6 Establishing legumes into existing perennial grass pastures

5.14.1 Seasonal conditions

Extreme drought continued throughout summer 2018-19 (Fig. 46) prompted an evaluation of the risks associated with attempting to establish legumes into existing pastures. Exploratory soil coring and a lack of green leaf in the pastures throughout summer 2018-19 confirmed that soil water content was extremely low. The continuing dry conditions posed excessive risks to successfully establishing legumes into the pasture, so the experiments were delayed until autumn 2020. Fallow treatments to prepare for sowing the winter legumes commenced after receiving 63 mm of rainfall in January 2020 (Fig. 46).

With the onset of above average rainfall in February 2020, maximum temperatures were below average (Fig. 46a, b). This pattern persisted for the remainder of the experimental period, with maximum temperatures rarely exceeding long-term average values, with October and November 2020 being the exceptions (Fig. 46b). Similarly, minimum temperatures were below average after February 2020 for the remainder of the experimental period (Fig. 46b).

Monthly rainfall totals were well above average in December 2020 and November 2021, which coincided with sowing the summer legume and the desmanthus establishment experiments, respectively. Further, monthly totals were well above average in February and March 2020, and above average in February and March 2021 (Fig. 46a).

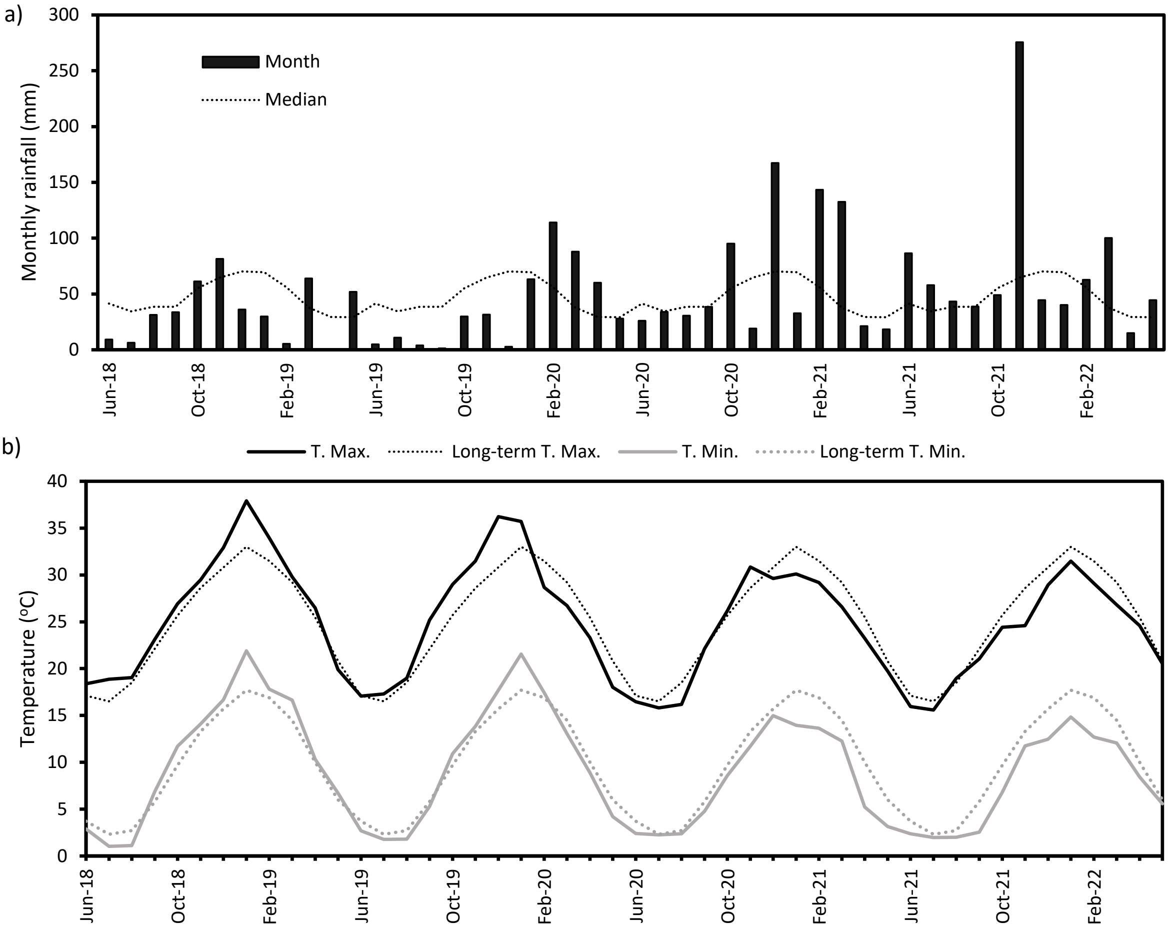


Fig. 46. a) Monthly total rainfall (mm, bars), and b) monthly average maximum and minimum temperatures compared with the long-term monthly values (dotted lines) for Tamworth Airport AWS.

5.14.2 Soil water content

The uniform increase in EC_a (10-20 dS/m) observed across the plots in the 0-week treatment indicated a general improvement of soil water conditions on each site during each of the fallow periods. For the winter legume experiment, this increase represented the improvement of conditions coming out of the drought in late summer and autumn 2020; the summer legume experiment represented 275 mm of rainfall in November 2021 (Fig. 47). However, a longer fallow period (16-week v. 8-week v. 0-week) led to greater soil water accumulation in the centre of the fallow strip (3.0 m distance, Fig. 47). In addition, the existing pasture had an edge effect, with EC_a values at 1.5 and 4.5 m being lower than the middle of the fallow (Fig. 47).

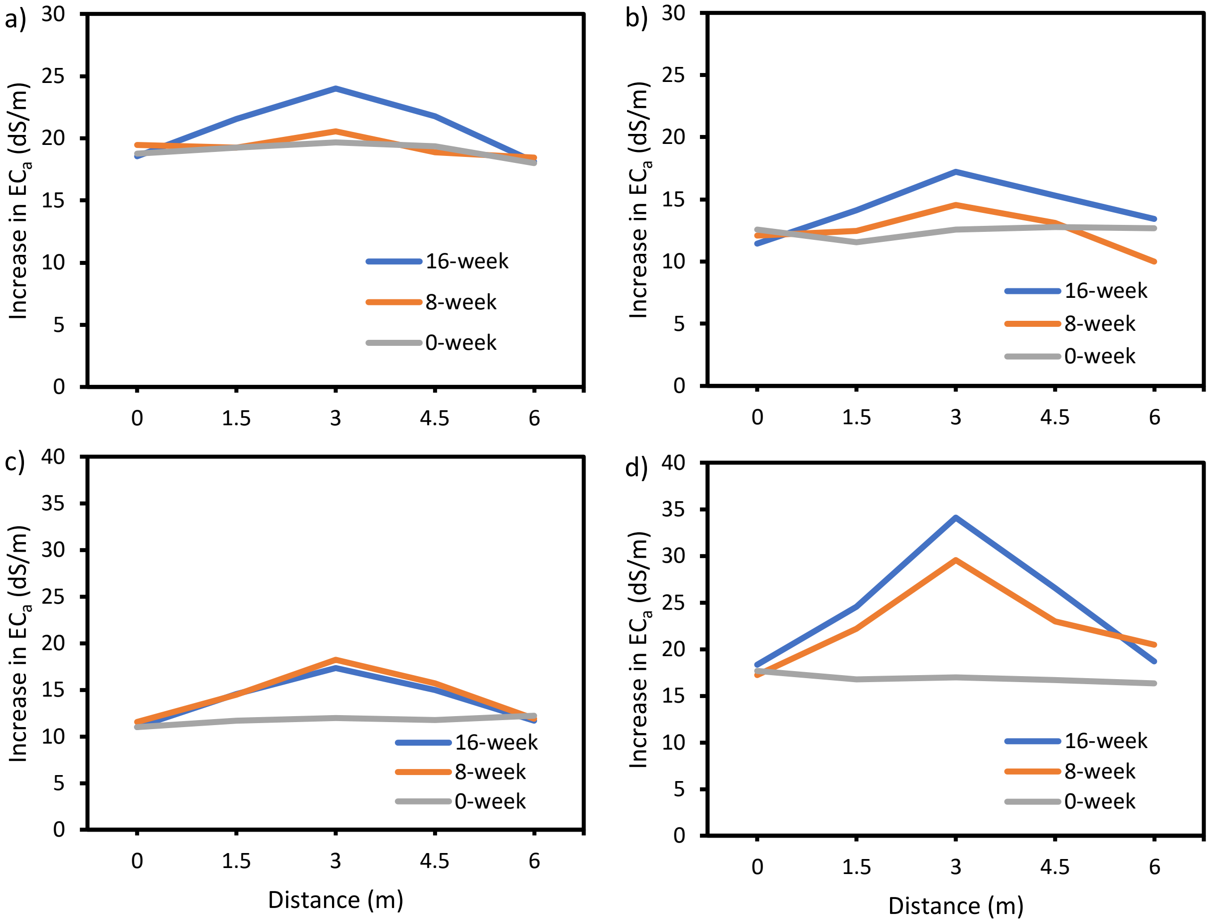


Fig. 47. Increase in electrical conductivity (EC_a, dS/m, as an indicator of increase in stored soil water) across plots for each fallow treatment prior to sowing the winter (a,b) and summer (c,d) legumes in the sown tropical (a,c) and native (b,d) pastures, respectively.

5.14.3 Groundcover

Groundcover in the fallow strips declined in direct proportion to the length of the fallow period (Fig. 48). Groundcover in the 0-week treatments was generally uniform across the plots. The impact of the spray fallow treatments was greatest at the native grass sites, with ground cover in the 16-week treatment declining to 30–50% (Fig. 48b,d). However, at the tropical grass pasture, the 16-week treatment reduced groundcover to 44–54% (Fig. 48a,c). The larger decline in groundcover in the native grass pasture was probably associated with the pasture being run down during the drought and having a lower basal area of perennial grasses.

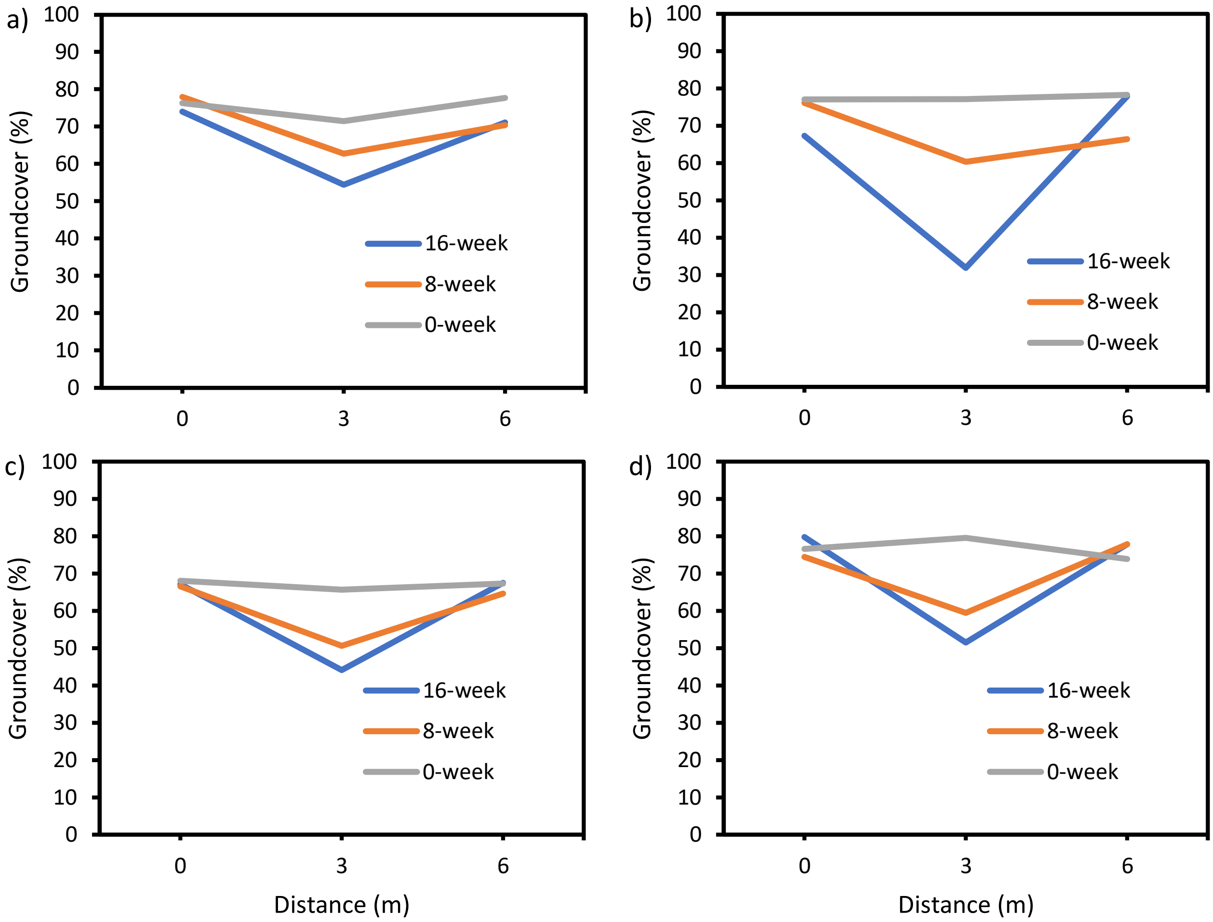


Fig. 48. Groundcover (%) for the existing pasture (0 and 6 m) and centre of the fallow strip (3 m) at sowing for each fallow treatment. Panels a) and b) are groundcover before sowing winter legumes in tropical and native grass. Panels c) and d) are groundcover before sowing summer legumes in tropical and native pastures, respectively.

5.14.4 Seedling counts

Winter growing legumes

Seedling densities were counted in early July 2020, approximately 6 weeks after sowing. Edge effects were readily apparent, with a lower density observed near the edge of the sowing strip (Fig. 49). For all species and in both pastures, total seedling density appeared to increase with a longer fallow period, although there were some overlaps between the densities in the 16- and 8-week treatments. The data suggest that interactions between soil water content and groundcover influenced the seedling density. Lucerne density was higher in the tropical grass pasture where we observed a more substantial increase in stored soil water and groundcover remained high. Conversely, we observed a higher annual legume density in the native grass pasture, where soil water content increased, but groundcover was slightly lower. The larger seed size of the annual legumes appeared to translate into higher seedling density, despite sowing fewer seeds (i.e., a higher 100-seed weight).

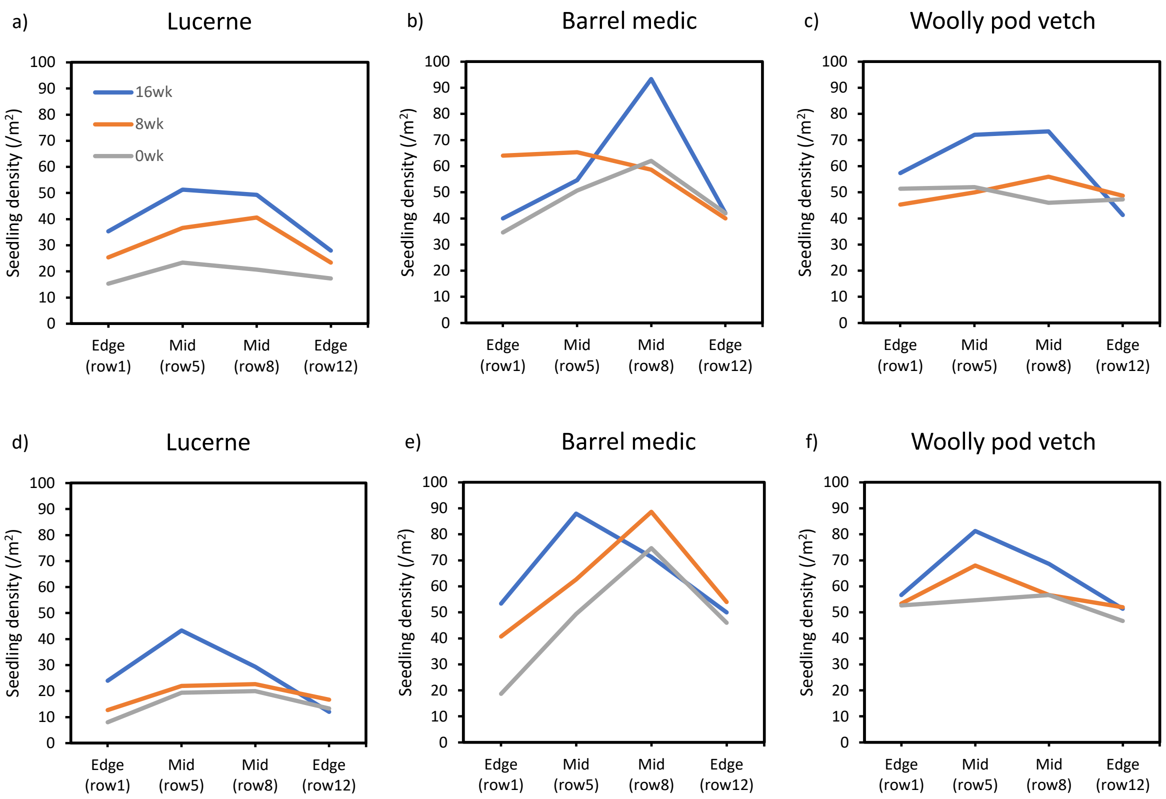


Fig. 49. Winter legume seedling densities in July 2020, 6 weeks after sowing in the tropical grass pasture (a, b, and c) and the native grass pasture (d, e, and f).

Summer growing legumes

Seedling densities were assessed in late December 2020, approximately 7 weeks after sowing. Again, edge effects were strongly apparent, with very few seedlings counted on the margins of the sowing strip. Curiously, we observed fewer seedlings at the downhill margin of the sowing strip, vis. row 12 (Fig. 50). Total seedling densities were reasonably consistent among the species at each pasture, with slightly higher densities at the native grass site. However, lucerne had lower seedling density when sown in spring compared with autumn (maximum 20–25 and 40–50 plants/m^2 respectively, Fig. 50 and Fig. 49).

The summer legume density data suggested an interaction between soil water content and groundcover, as we observed for the winter legumes. This was most evident in the native pasture, where the 16-week treatment showed the highest increase in soil water but the sharpest decrease in groundcover. Conversely, the 0-week treatment, had no additional soil water in the sowing strip compared with the background pasture, but groundcover remained high (near 80%). Subsequently, the 0-week treatment resulted in seedling densities for all species equal or greater than the 16-week treatment (Fig. 50).

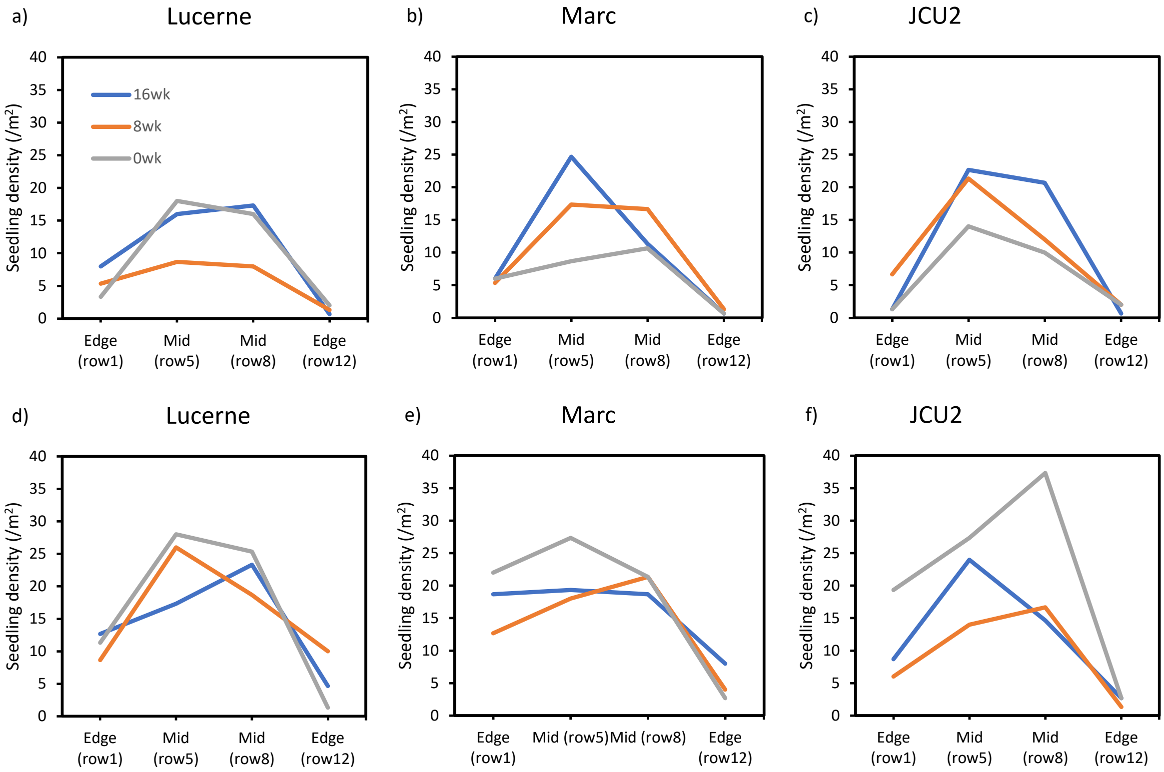


Fig. 50. Summer legume seedling densities in December 2020, 7 weeks after sowing in the tropical grass pasture (a, b, c) and the native grass pasture (d, e, f).

5.14.5 Peak standing dry matter

Winter growing legumes

The growth response of each winter legume dictated the timing when we observed peak standing dry matter. For example, dry matter of woolly pod vetch peaked first at both sites in September 2020, barrel medic reached its peak in November 2020 and finally lucerne in January 2021.

Woolly pod vetch had particularly vigorous growth, achieving 2400 and 3400 kg DM/ha at the tropical grass and native grass sites respectively in the 16-week treatment (Fig. 51). In addition, with its sprawling growth habit, the vetch quickly generated a canopy over the plots, which provided competition for weeds (Fig. 51).

Barrel medic had the lowest total dry matter, but our assessment method likely underestimated the dry matter in this species because of its prostrate growth habit. Where groundcover was low at sowing, we recorded less barrel medic, but where there were residual grass tussocks, the medic grew taller and was more assessable.

Lucerne generated 2000–2500 kg DM/ha at its peak in all treatments, but one, the 0-week on tropical grass, which was c. 700 kg DM/ha (Fig. 51). The 0-week treatment had minimal effect on the tropical grass, which regrew, directly competing with the lucerne in spring and summer. Subsequently, at the tropical grass site, lucerne peak dry matter declined with shorter fallow length, but perennial grass regrowth increased (Fig. 51). At the native grass site, however, lucerne growth was consistent among the treatments (c. 2500 kg DM/ha), but native grass regrowth was modest, increasing among the treatments from 150 to 350 kg DM/ha (Fig. 51).

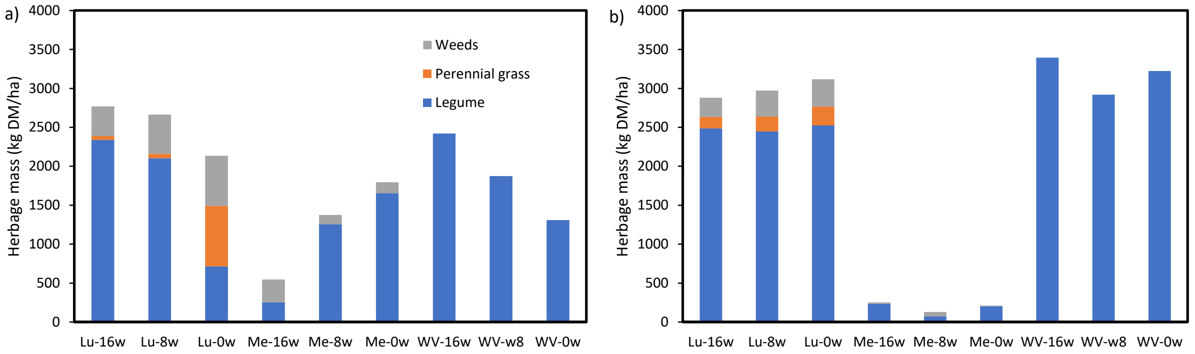


Fig. 51. Peak standing dry matter of winter legumes (Lu – lucerne, Me – barrel medic, WV – woolly pod vetch) with high (16W), medium (8W) and low (0W) soil water accumulation periods in a) tropical grass pasture and b) native grass pasture.

Summer growing legumes

Standing dry matter for the summer growing legumes increased each month after sowing until the end of the summer growing season in April 2021.

Several key findings were evident. First, the maximum total dry matter for all the summer legume species was starkly lower than that of the winter legumes. Second, grasses at both pasture sites outcompeted the seedling legumes. At the tropical grass site, the perennial grasses dominated the summer herbage production, while at the native grass site, annual grass weeds [mainly liverseed grass (*Urochloa panicoides*)] dominated production. Third, sowing lucerne in spring is less reliable than sowing in autumn. And finally, using this approach, we struggled to establish desmanthus and achieve seed set before autumn.

Total dry matter (legume + perennial grass + weeds) for each legume treatment declined with a shorter fallow period (Fig. 52). For example, total herbage for the 16-week fallow was always greater than for the 0-week fallow (Fig. 52), demonstrating the benefit of accumulating soil water. However, the legume response to increasing fallow length was not discernible. This was because the grasses were the primary beneficiaries of the accumulated water and/or mineralised nitrogen during the fallow. Further, the grasses benefitted from the above-average rainfall during the summer.

The peak dry matter recorded for lucerne at both sites demonstrated that sowing lucerne in spring is less reliable in achieving a productive stand. For example, the maximum lucerne dry matter for the 16-week fallow at the tropical grass site was just 218 kg DM/ha (Fig. 52), compared with 2338 kg DM/ha sown in autumn (Fig. 51). On the other hand, the outcome for the spring sown lucerne at the native grass site marginally improved with 859 kg DM/ha compared with 2486 kg DM/ha sown in autumn (Fig. 52).

Desmanthus cv. JCU2 sown at the native grass site in the 0-week treatment achieved the maximum herbage mass of 810 kg DM/ha (Fig. 52). However, none of the desmanthus treatments achieved a robust stand, and most plants struggled to seed set before autumn. Indeed, on a percentage basis, the contribution of desmanthus to total dry matter was modest to negligible.

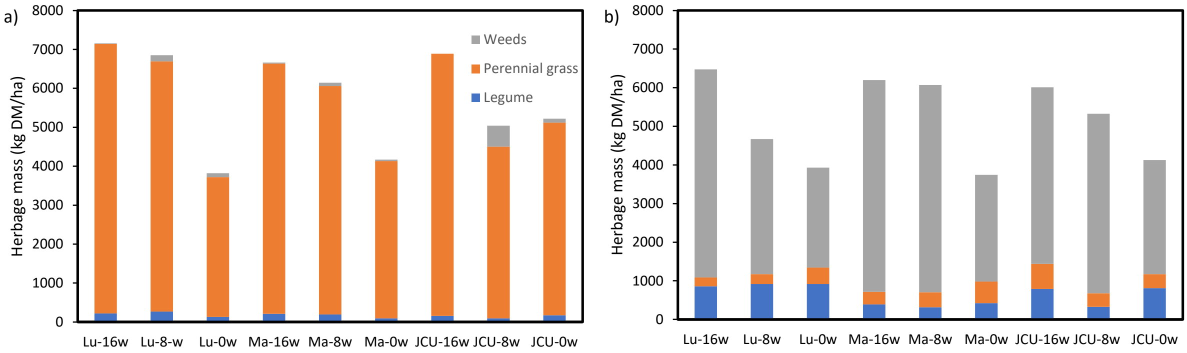


Fig. 52. Summer legume (Lu – lucerne, Ma – Desmanthus cv. Marc, JCU – Desmanthus cv. JCU2) peak standing dry matter with high (16W), medium (8W) and low (0W) soil water accumulation periods in a) tropical grass pasture, and b) native grass pasture.

5.14.6 Regeneration plant counts

Winter growing legumes

Above-average rainfall in February–March 2021 triggered seedling regeneration of both barrel medic and woolly pod vetch. Barrel medic showed excellent regeneration with seedling densities equal to (native grass site) and higher (tropical grass site) than at sowing (Fig. 53a,c). Adverse edge effects were not apparent, and seedling density did not appear correlated with fallow treatments. Seedling densities at the tropical grass site (c. 100–200 plants/m^2) were higher than those at the native grass site (50–100 plants/m^2), which reflected the differences in peak standing dry matter in the establishment year.

Woolly pod vetch showed mixed regeneration with seedling densities equal to or lower than at sowing (Fig. 53b,d). But, again, adverse edge effects were not apparent or consistent. At the tropical grass site, there appeared to higher seedling density near the edges, but at the native grass site, density was higher near the middle.

Mouse activity was observed at both sites during spring and summer. A baiting program was conducted to limit seed predation; however, seed numbers were most likely impacted, especially woolly pod vetch which we noted was preferentially predated. Given the high herbage mass and seed set in the establishment year, the regeneration of vetch was less than anticipated.

Summer growing legumes

Desmanthus grows as a short-lived perennial in the North-West Slopes of NSW environment, so the ability to set seed and regenerate from seed is critical for its long-term viability. We assessed over-winter survival and/or seedling regeneration with plant counts in January 2022. The plant counts recorded the total number of desmanthus plants, regardless of whether they were from sowing or regeneration from seed.

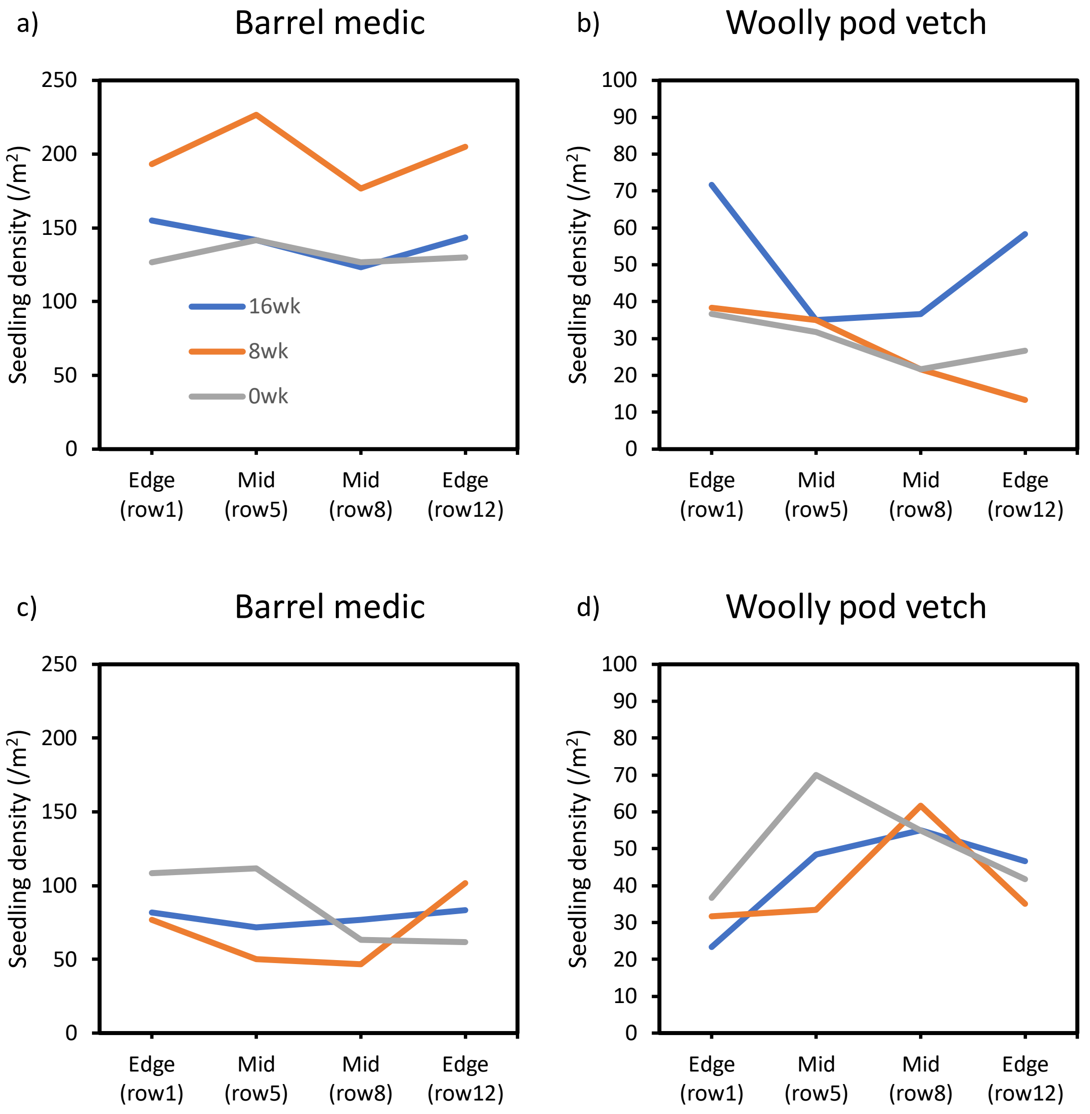


Fig. 53. Seedling regeneration counts for annual winter legumes in tropical perennial grass (a and b) and native perennial grass (c and d) pastures.

Plant density in year 2 was distinctly lower than the year of sowing. For example, at the tropical grass site, plant density of both desmanthus species had declined from 5–25 plants/m^2 after sowing to <2 plants/m^2 (Fig. 54a,b). Further, at the native grass site, desmanthus density had declined from 5–30 plants/m^2 to <10 plants/m^2 (Fig. 54c,d). The higher density at the native grass site indicated the higher density at sowing, the higher peak standing dry matter, and the degree of maturity achieved in the sowing year.

Importantly, we identified no new seedlings in the follow-up assessment. This is despite >400 mm of rainfall from October 2021 to January 2022.

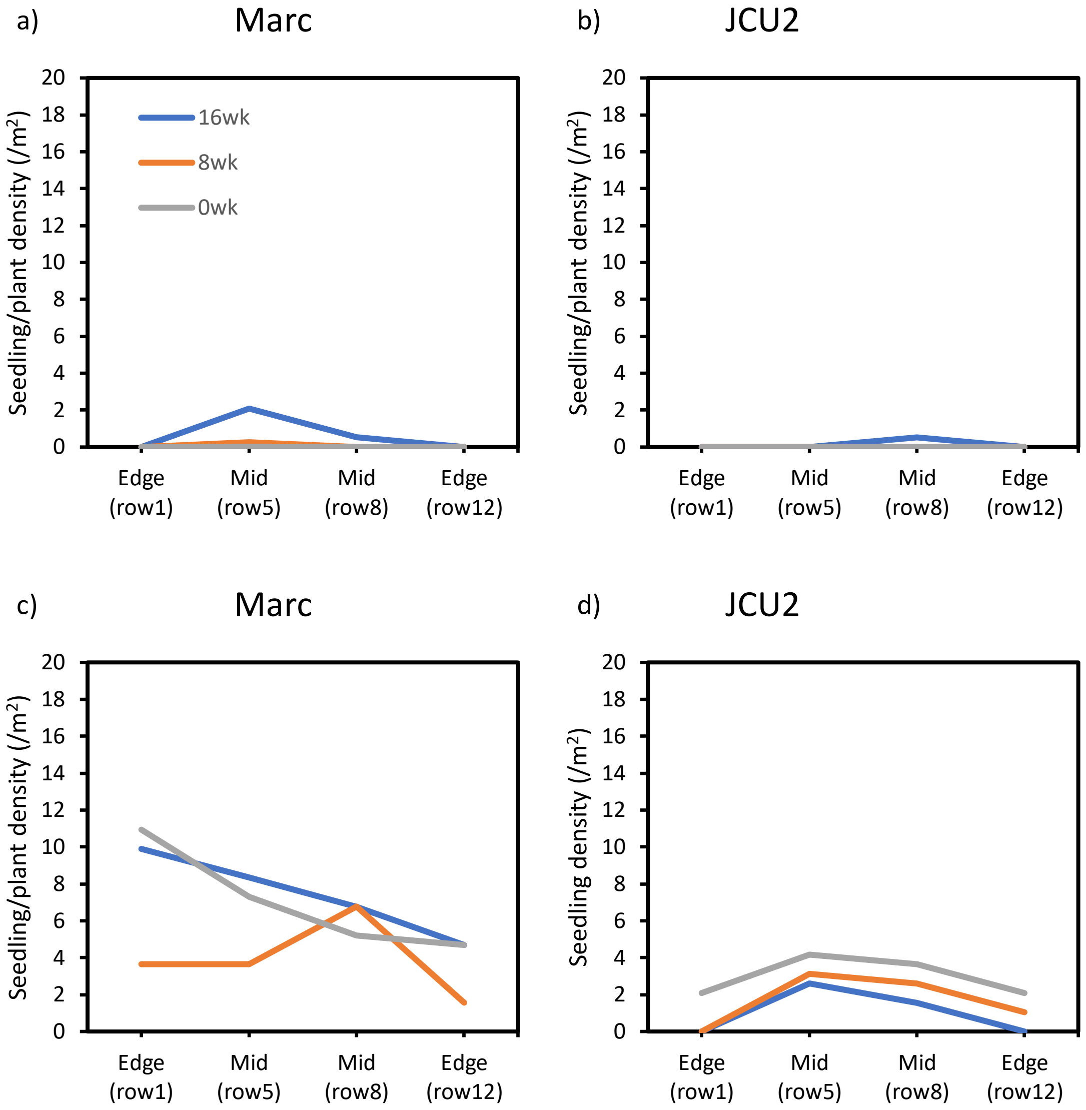


Fig. 54. Seedling or plant regeneration counts for summer legumes (Marc – Desmanthus cv. Marc, JCU2 – Desmanthus cv. JCU2) in tropical perennial grass (a and b), and native perennial grass (c and d) pastures.

5.14.7 Reducing tropical grass competition to improve desmanthus establishment – desmanthus establishment #2

Soil water and groundcover

The wet winter and spring (551 mm, June to November) resulted in stored soil water increasing by similar amounts in all fallow treatments (Fig. 55a). For example, the increase in ECa (dS/M) in the 16-week treatment was only marginally higher than the background pasture. Therefore, soil water content across the site and among the treatments appeared uniform.

The fallow treatments reduced groundcover similarly to our initial experiment. By controlling annual winter weeds, the 16-week treatment had the lowest groundcover in the centre of the treatment strip (Fig. 55b). In contrast, the 0-week treatment had no effect on groundcover (Fig. 55b).

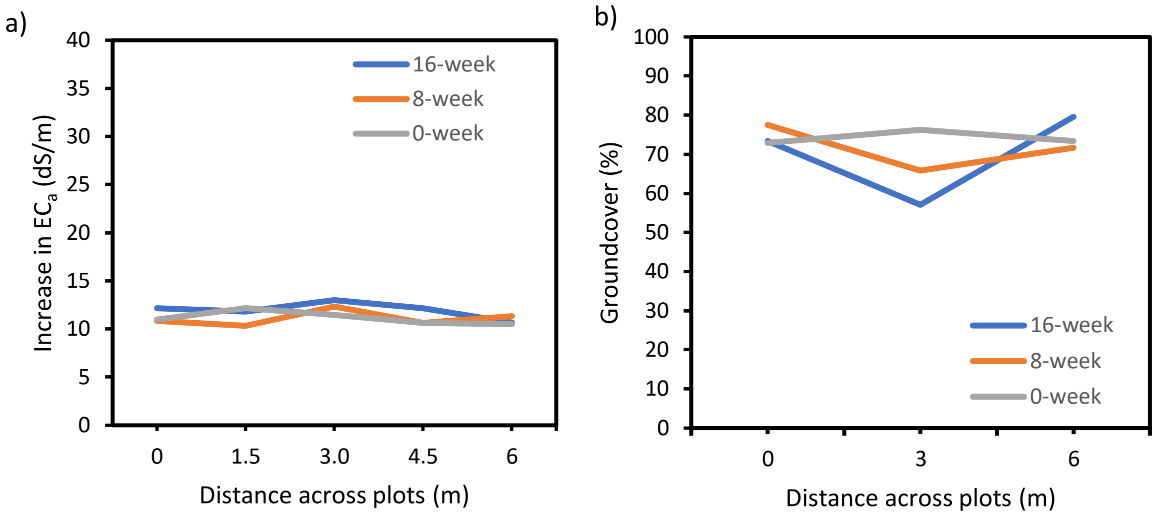


Fig. 55. Changes in a) EC_a and b) groundcover during the fallow treatment periods in preparation for sowing desmanthus cv. Marc.

Seedlings

The 8-week fallow period resulted in higher seedling density than the 16-week or 0-week treatments (Fig. 56a). But, again, adverse edge effects were apparent, with a lower density in the edge rows. Interestingly, despite the 0-week treatment having similar soil water conditions and high groundcover at sowing, it clearly resulted in lower seedling density (Fig. 56a).

Plant counts were also assessed 4-weeks after the Group 1 herbicide. This was to determine whether the herbicide had an adverse impact on desmanthus seedling density. For the main fallow treatments (i.e., 16-week, and 8-week fallow), seedling density marginally increased. This increase could indicate further emergence or seedlings increasing in size to be more visible, which was most discernible in the 16-week treatment (Fig. 56d,e,f). Application of the Group 1 herbicide had no discernible effect on the absolute plant density, apart from the 0-week minus Group 1, where density declined in rows 8 and 12 (Fig. 56b,e).

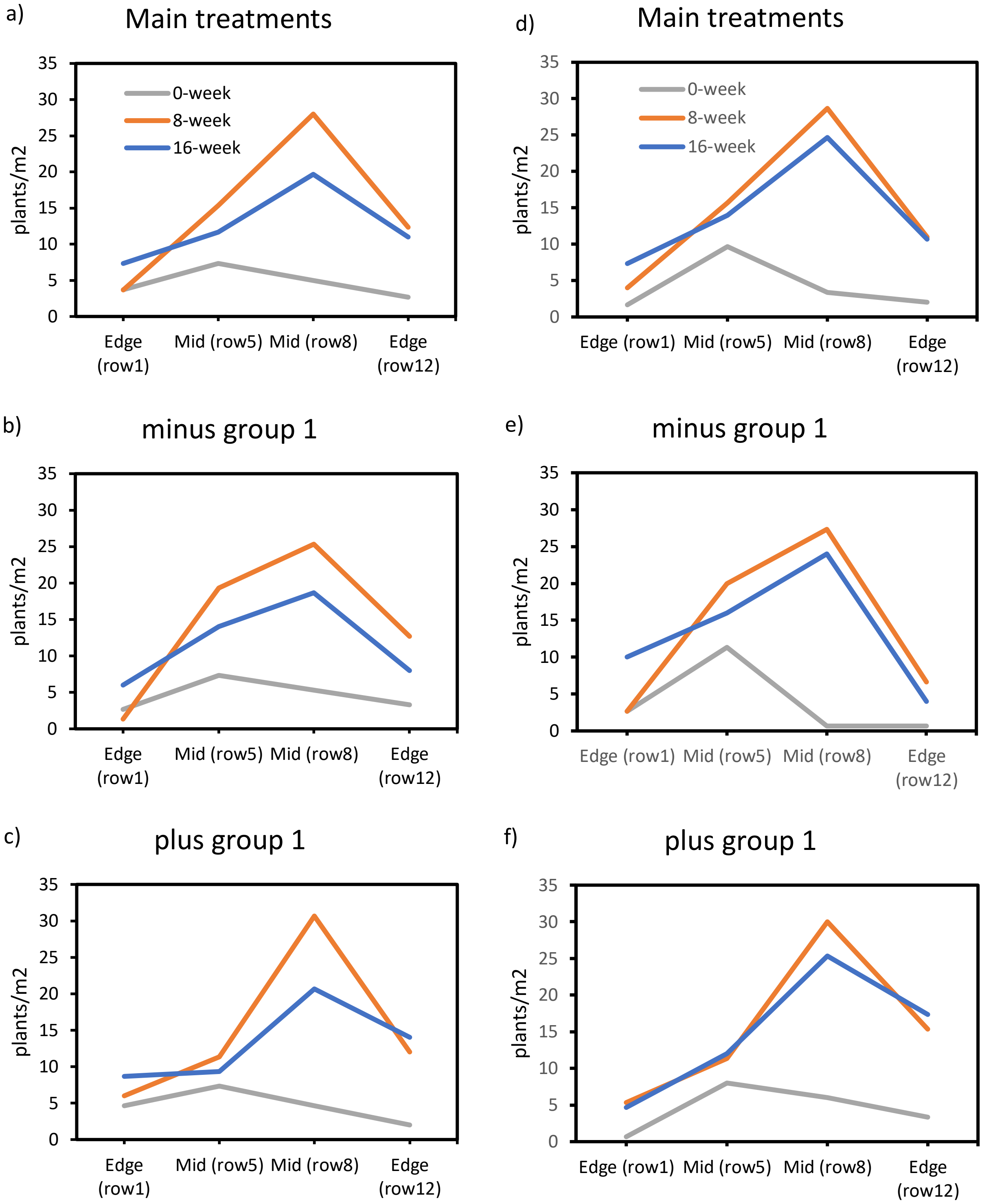


Fig. 56. Plant density (plants/m^2) of desmanthus cv. Marc after emergence (a-c) and post-application of Group 1 herbicide (d-f) for the main and sub plot treatments.

Peak standing dry matter and desmanthus phenological development

By the end of the growing season, the peak standing dry matter data demonstrated the effect of the primary fallow length treatments and their interaction with the Group 1 herbicide. The 0-week treatment resulted in no desmanthus, regardless of the Group 1 herbicide application (Fig. 57). Maximum total herbage mass (perennial grass + desmanthus + weeds) occurred in the 8-week fallow minus Group 1 herbicide treatment. Similar to the initial experiment, the tropical grass dominated the herbage mass, with desmanthus contributing only 158 kg DM/ha.

Desmanthus herbage mass was highest in the 16-week treatment plus Group 1 herbicide (629 kg DM/ha, Fig. 57). The second highest mass of desmanthus occurred in the 8-week treatment plus Group 1 (420 kg DM/ha). These values are 3 and 2 times greater than the herbage mass achieved for cv. Marc in the initial summer legume experiment respectively (200 kg DM/ha).

While desmanthus dry matter was only modest, the impact of the Group 1 herbicide on the tropical grass herbage mass was stark. The Group 1 herbicide reduced tropical grass herbage mass from 1700 to 680 and 2200 to 630 kg DM/ha in the 16-week and 8-week treatments, respectively (Fig. 57). Reducing the grass competition had a beneficial outcome for the desmanthus growth and phenological development.

At the end of the growing season desmanthus vigour, the number of stems and seed pod density were less with a shorter fallow period (Fig. 58). Further, the Group 1 herbicide improved each parameter for the 16- and 8-week fallow treatments, offering evidence of the benefit of the herbicide application. Desmanthus plants in the 16-week plus Group 1 treatment produced the most stems with more mature seed pods before the onset of frosts (Fig. 58). Plant density will be reassessed in summer 2022-23 to determine desmanthus persistence and/or regeneration from the seed set.

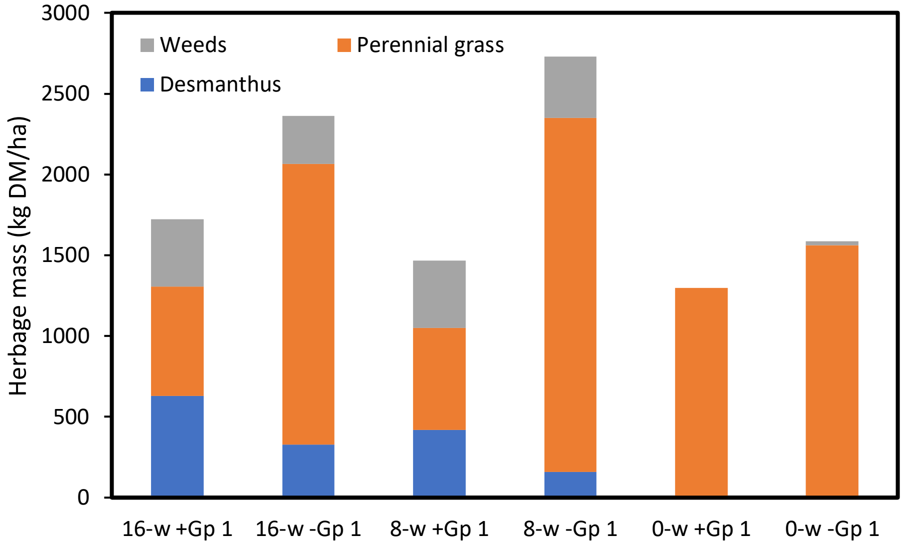


Fig. 57. Desmanthus establishment peak standing dry matter (kg DM/ha) in the three fallow treatments (16-w, 8-w, and 0-w) and Group 1 herbicide treatments, plus Group 1 (+Gp 1), and minus Group 1 (-Gp 1).

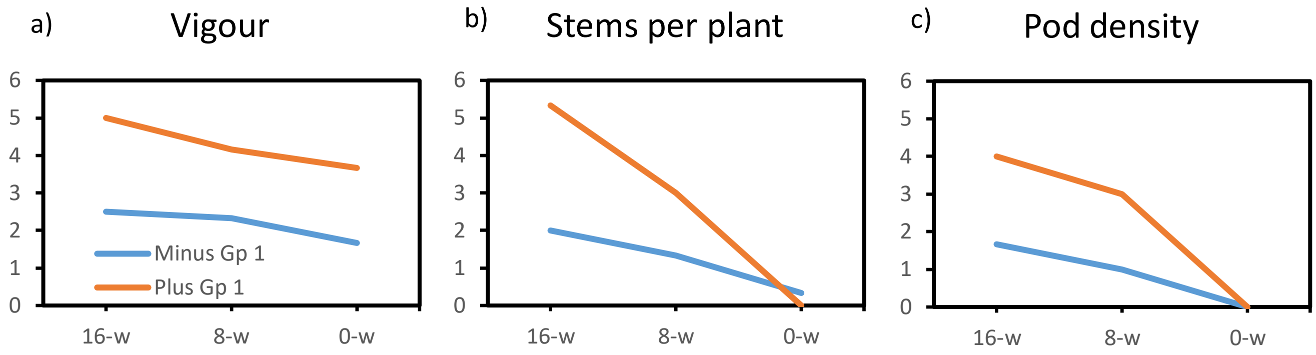


Fig. 58. The effect of plus and minus Group 1 herbicide on desmanthus vigour, number of stems per plant and pod density at end of growing season for main treatments.

4.7 Proportion of digit grass and lucerne in mixes to optimise dry matter, water productivity and nitrogen fixation

5.15.1 Seasonal conditions

Conditions for the first half of the experiment were dry and hot, while that for the latter half were wet and mild. The experiment experienced challenging and variable growing conditions immediately after establishment. Rainfall at the site for the initial 12-months was just 334 mm, equivalent to a 1st percentile. Temperatures were also largely above average. In stark contrast, rainfall totals for 2020 and 2021 were 926 and 947 mm, respectively (90th and 94th percentiles) and temperatures were largely below average, apart from spring 2020 (Fig. 59).

The timing and amounts of rainfall strongly influenced the growth response of each species in these pasture mixtures. The abrupt change in growing conditions provided a distinct contrast and so a basis for comparing the treatments in dry versus wet growing conditions (2018-19 and 2019-20 v. 2020-21 and 2021-22). The differences in growing conditions between these two groups of years is illustrated by comparing GDD (Fig. 59c). Cumulative GDD values for the 2018-19 and 2019-20 seasons (mean of 1276°C) were 1.5 times higher than those in the latter seasons of 2020-21 and 2021-22 (mean of 810°C).

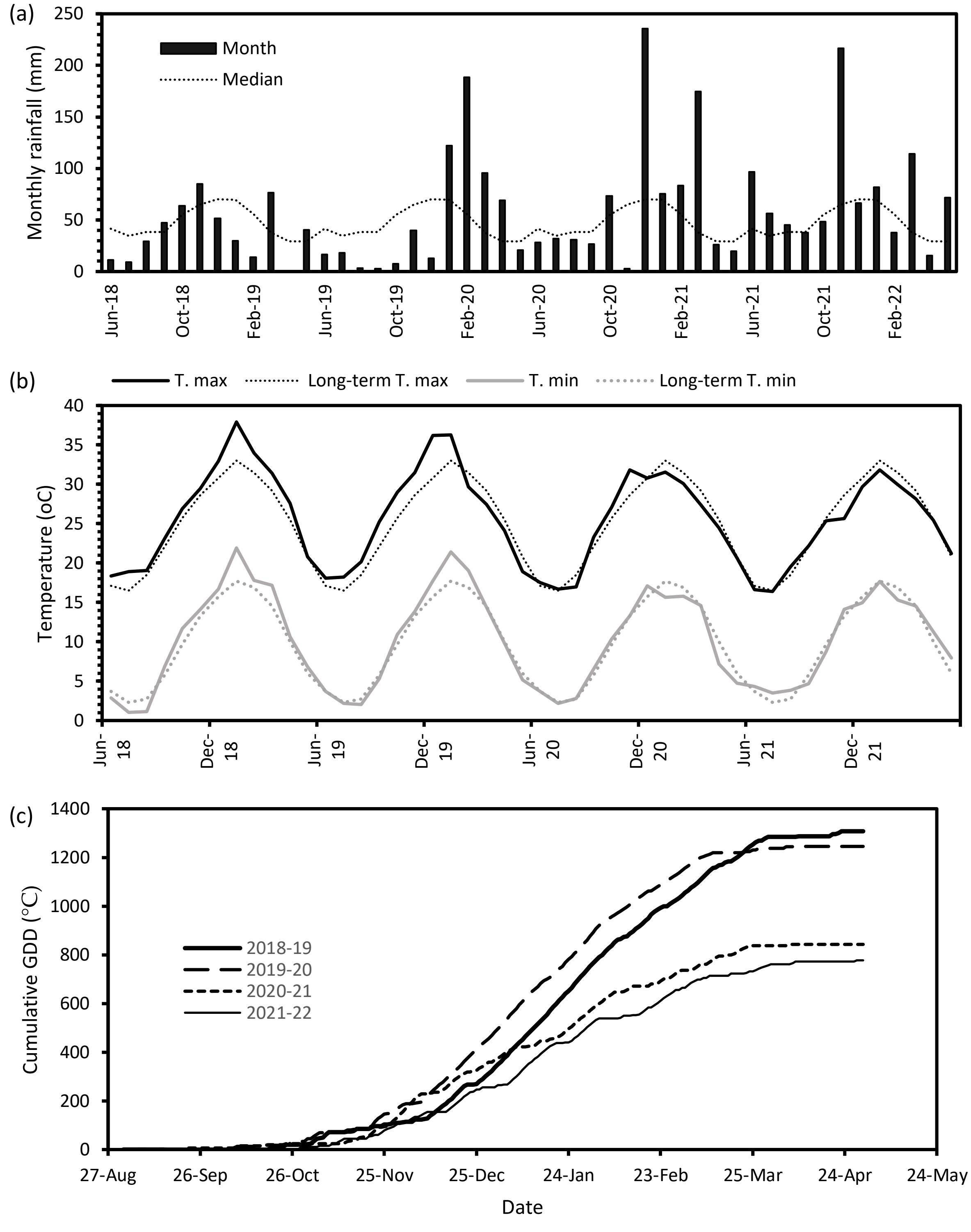


Fig. 59. a) Monthly total rainfall (mm, bars), b) site average maximum and minimum monthly temperatures (°C) compared with the long-term mean monthly values for Tamworth Airport automatic weather station, and c) cumulative growing degree days (°C) for each growing season (1 September to 30 April).

5.15.2 Soil water content

Trend through time

The total profile stored soil water trend was characterised by a strong drawdown from the start of the experiment in November 2018 to January 2020. This is typical of an establishing pasture, but the speed and extent reflected the prevailing hot and dry weather conditions (Fig. 60). Treatments with a higher proportion of digit grass led to lower total stored soil water and by January 2020, L0 was the driest and L100 the wettest (Fig. 60). Generally, all treatments followed a similar overall pattern, with drawdown occurring in the growing season, and some refill occurring in the cooler months, subject to rainfall.

Interestingly, L0 (pure digit grass) showed the strongest drawdown of total water to January 2020, becoming the driest of the treatments while L100 (pure lucerne) was the wettest. The mixes were intermediate and generally ranked as those with a higher proportion of lucerne have the wettest soil. However, with the onset of rainfall in January 2020, L0 became the wettest treatment, and by April 2020 remained the wettest treatment for the remainder of the experiment.

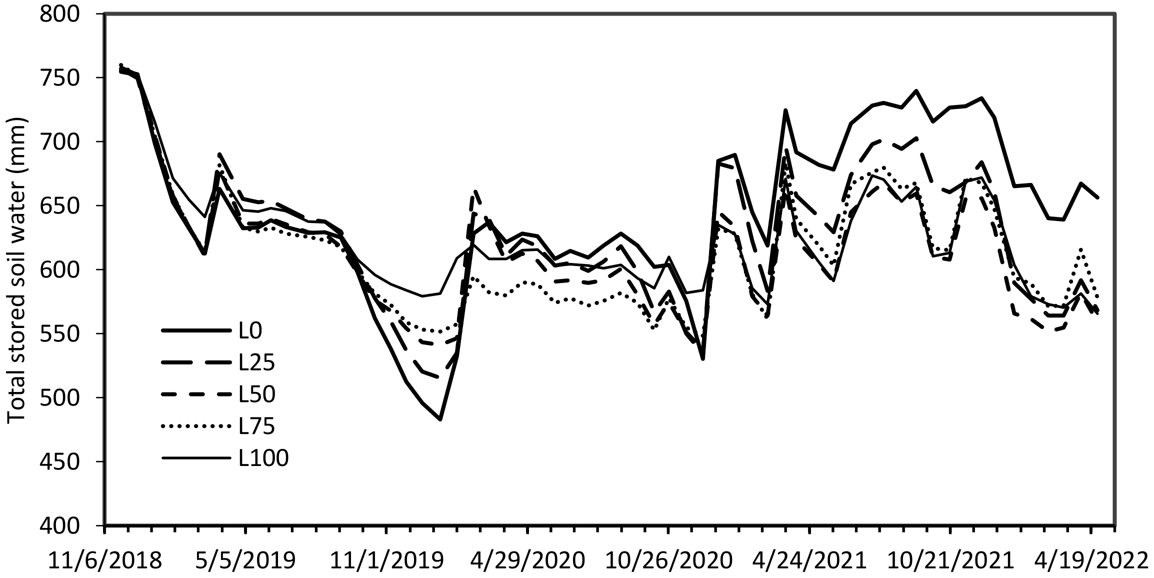


Fig. 60. Total profile (0.1-1.9 m) stored soil water (mm) from November 2018 to May 2022.

Extractions and rooting depth

Lucerne (L100), in all years, extracted less soil water than the other treatments (Table 84). The maximum difference between lucerne's extraction and the other treatments was 97 mm compared with digit grass (L0) in 2019-20 (Table 84). The middle profile (70–130 cm) was perhaps the zone where the greatest differences occurred. Maximum extraction occurred in the mixtures, with L25 showing the highest levels in 2 of the 4 years (113 and 139 mm in 2019-20 and 2021-22, respectively), and was equal with L75 in 2018-19 (145 v. 146 mm, Table 84).

Lucerne (L100) achieved a maximum rooting depth of 1.4 m in 2018-19, while all other treatments achieved their maximum of 1.8 m in 2019-20. The rooting depth for lucerne (L100) was less than for the other treatments in each subsequent year.

Table 84. Maximum soil water extraction (mm) in each growing season calculated for the total, upper, middle and lower profile zones and maximum rooting depth (m).

	L0	L25	L50	L75	L100
		Total profile (10–190 cm) extraction			
2018-19	-143	-145	-144	-146	-117
2019-20	-140	-113	-75	-64	-43
2020-21	-98	-84	-63	-33	-20
2021-22	-99	-139	-108	-96	-92
		Upper profile (10–70 cm) extraction			
2018-19	-89	-92	-89	-95	-74
2019-20	-63	-45	-28	-26	-19
2020-21	-66	-56	-47	-28	-13
2021-22	-68	-79	-87	-72	-78
		Middle profile (70–130 cm) extraction			
2018-19	-50	-48	-48	-47	-38
2019-20	-50	-37	-24	-20	-10
2020-21	-23	-18	-12	-1	-3
2021-22	-28	-53	-22	-23	-14
		Lower profile (130–190 cm) extraction			
2018-19	-4	-4	-7	-4	-5
2019-20	-27	-31	-23	-19	-14
2020-21	-9	-10	-4	-5	-4
2021-22	-3	-7	2	0	1
		Rooting depth (m)			
2018-19	1.4	1.4	1.4	1.4	1.4
2019-20	1.8	1.8	1.8	1.8	0.4
2020-21	0.8	1.2	1	0.8	0.6
2021-22	1	1.4	1	1	0.8

Refill

Soil water replenishment of these pasture species typically occurs in the cool season when growth rates and potential evapotranspiration are low. Differences in profile refill were not apparent at first glance (Table 85). However, several important observations can be made that reflect the process of soil water movement under these pastures.

Firstly, more rainwater tended to infiltrate to deeper soil layers (i.e., 70–130 cm, and 130–190 cm) as the proportion of digit grass in the pasture increased (i.e., L0, L25 and L50, Table 85). For pure lucerne (L100), we recorded little or no replenishment in these deeper layers compared with all treatments containing ≥50% digit grass.

Secondly, for substantial rainfall events, particularly coming out of dry times, treatments with increasing digit grass had higher refill efficiency (e.g., 2020, Table 85). This was likely due to the higher levels of ground cover provided by each plant of digit grass. As digit grass plants mature, they develop large spreading crowns, resulting in high plant frequency and ground cover. For plots dominated by lucerne, plant frequency and ground cover were lower, likely reducing rainfall capture, infiltration and storage.

Table 85. Soil profile refill (mm) in each non-growing season calculated for the total, upper, middle and lower profile zones, together with rainfall (mm) and rainfall refill efficiencies (%).

	L0	L25	L50	L75	L100
		Total profile (10–190 cm) refill			
2019	51	65#	68	68	35
2020	144	126	121	41	36
2021	61	73	69	64	74
		Upper profile (10–70 cm) refill			
2019	40	52	44	49	28
2020	70	78	86	43	34
2021	29	40	54	50	63
		Middle profile (70–130 cm) refill			
2019	13	16	24	21	7
2020	55	28	34	0	2
2021	14	31	16	15	12
		Lower profile (130–190 cm) refill			
2019	-2	-3	0	-1	-1
2020	19	20	1	-1	0
2021	18	3	-1	-1	-1
		Rainfall (mm)			
2019	70	70	70	70	70
2020	237	237	237	237	237
2021	211	211	211	211	211
		Rainfall refill efficiency (%)			
2019	72	93	96	97	49
2020	61	53	51	17	15
2021	29	35	33	30	35

only replicate 1 and 2 plot values were used as replicate 3 showed excessive soil movement.

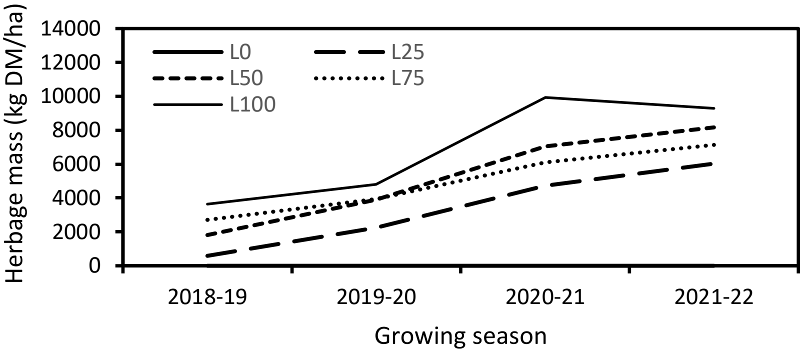
5.15.3 Agronomy

Annual herbage mass production

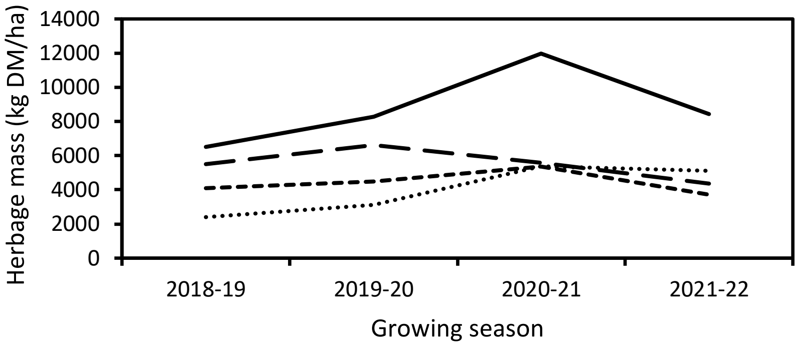
Total annual (July–June) herbage production increased year on year for the first three growing seasons (2018-19 to 2020-21) for all treatments (Fig. 61). Across those three seasons L100 had the lowest value in the initial year of 4.8 t DM/ha, while L50 had the highest value in the third year of 12.4 t DM/ha. Production of lucerne in each treatment increased year on year, apart from L100, which declined in the final year. This is typical of lucerne, which displays compensatory growth even though density declines. The productivity of digit grass, however, was mixed. The all-digit grass treatment, L0, increased for the first three years, then substantially declined in the final year from 12.0 to 8.4 t DM/ha. For the mixtures, digit grass production peaked in the second (2019-20, L25) or third year (2020-21, L50 and L75) then declined. The most consistent production came from L50, with production from the digit grass being stable and lucerne increasing.

Interestingly, in the third year (2020-21), digit grass production was virtually identical across the mixtures, regardless of the density of plants (c. 5.4–5.6 t DM/ha for L25–L75), while pure digit grass (L0) produced 12.0 t DM/ha (Fig. 3). This is the season that N fixation studies were completed at the site (Schwenke et al. 2022, Appendix 20) and these annual production figures help put those findings into context. The year-on-year production from digit grass appears to have plateaued after only 2–3 years, regardless of lucerne density.

(a) Lucerne



(b) Digit grass



(c) Lucerne + digit grass

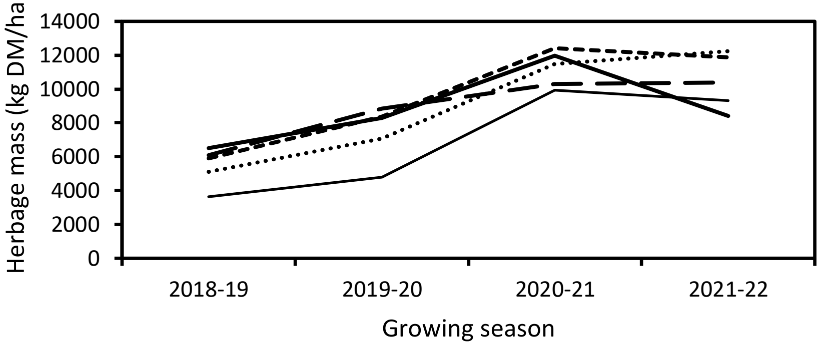


Fig. 61. Annual (July to June) herbage production (kg DM/ha) for the four years of the experiment for a) digit grass, b) lucerne, and c) combined digit grass and lucerne.

Cumulative herbage mass production

The 50% lucerne treatment (L50) achieved the highest total production of 38.6 t DM/ha and the treatment with pure lucerne (L100) the least 27.7 t DM/ha. Typically, at the end of summer in each of the first three years, pure digit grass (L0) had accumulated the highest yield, but by autumn of the fourth year, all the mixtures had a higher cumulative yield.

The first two years (2018-2020) provided approximately a third of the total herbage mass compared with the two thirds in the latter two years (2020-2022). Growing conditions in the first part of the experiment were not favourable due to drought, but they were more suitable for digit grass than lucerne, allowing digit grass to dominate the mixtures. Growing conditions in the latter part of the experiment were more conducive and more suitable for lucerne than digit grass growth, allowing lucerne to dominate the mixtures.

Plant frequency

Plant frequency of digit grass showed an overall increasing trend with values higher at the end of summer (Fig. 62a). Digit grass frequency increased more in treatments with lower proportion of digit. Interestingly, while there were large increases in digit grass frequency, this was not associated with equivalent increase in herbage mass production.

Lucerne plant frequency also increased, but to a lesser degree, reaching a plateau in the middle of the experiment, then declining in the latter seasons (Fig. 62b). The treatment with the smallest proportion of lucerne (L25) remained the most constant, but those with higher proportions declined by up to 10 percentage points. Plant losses due to disease were noticeable in the wet spring-summer of 2021-22. In contrast to digit grass, lucerne herbage production increased across the four years in all treatments despite frequency plateauing and then declining, apart from L100, whose productivity declined in the final year.

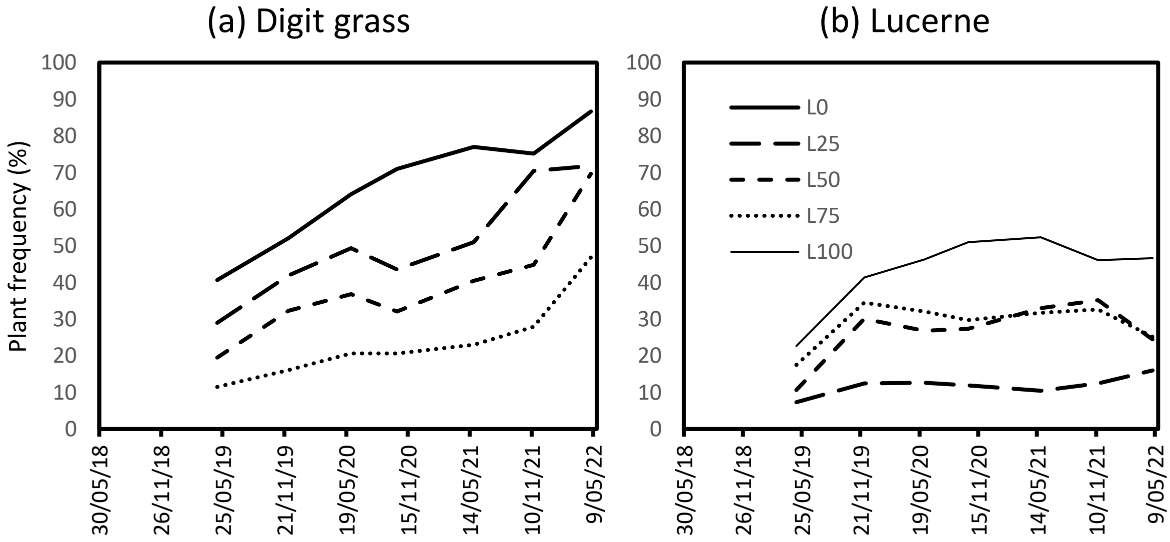


Fig. 62. Plant frequency (%) recorded in autumn and spring for a) digit grass and b) lucerne.

Lucerne persistence

Digit grass plants survived transplanting and persisted for the entire experiment, thereby maintaining the relevant proportion in each treatment. However, all treatments containing lucerne suffered plant losses over time. Greater losses were recorded in the treatments with a higher proportion of lucerne (vis. L75 and L100). During the experiment's latter stages, lucerne persistence in L75 and L100 declined by 40 and 30% of the original population, respectively (Fig. 63). In May 2022, final densities were 1.75, 3.5, 3.58 and 5.58 plants/m^2, compared with the original 2, 4, 6 and 8 plants/m^2 for L25, L50, L75 and L100 treatments, respectively.

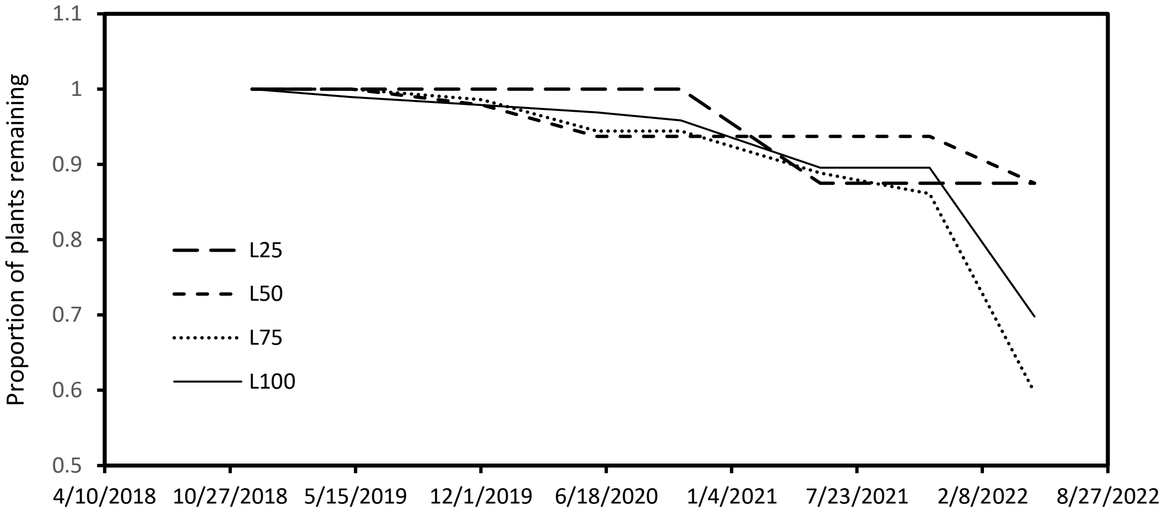


Fig. 63. Proportion of the original lucerne plants remaining through time for treatments containing lucerne.

de Wit replacement series

Optimum proportion of lucerne in a digit grass mix changed from the initial 2 years to the latter 2 years. In the earlier years L25 and L0 yielded similar (average 11.6 t DM/ha), and nearly doubled production of L100 at 6.2 t DM/ha (Fig. 64). In the latter two years, L50 and L75 out-yielded L0 (i.e., 27.6 and 26.8 t DM/ha v. 23.9 t DM/ha), producing 25% more than L100 (21.5 t DM/ha). For all growing seasons combined, productivity of all treatments containing lucerne was similar, L50 modestly out-yielding all other treatments containing grass (i.e., 38.6 v. 35.2-35.9 t DM/ha), but strongly out-yielded L100 (27.7 t DM/ha)(Fig. 64).

This finding reflects the strong growth of digit grass commonly observed during the initial years, and lucerne's subsequent comparatively strong growth in the latter years when growing conditions suited lucerne better. In the initial years of a digit grass pasture, available soil water and nitrate tends to be high, effectively supplementing our additions of urea fertiliser. Once those soil reserves are depleted, the pasture becomes dependent upon fertiliser inputs. The data from 2020-22 suggests that 25% lucerne perhaps maintained the status quo for total herbage production, but higher proportions of lucerne were required to elevate production.

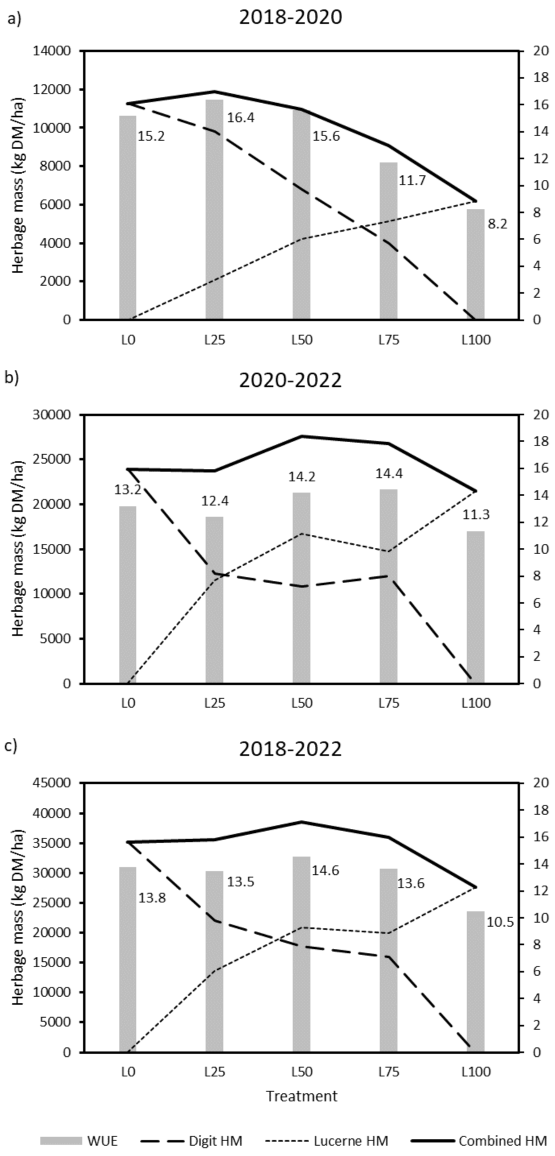


Fig. 64. Total combined, digit grass and lucerne herbage mass (kg DM/ha) for a) the first two growing seasons, b) the latter two growing seasons, and c) the entire experiment, together with rainwater productivity expressed as water use efficiency (WUE, kg DM/ha/mm).

5.15.4 Water productivity

Contrasting seasons experienced in the experiment coincided with a flip among the treatments in their water productivity. Total water use increased in all treatments year on year (from 367 to 844 mm, Table 86). However, annual herbage production also increased in most treatments year on year, but not in L0 and L50, which declined in the final year (Table 86). In the earlier hotter and drier period (2019-20), treatments dominated by digit grass had higher water productivity (14, 13.2 and 11 kg DM/ha/mm for L25, L50 and L75, respectively, Table 86). In contrast, during the mild and wetter period (2021-22), treatments dominated by lucerne had higher water productivity (11.9, 14.6 and 14.9 kg DM/ha/mm for L25, L50 and L75, respectively, Table 86). Overall, L50 achieved the highest water productivity (2018-22; 14.6 kg DM/ha/mm), perhaps reflecting the equal densities of each species and their relative contributions in the two contrasting periods. Of note, is that L0 achieved the highest annual water productivity value (2018-19; 17.7 kg DM/ha/mm) and L100 the lowest (2019-20; 7.6 kg DM/ha/mm). The difference between these treatments was also reflected in the overall WUE with L0 being higher than L100 (13.8 v. 10.5 kg DM/ha/mm, Table 86).

Table 86. Herbage production (kg DM/ha) of grass, legume, and total for each year, with rainfall (mm), total evapotranspiration (ET_a, mm) and water productivity (kg DM/ha/mm).

Component/year	L0	L25	L50	L75	L100
		2018-19 herbage production (kg DM/ha)			
Grass	6510	5507	4090	2400	0
Legume	0	586	1814	2710	3638
Total	6510	6093	5904	5110	3638
		2019-20 herbage production (kg DM/ha)			
Grass	8289	6616	4496	3126	0
Legume	0	2230	3887	3942	4793
Total	8289	8847	8383	7067	4793
		2020-21 herbage production (kg DM/ha)			
Grass	11973	5576	5359	5375	0
Legume	0	4716	7056	6118	9934
Total	11973	10293	12415	11493	9934
		2021-22 herbage production (kg DM/ha)			
Grass	8416	4361	3715	5106	0
Legume	0	6028	8166	7135	9309
Total	8416	10389	11881	12240	9309
		Rainfall (mm)			
2018-19	250	250	250	250	250
2019-20	584	584	584	584	584
2020-21	809	809	809	809	809
2021-22	811	811	811	811	811
		Total ET_a (mm)			
2018-19	367	353	365	377	360
2019-20	614	634	633	643	628
2020-21	739	782	809	779	820
2021-22	833	872	843	836	837
		Water productivity (kg DM/ha/mm)			
2018-19	17.7	17.3	16.2	13.6	10.1
2019-20	13.5	14.0	13.2	11.0	7.6
2020-21	16.2	13.2	15.4	14.7	12.1
2021-22	10.1	11.9	14.1	14.6	11.1
		Total production (2018-2022)			
Total HM	35188	35621	38583	35911	27674
Total ET_a	2552	2641	2649	2634	2646
Total WUE	13.8	13.5	14.6	13.6	10.5

5.15.5 Nitrogen fixation (2-20-21 growing season)

Soil mineral N

Results of full profile soil cores collected at the beginning of the 2020–21 pasture-growing season (Fig. 65a) showed generally low stocks of mineral N in the soil, with an average total mineral N in the profile (0–190 cm) of only 38 kg N/ha, with no statistical difference between pasture mix treatments. This was despite an apparent bulge in mineral N between 50 and 90 cm depth in the L0 treatment, which may indicate downward movement of underutilised fertiliser N applied in previous droughted seasons. There was also higher mineral N 30–70 cm in one of the two outside-experimental digit grass sampling areas, but not in the other three outside plots. Sampling at the end of the season in

May 2021 found even lower stocks of soil mineral N with profile totals averaging just 26 kg N/ha (Fig. 65b).

Soil total N and C

Total soil N and C were analysed on composite samples of the L0 treatment and the grass sampling areas outside of the experimental area. There was no difference in soil total N at any point in the soil profile between the two sampled areas (Fig. 66a). Similarly, there was little difference between the two composite sample sets in terms of soil organic C (Fig. 66c), except perhaps in the mid-profile section from 60–100 cm.

Mass spectrometer analysis of the same samples for the natural abundance of ^{15}N and ^{13}C isotopes in the soil showed a typical δ^{15}N profile for the Tamworth region of around 6 (Fig. 66b), except for two much lower δ^{15}N results at the 100 and 160 cm depths. However, these anomalies are likely an error in the laboratory analysis of those two samples which retesting could confirm. The δ^{13}C profile (Fig. 66d) indicated a mixed history of the organic matter accretion within this profile. Carbon at depths below 40 cm appears dominated by contributions from C_4 plant species (e.g., pre-cultivation native vegetation), and the C above 40 cm depth dominated by C-inputs from C_3 species, particularly at the soil surface, which tend to have more negative δ^{13}C signatures.

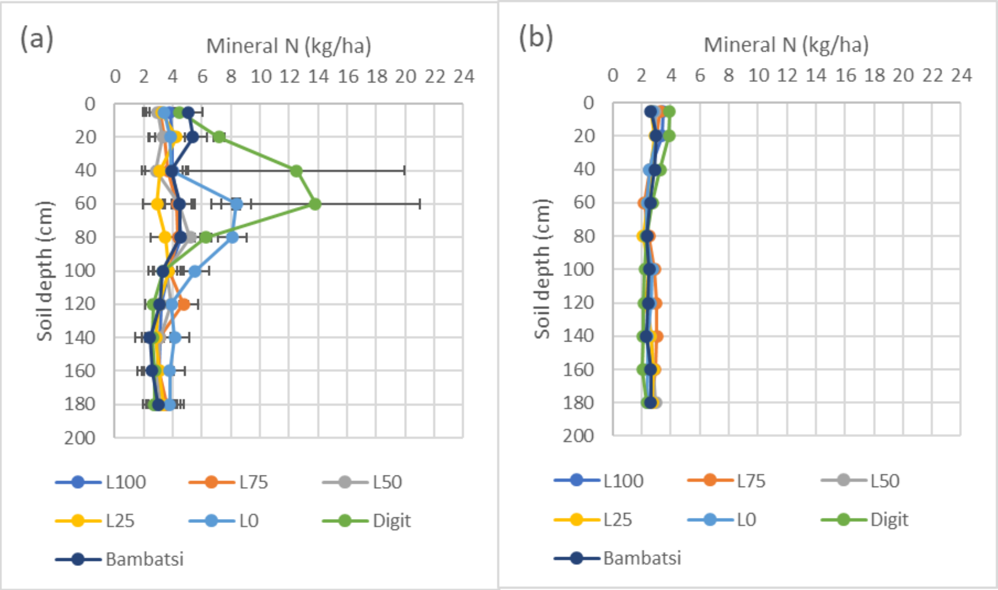


Fig. 65. Soil mineral N (kg N/ha) at (a) the beginning and (b) the end of the 2020–21 pasture growing season. Data are means of three (in experiment; L100-L0) or two (outside experiment; digit grass and Bambatsi panic) replicate plots, with bars in (a) showing the standard error.

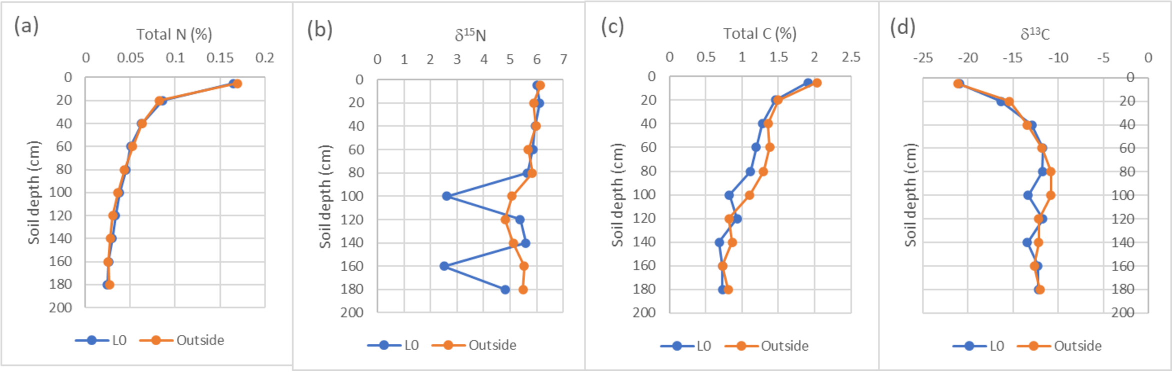


Fig. 66. Soil (a) total N, (b) δ^{15}N, (c) total C and (d) δ^{13}C in composite samples from the L0 (D100_L0) plots and the four outside-experiment grass-sampling areas.

Plant biomass

Dry matter production during the 2020-21 growing season (Fig. 67a) showed several distinct periods of high growth interspersed with periods of lower productivity and by the different growing seasons of the constituent species. Samples cut at the end of December 2020 showed the greatest production of digit grass, particularly in the pure digit grass pasture (L0) that had received fertiliser N since the previous sampling time. The mixed swards also showed a significant boost in digit production even without fertiliser N, which during the same period appeared to be to the detriment of lucerne production—lucerne biomass was stable or declined in mixed pastures but increased in the pure lucerne (L100). There was a second peak in digit grass production between the January and March sampling times. After March, the digit grass production rapidly declined to nil by the May sampling due to frosts, whereas lucerne production peaked in April and continued growth throughout autumn into May.

Cumulative total dry matter across the whole study season ranged from 9.3 t/ha in L100 up to 12.0 t/ha in the N-fertilised L0 treatment, with the mixed pasture treatments in-between. Of the mixed-species treatments, the L50 treatment had the greatest cumulative biomass, 11.6 t/ha. In terms of water-use, the mixed species treatments tended to be more like the pure lucerne than the pure digit grass sward, particularly after December, although the L25 treatment was more similar to the digit grass at this stage (wetter after rain), perhaps indicating greater rainfall infiltration where there was greater ground cover provided by the digit grass.

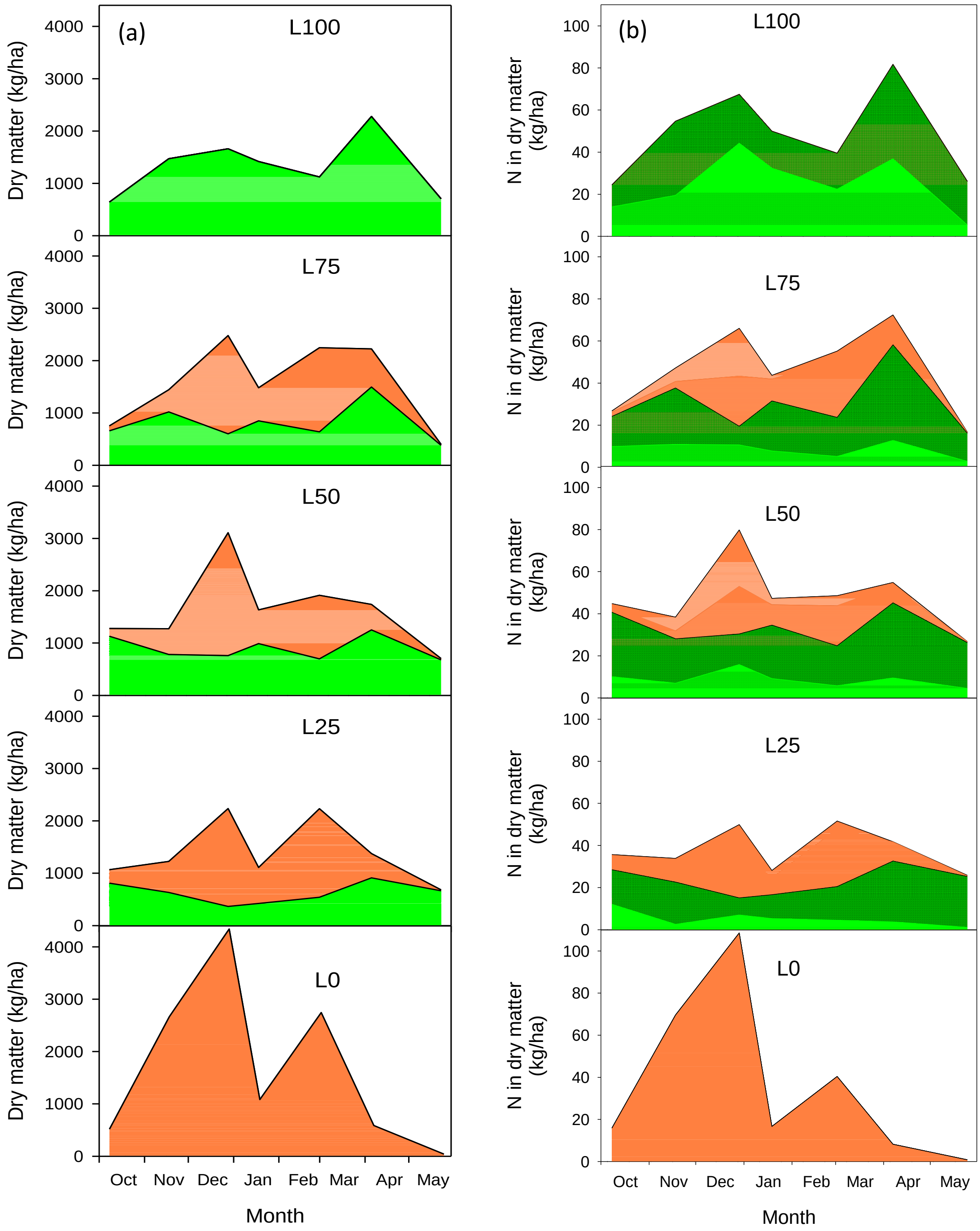


Fig. 67. Combined-species biomass (a) dry matter and (b) N content for the five pasture treatments measured throughout the 2020–21 growing season. The lucerne component is shown in green, digit grass in brown. In (b), the green hatched area depicts the lucerne N that was derived from the atmosphere by N_2 fixation; the unhatched green area shows N derived from the soil. N fertiliser was applied to L0 only (100 kg N/ha on 23 October 2020).

Plant N concentration and biomass N content

Throughout the study, the concentration of N in aboveground lucerne biomass was remarkably constant, averaging 3.7% across all treatments and all sampling times. Only in December was there a slight increase in average N concentration up to 3.9%. There was no difference in lucerne N concentration according to pasture mix treatment at any measurement time.

In contrast, the N concentration in digit grass samples varied between treatments several different times during the study. Initially, all treatments were similar at 2.8%N, then with the fertiliser addition, the L0 treatment remained at 2.6% while the L25 declined to 1.9% and the other treatments were intermediate (2.1–2.2%N). There were no further treatment differences December–April, when the L0 declined to 1.4% while all treatments containing lucerne were 2.0%N.

The N content of the different pastures is shown in Fig. 67b. The patterns of N in biomass were similar to those of the total biomass weight (Fig. 67a) although the contribution of lucerne to pasture N content tended to be proportionally greater than its contribution to the overall biomass weight, with this difference becoming more pronounced in the later months of the study. This was due to its higher N concentration. The cumulative total N collected throughout the season was significantly lower in the nil- and low-legume pastures (260 and 267 kg N/ha in L0 and L25, respectively) than in those with 50% or greater proportion of lucerne (341, 328 and 344 kg N/ha in L50, L75 and L100, respectively).

The $\delta^{15}N$ of the digit grass samples from the L0 treatment were similar to those in the digit grass from outside the experimental area in October. However, while the outside-area $\delta^{15}N$ rose to 6.8 in November due to the uptake of newly mineralised N from the soil organic matter, the $\delta^{15}N$ of the L0 dropped to 0.2 in response to the addition of N fertiliser. The influence of the fertiliser on $\delta^{15}N$ value declined in the following months until April when the unfertilised and fertilised digit grass again showed the same $\delta^{15}N$ signature.

Legume N_2-fixation

The percentage of N in lucerne dry matter that was sourced from the atmosphere via N_2-fixation, %Ndfa (as opposed to coming from soil mineral N) ranged 34–95% across all treatments. This proportion was affected by the availability of soil mineral N, which was, in turn, affected by environmental conditions of moisture and temperature that drive the mineralisation of soil organic matter. The more mineral N present in the soil, the less of the legume's N was fixed by rhizobia. The pure lucerne stand (L100) had the lowest %Ndfa throughout the study—lower than lucerne in mixed pastures in most months. This is because the pure lucerne had no competition for the available soil mineral N, whereas in the mixed pastures, there was competition with the digit grass for the meagre soil mineral N reserves and newly-mineralised N. There was no statistical difference in %Ndfa of lucerne between the different mixed pasture treatments in any month of the season.

The amount of N in the legume that was derived from the atmosphere (Ndfa) is shown in Fig. 67b. Legume N_2 fixation was fairly consistent throughout the study period with the exception of the December sampling where the contribution of soil mineral N potentially peaked due to recent rainfall and warm temperatures—as shown by the increase in soil N in the pure lucerne treatment at this time, also coinciding with the increases in digit grass N uptake at the same time (Fig. 67b). The total amount of N_2 fixed during the study season averaged 153 kg N/ha, with no statistical difference between pasture mix treatments including L100. This is intriguing given the treatment differences in lucerne plant density and total legume dry matter grown.

The lucerne fixed from 12–36 kg N/t biomass (average of 25 kg N/t), with results from the pure lucerne treatment initially being less than those in the mixed swards (October) and again from January–April.

4.8 Persistence and productivity of leucaena in northern and central NSW

5.16.1 Rainfall

Rainfall at each site over the 10 years has been characterised by highly variable seasonal conditions; fluctuating from extremely dry to extremely wet years. Of particular note across all three sites was 2018–19 which was the worst drought on record in these locations (BOM 2019) followed by wetter than average years in 2020–21 and 2021–22.

The Northern Inland sites (Bingara and Manilla) experienced below average rainfall in 6–7 out of 10 growing seasons (November–April) with rainfall ranging from 16–61% (Bingara) and 11–55% (Manilla) below average (Table 87). At Bingara the three remaining growing seasons were average to 10% above average. At Manilla the remaining growing seasons were 16–47% above the average rainfall. The non-growing season (May–October) rainfall at both sites was below average in 78% (Bingara) and 44% (Manilla) of years (Table 87).

The Trangie site experienced below average rainfall in 5 out of 10 growing seasons with rainfall ranging from 15–68% below average (Table 87). The remaining growing seasons were average or 28–74% above average. The non-growing season rainfall was below average in 67% of years (Table 87).

Table 87. Rainfall (mm) received during each leucaena growing season (Grow, November–April) and non-growing season (Non-grow, May–October) from January 2013 to April 2022, at the Bingara, Manilla and Trangie sites. Long-term average (LTA) rainfall data are from Bureau of Meteorology sites Bingara (054004), Manilla (55331) and Trangie (51049).

	Bingara		Manilla		Trangie	
Year	Grow	Non-grow	Grow	Non-grow	Grow	Non-grow
2013[1]	316	211	274	221	90	212
2014	172	99	343	183	237	142
2015	482	252	447	260	271	200
2016	333	411	283	481	289	492
2017	362	259	297	273	235	140
2018	217	110	251	124	122	134
2019	170	46	175	117	167	45
2020	367	242	386	271	355	210
2021	479	356	515	308	464	268
2022	416		566		485	
LTA	*436*	305	386	250	278	217

[1] Growing season rainfall for 2013 was for the period January–April 2013

5.16.2 Leucaena persistence

Despite the dry conditions at the Northern Inland sites plant survival was high >70% (Bingara) and >95% at Manilla (Table 88) from spring 2017 to autumn 2022.

At the Bingara site the four commercial cultivars had similar plant survival (81–85%) and S&D#36 was the least persistent at 71% (Table 88). Although there were no plant losses at the Bingara site, during the drought (2018–19 growing season), a high percentage of plants were rated as being in poor condition. Across all cultivars approximately half of the plants were assessed as having reduced growth, being spindly and generally exhibiting ill-thrift. These poor plants appeared to be random and not cultivar dependent, although cv. Peru did have a higher number of plants in poor condition (approximately 65%). Soil tests were taken at the site to determine whether soil dispersion (sodicity) or pH was contributing to the poor growth. Soil tests were collected adjacent to plants that showed good growth and poor growth. The results indicated that neither sodicity nor pH were an issue and hence concluded not affecting the plant growth. At the Bingara site approximately 250 mm fell over late January and February in 2020, after this rainfall the number of plants assessed as being in a poor condition decreased to less than 5% in autumn 2020.

At the Manilla site there were no plant losses of cvv. Peru, Tarramba and Wondergraze over the course of the whole experimental period (10 years). The experimental line S&D#36 declined by 2% over the first winter (2013) but remained steady for the remainder of the experiment. Cultivar Cunningham declined by 2% over the first winter (2013) of the experiment and declined a further 2% over the winter of 2015, but no there were no further plant losses over the remaining years and persistence was high (96%) at the end of the experiment (Table 88).

At the Trangie site, persistence in spring 2017 was lower than the two Northern Inland NSW sites, as initial plant numbers were lower due to poor establishment; persistence recorded as 50 (S&D#36)–70% (Tarramba) in late January 2014 (Boschma *et al*. 2018). With the exception of cv. Cunningham where there were no plant losses there were small declines (1–2%) for cvv. Peru, Tarramba, Wondergraze and the experimental line S&D#36 (Table 88).

Table 88. Persistence (measured as % surviving plants) for each cultivar/line for the three experimental sites from Spring 2017 to Autumn 2022.

Cultivar/line	Bingara		Manilla		Trangie	
	Spring 2017	Autumn 2022	Spring 2017	Autumn 2022	Spring 2017	Autumn 2022
Cunningham	83	83	96	96	56	56
Peru	85	85	100	100	54	50
Tarramba	85	85	100	100	65	63
Wondergraze	81	81	100	100	50	48
S&D#36	71	71	98	98	25	23
Av	*81*	*81*	*99*	*99*	*50*	*48*

5.16.3 Leucaena edible herbage production

Over the 10 years of the experiment (2013–2022) total herbage mass was highest at Bingara (52.2 t DM/ha), followed by Manilla and Trangie (34.1 and 17.7 t DM/ha respectively) (Table 89). Cultivar/line production varied at each site, but over the three sites cvv. Wondergraze and Cunningham produced the highest average herbage mass (42.5 and 37.6 t DM/ha respectively). When cultivar persistence and herbage production were plotted for each site (Fig. 68), the highest ranked cultivar for both parameters at Bingara was Wondergraze. At Manilla cv. Cunningham and Wondergraze were the highest ranked for production and comparable to the other cvv. for persistence. At Trangie cv. Wondergraze had the highest production, but not persistence.

Although total production over the experimental period (2013–22) was highest at the Bingara site, growing season herbage production at this site was the most variable, ranging from 1.5–10.8 t DM/ha (average of cultivars) and was closely related to the rainfall received at the site. At Bingara herbage mass was highest in 2016–17 and 2020–22, the wetter years, and lowest during drought years of 2018–2020 (Fig. 69a).

Table 89. Total edible herbage production (t DM/ha) from 2013 to 2022 of the five leucaena cultivars/line at the three experimental sites in Northern Inland and Central West NSW.

	Total herbage production (t DM/ha)		
Cultivar/line	Bingara	Manilla	Trangie
Cunningham	55.9	39.9	17.0
Peru	37.6	31.7	17.6
S&D#36	48.9	29.0	15.6
Tarramba	50.8	31.7	16.9
Wondergraze	67.9	38.2	21.5
Av	*52.2*	*34.1*	*17.7*

Over the experimental period at Manilla herbage mass production of leucaena averaged (across cultivars) 3.8 t DM/ha per growing season, ranging from 1.0–6.1 t DM/ha, reflecting the rainfall received. Herbage production was higher than Bingara during the drought years (2018–2020), but lower in the wetter years (2016–17; 2020–22) (Fig. 69b).

At Trangie herbage mass production of leucaena was the lowest of the three experiments. Production averaged 2.0 t DM/ha per growing season, but was less variable from year to year ranging from 1 t DM/ha (2014–15) to 3.8 t DM/ha (2020–21) (Fig. 69c).

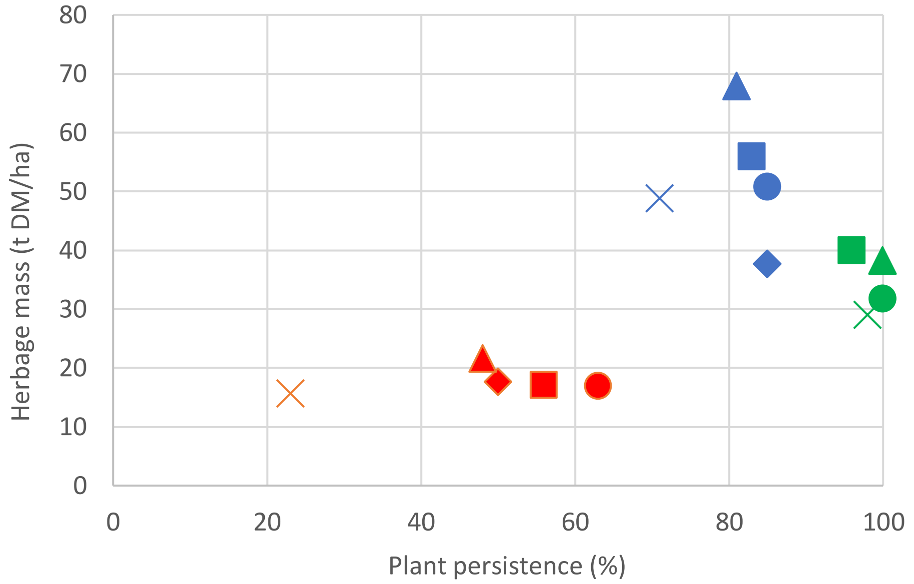


Fig. 68. Plant persistence (%) in autumn 2022 and herbage mass (t DM/ha) of leucaena cultures/line from 2013 to 2022 at Bingara (blue), Manilla (green) and Trangie (red) in Northern Inland and Central West NSW. The cultivars are Cunningham (square), Peru (diamond), S&D#36 (cross), Tarramba (circle) and Wondergraze (triangle). Note Peru for the Manilla site is obscured by Tarramba.

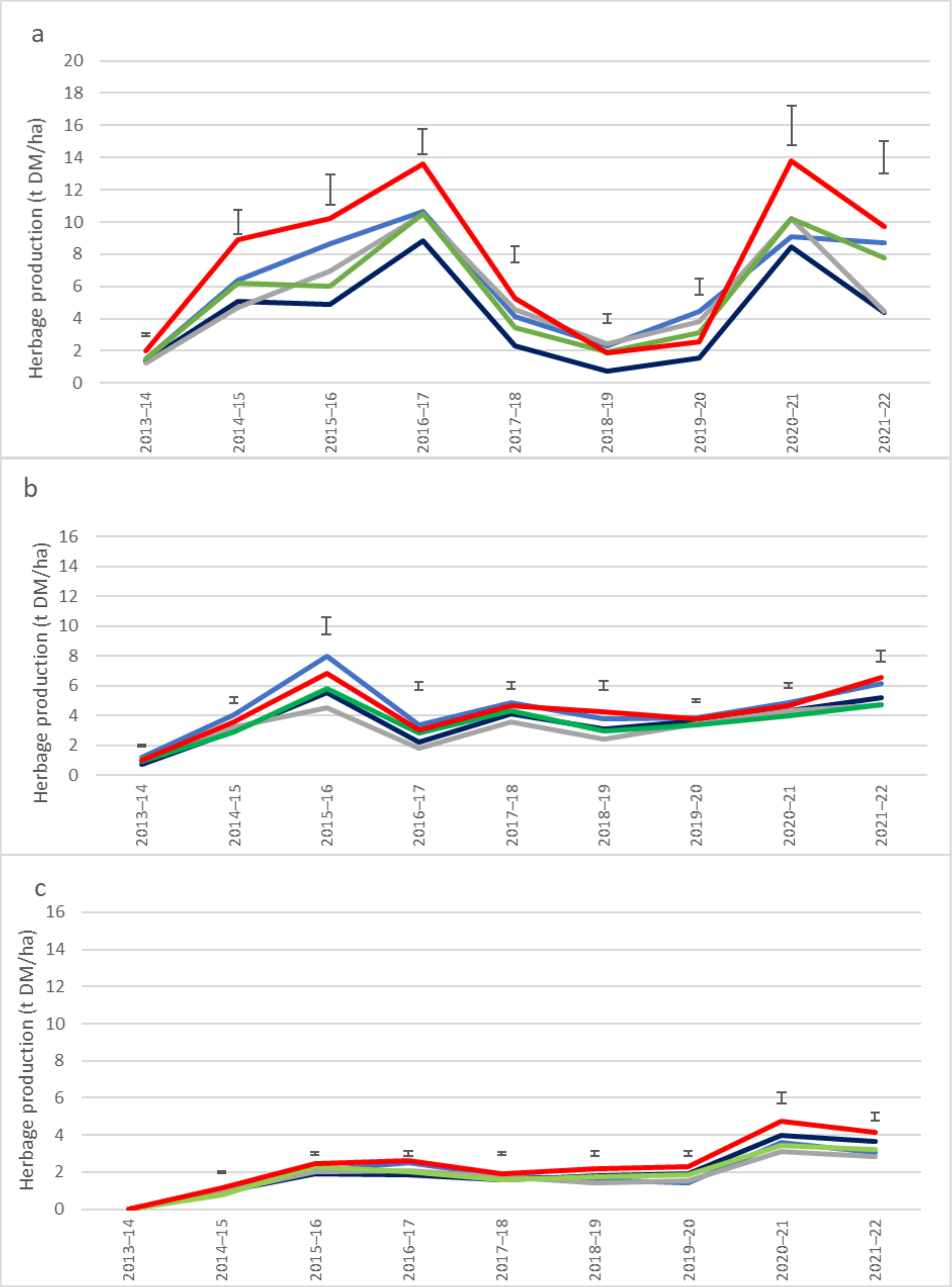


Fig. 69. Yearly leucaena production (t DM/ha) from 2013–14 to 2021–22 of 5 cultivars/lines (Cunningham=light blue, Peru=dark blue, S&D#36=grey, Tarramba=green and Wondergraze=red) for three sites a) Bingara, b) Manilla and c) Trangie. Error bars represent standard errors.

4.9 Herbage and water productivity of lucerne, desmanthus, leucaena and digit grass in pure and mixed and swards

5.17.1 Soil water dynamics

Seasonal rainfall at the site demonstrated distinct periods of above and below average totals (Fig. 70). Totals were well above average for a 6-month period when the experiment commenced (e.g., summer 2014-15 and autumn 2015). In the following 2-years, seasonal rainfall totals from winter 2015 to autumn 2016 were below average. Rainfall was well above average winter 2016–autumn 2017 with total rainfall for the 12-months to end of May 2017 being 940 mm (94th percentile). The final year of the experiment was exceedingly dry, with total rainfall for the 12-months to end of May 2018 being 337 mm (3rd percentile).

The heat maps of soil water content provide a visual representation of soil water dynamics through time and depth (Fig. 71). They show the summer active pasture species had a repeating pattern of the soil profile drying in summer and wetting in winter when they were largely inactive. Soil water contents were lowest in the autumn and highest in the spring.

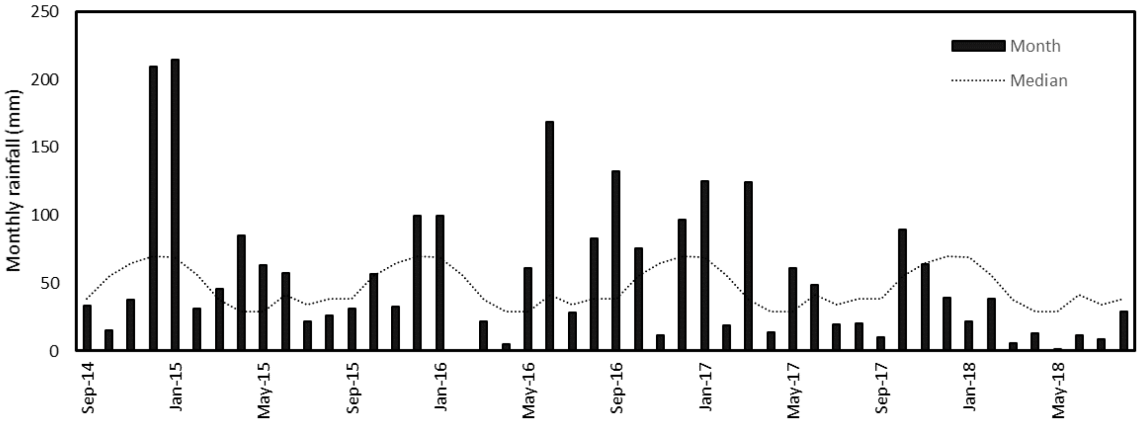


Fig. 70. Monthly site rainfall (mm, solid bars) and long-term (1900-2018) median monthly rainfall at Tamworth airport (dotted line) (Source: Murphy et al. 2022).

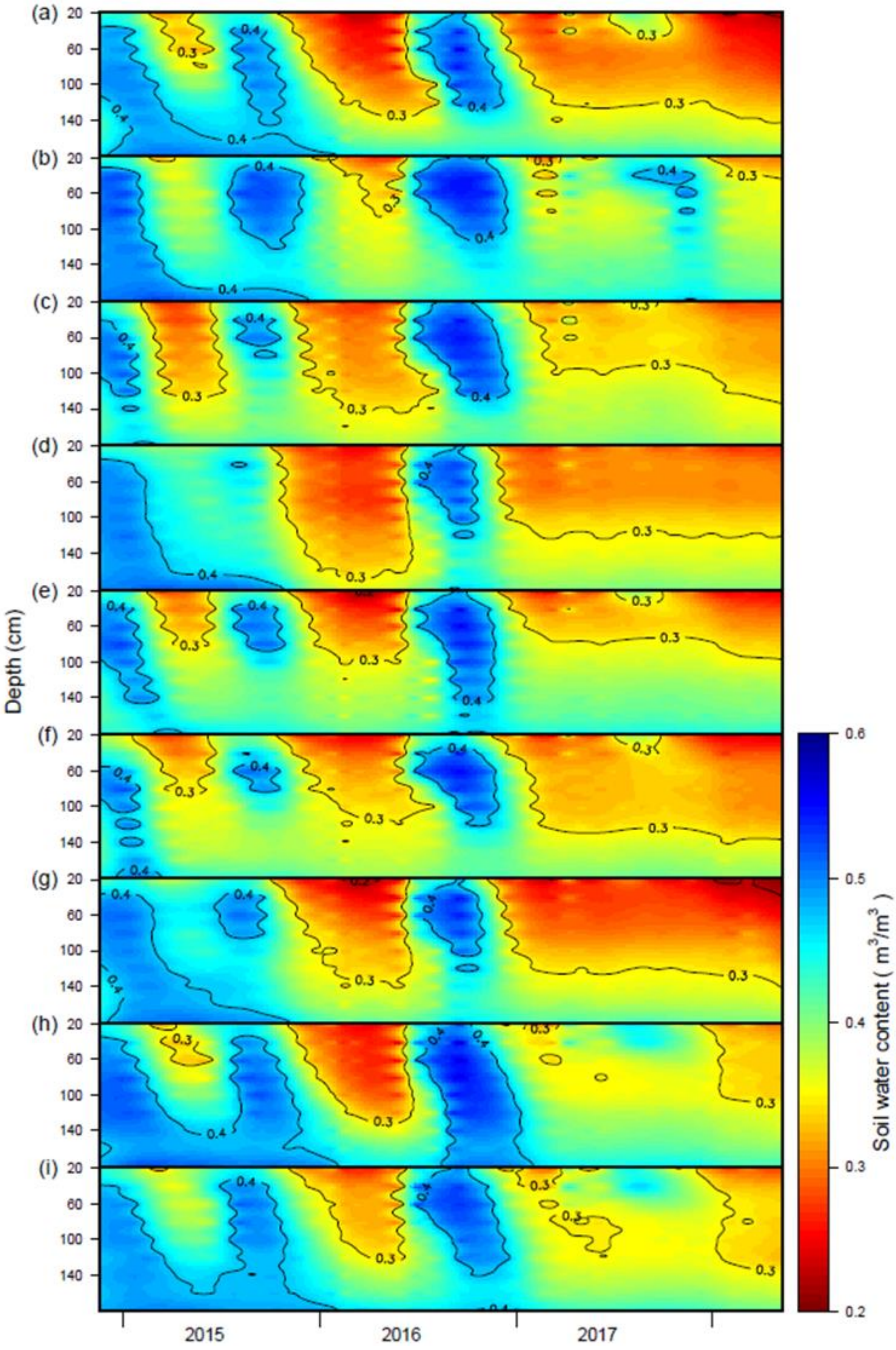


Fig. 71. Patterns of distribution of profile (20-180 cm) soil water content (m³/m³) through time for (a) digit grass, DI (b) leucaena, LE (c) desmanthus, DE (d) lucerne, LU (e) leucaena-digit grass, LE-DI (f) desmanthus-digit grass, DE-DI (g) lucerne-digit grass, LU-DI (h) leucaena-digit grass inter-row, LE-DI IR and (i) leucaena inter-row, LE-IR from November 2014 to May 2018 (Source: Murphy et al. 2022).

5.17.2 MEW and plant root depth

In 2015, DE (191 mm) extracted more soil water than five of the other treatments (LU-DI, LU, LE-IR, LE-DI IR, and DI, 56–113 mm, $P < 0.05$, Table 90). However, in 2016 and 2017, all treatments extracted similar amounts of soil water ($P > 0.05$), with the 2017 mean value (224 mm) being highest of all years. After a closer examination of the data, we found that the residuals were large for a single treatment plot in one replication of different treatments in 2016 and 2017. These large residuals resulted in non-significant differences between the treatments. Mean MEW was lowest in 2018, while LU extracted the least ($P < 0.05$). Soil water extraction and subsequent root depth for 2017 and 2018 are illustrated graphically in Fig. 72.

Plant root depth varied considerably between treatments and between years. All treatments achieved their maximum root depth in either 2015 (1.68–1.80 m) or 2016 (1.56–1.80 m) and expressed their minimum root depth in 2018 (0.20-1.08 m, Table 90). Five treatments (DE, LU, LU-DI, LE-DI, and LE-DI IR) achieved a maximum root depth of 1.80 m, while four (DI, LE, LE-IR and DE-DI) ranged 1.56–1.75 m.

Table 90. Maximum extractable water (MEW, mm) and plant root depth (m) for treatments in each of four growing years. Least significant differences (LSD; P = 0.05) among treatment means for each year is provided where appropriate (Source: Murphy et al. 2022).

Treatment	MEW (mm)				Root depth (m)			
	2015	2016	2017	2018	2015	2016	2017	2018
DI	113	247	249	87	1.30	1.56	1.46	0.81
DE	191	183	218	50	1.80	1.80	1.36	0.20
DE-DI	162	144	217	57	1.75	1.12	1.44	0.62
LU	69	221	239	16	0.40	1.80	1.71	0.20
LU-DI	56	242	257	44	1.24	1.80	1.47	0.44
LE	128	198	175	67	1.68	1.54	1.48	0.80
LE-IR	79	199	202	76	1.29	1.69	1.55	0.78
LE-DI	158	174	226	49	1.53	1.80	1.60	1.08
LE-DI IR	109	261	235	74	1.10	1.80	1.80	0.72
Mean	118	208	224	58	1.34	1.66	1.54	0.61
LSD	67.6	ns[1]	ns	27.7	-[2]	-	-	-

[1] ns, not significant

[2] not applicable

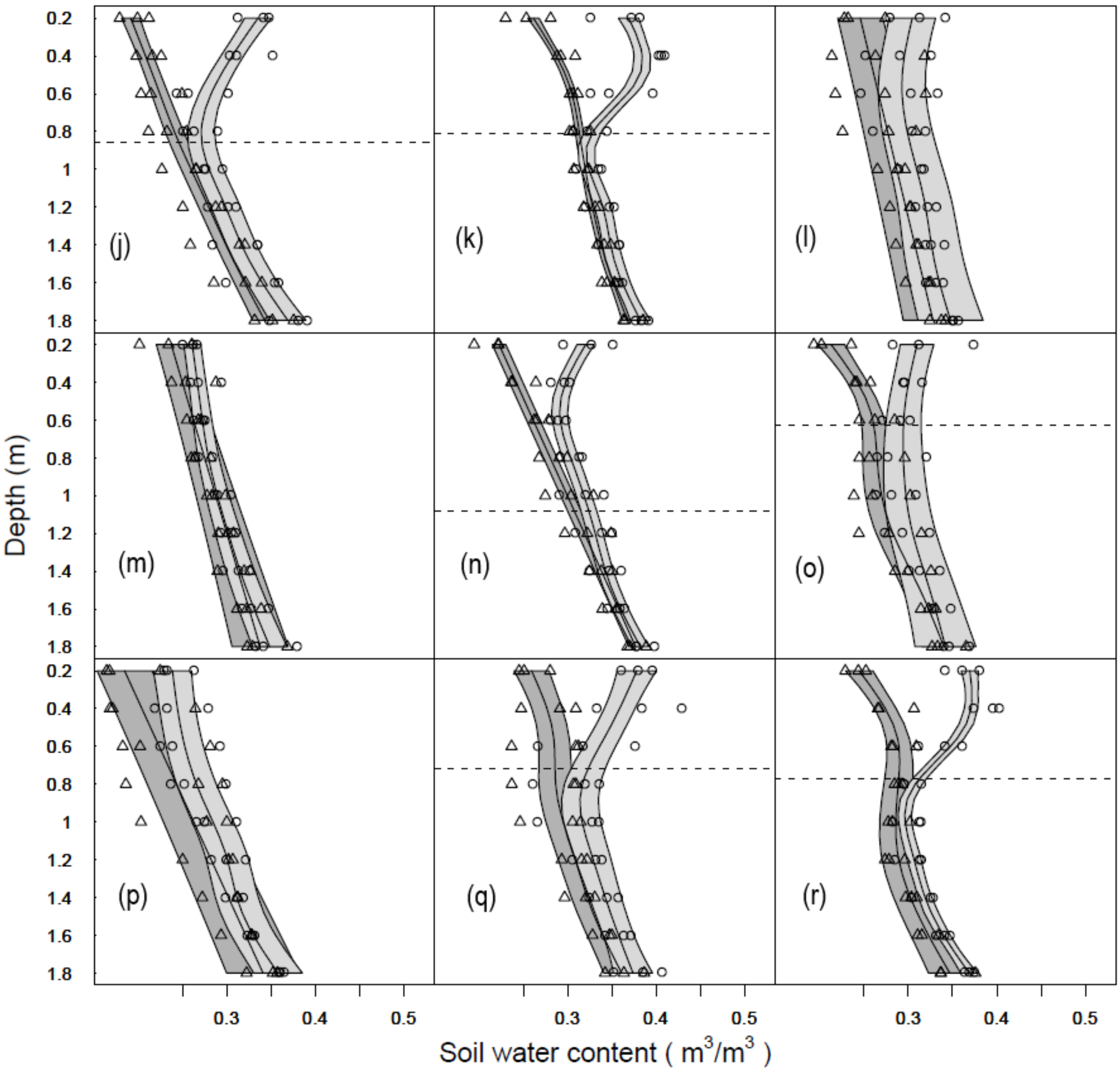


Fig. 72. Soil water extraction patterns observed in 2017 and 2018 for each treatment (a, j) digit grass, DI (b, k) leucaena, LE (c, l) desmanthus, DE (d, m) lucerne, LU (e, n) leucaena-digit grass, LE-DI (f, o) desmanthus-digit grass, DE-DI (g, p) lucerne-digit grass, LU-DI (h, q) leucaena-digit grass inter-row, LE-DI IR and (i, r) leucaena inter-row. Replicate values of maximum (○) and minimum (Δ) volumetric soil water content (m³/m³) are shown. Shaded areas represent the predicted soil water content ± s.e. of the prediction. The open areas between maximum and minimum water content indicate the maximum extractable water (mm). The horizontal dot line indicates root depth (Source: Murphy et al. 2022).

Rainfall refill efficiency

Change in profile stored soil water (mm) and rainfall refill coefficient (%) were different ($P < 0.05$) among the treatments for 2015 and 2017, but not 2016 (Table 91). The mean soil profile refill largely reflected the amount of rainfall received when pastures were inactive. Profile refill in 2016 (254 mm) was more than double that of 2015 (100 mm), and 6 times that of 2017 (41 mm). While the mean rainfall refill coefficients in 2015 and 2016 were similar (59 v. 62%) and three times greater than in 2017 (15%), values among treatments were significantly different ($P < 0.05$) only in 2015. In 2015, LU and LU-DI treatments (22 and 33 mm) captured less ($P < 0.05$) winter rainfall than the other treatments, while DE (167 mm) captured more than LE-IR (87 mm). At the start of winter in 2015, these lucerne treatments had wetter soil profiles (Fig. 71), which resulted in little available storage capacity to capture rainfall. In 2017, LU and LU-DI captured significantly less, of the below-average winter rainfall, than most other treatments, resulting in significantly lower rainfall refill coefficients (Table 91). In the latter year, low groundcover in the LU and LU-DI together with below-average rainfall suppressed rainfall capture.

Table 91. Change in the profile stored soil water (SSW, mm) and rainfall refill efficiency (%) for each winter rainfall refill period. Least significant differences (LSD; P = 0.05) among treatments means for each year is provided where appropriate (Source: Murphy et al. 2022).

Treatment	Change in SSW (mm)			Rainfall refill coefficient (%)		
	2015	2016	2017	2015	2016	2017
DI	114	268	53	70	67	20
DE	167	248	32	102	54	12
DE-DI	116	214	39	71	46	15
LU	22	280	20	16	70	8
LU-DI	33	275	17	24	69	6
LE	113	201	77	58	51	29
LE-IR	87	222	50	53	56	19
LE-DI	126	263	37	64	66	14
LE-DI IR	119	317	46	73	80	17
Mean	100	254	41	59	62	15
LSD	59.5	ns[1]	17.7	36.3	ns	6.7

5.17.3 Plant production

Herbage mass and proportion of legume

Productivity of digit grass as a pure sward (DI) ranged 4070–13286 kg DM/ha, with total water use ranging 384–855 mm, resulting in water use efficiency values of 10.6–19.1 kg DM/ha/mm (Table 92). As a pure grass sward, DI generally had greater ($P < 0.05$) grass herbage mass compared with the grass component in each of the legume mixtures (DE-DI, LU-DI and LE-DI; 3928–12325 kg DM/ha, Table 5). However, grass herbage mass in 2016 for LE-DI (10424 kg DM/ha) was like that of DI (13286 kg DM/ha, Table 5). Grass herbage mass for LE-IR (8283–12325 kg DM/ha), LE-DI-IR (9732–10825 kg DM/ha) and DI (10819–13286 kg DM/ha) were all similar ($P < 0.05$) in the early stage of the experiment in the 2015 and 2016 seasons. But, as the experiment progressed, the interrow treatments produced less grass ($P < 0.05$) than DI (Table 92).

Legume herbage mass differed ($P < 0.05$) among the treatments each year, but the best performing legume also varied each year. In 2015, DE (14370 kg DM/ha) had the greatest ($P < 0.05$) legume herbage mass. In 2016, legume herbage masses for DE, LU and LU-DI were similar ($P < 0.05$, 8185-10669 kg DM/ha) but greater than LE (4731 kg DM/ha) and the lowest was LE-DI (1355 kg DM/ha). In 2017, legume herbage mass for LU (16913 kg DM/ha) was greatest ($P < 0.05$), while DE-DI and LE-DI (2547 and 2638 kg DM/ha, respectively) were lowest ($P < 0.05$). Leucaena as a pure stand (LE) produced more ($P < 0.05$) legume herbage mass (4512–10326 kg DM/ha) than its mixture with digit grass (LE-DI, 1355–2638 kg DM/ha) in all years.

The changes in legume production influenced the proportion of legume in total herbage mass within treatments and between years. The proportion of leucaena in LE-DI increased each year of the experiment from 12 to 42% (mean 26%). In contrast, the proportion of desmanthus in DE-DI decreased each year from 71 to 23% (mean 41%). The proportion of lucerne in LU-DI fluctuated, ranging 59–75% with a higher mean level of 67%.

Table 92. Herbage mass, total water use, water use efficiency of treatments in four growing years (Source: Murphy et al. 2022).

Treatment	Herbage mass (kg DM/ha)												Total water use (mm)				Water use efficiency (kg DM/ha/mm)			
	Grass				Legume				Total											
	2015	2016	2017	2018	2015	2016	2017	2018	2015	2016	2017	2018	2015	2016	2017	2018	2015	2016	2017	2018
DI	10819	13286	12041	4070					10819	13286	12041	4070	731	694	855	384	14.8	19.1	14.1	10.6
DE					14370	8487	8245	4386	14370	8487	8245	4386	819	603	848	349	17.6	14.1	9.7	12.6
DE-DI	3928	4172	6754	2297	9841	2913	2547	713	13769	7085	9301	3010	766	614	850	354	17.9	11.5	10.9	8.5
LU					2842	10669	16913	3869	2842	10669	16913	3869	734	641	886	316	3.8	16.5	19.1	12.2
LU-DI	2258	2774	4145	1719	3277	8185	11951	2528	5534	10959	16096	4246	682	675	904	346	7.9	16.2	17.8	12.3
LE					na[2]	4731	10326	4512	na	4731	10326	4512	767	653	845	359	na	7.3	12.4	12.5
LE-IR	8283	12325	9523	2725					8283	12325	9523	2725	724	649	856	377	11.4	19.5	11.1	7.2
LE-DI	4348	10424	8641	2822	na	1355	2638	2044	4348	11779	11279	4866	774	595	827	348	5.5	19.8	13.7	13.9
LE-DI IR	10825	9732	7823	2437					10825	9732	7823	2437	760	670	834	370	14.2	14.7	9.4	6.6
Mean	6743	8786	8154	2679	7582	6057	8770	3009	8849	9895	11283	3792	751	644	856	356	11.6	15.4	11.1	7.2
LSD	4612.3	4659.8	3201.5	558	5944.9	2470.9	2426.3	1271.4	4787.1	4185.0	2937.3	857.7	ns[1]	ns	ns	27.1	5.57	6.45	3.62	2.58

***Leucaena* hedgerow dimensions**

At every sample date, the pure swards of leucaena (LE) were taller (range 0.1–0.61 m, mean 0.32 m) and wider (range 0.23–0.74 m, mean 0.49 m) than those in the LE-DI treatment (Fig. 73a, b). These differences reflected the variation in treatment legume herbage mass as described above.

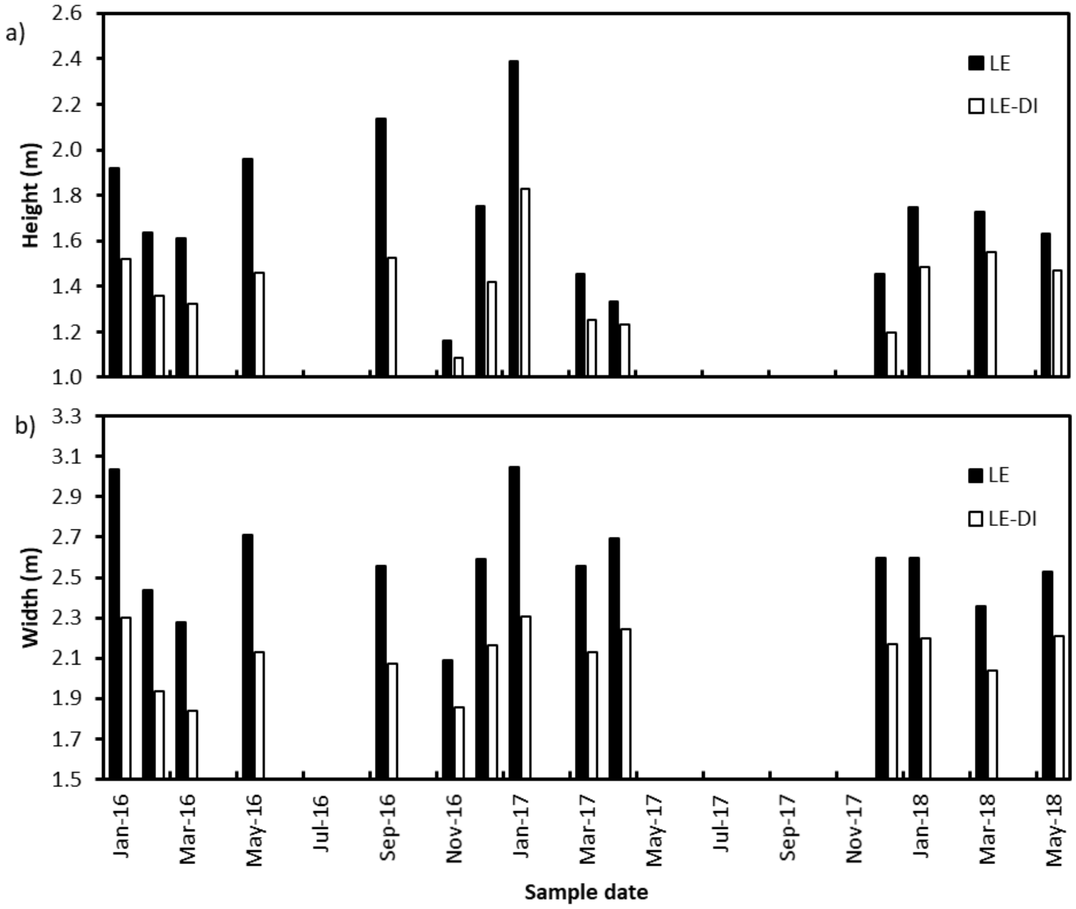


Fig. 73. a) Mean height (m) and b) mean width (m) of leucaena hedgerows in treatments of pure leucaena (LE) and leucaena-digit grass mix (LE-DI) on each date when herbage mass was assessed (Source: Murphy et al. 2022).

5.17.4 Water use and water use efficiency

Total water use among the treatments in the 2015–2017 growing years, despite variation in values, was largely similar (P > 0.05, Table 92). Mean values of total water use varied by >100 mm from year to year (751, 644 and 856 mm for 2015, 2016 and 2017 respectively). In 2018, however, LU used less water (P < 0.05) than all other treatments (316 c. 346–384 mm).

Water use efficiency among the treatments differed in all years (P < 0.05, Table 92). In 2015, treatments containing lucerne or leucaena (3.8–7.9 kg DM/ha/mm) were less efficient than all other treatments (11.4–17.9 kg DM/ha/mm). In 2016, LE and DE-DI (7.3 and 11.5 kg DM/ha/mm, respectively) were less efficient than DI, LE-IR or LE-DI (19.1–19.8 kg DM/ha/mm). In 2017, LU-DI and LU (17.8 and 19.1 kg DM/ha/mm, respectively) were the most efficient treatments. Among the other treatments, DI and LE-DI (14.1 and 13.7 kg DM/ha/mm) were more efficient than DE and LE-DI-IR

(9.7 and 9.4 kg DM/ha/mm). In 2018, the leucaena inter rows and DE-DI (6.6–8.5 kg DM/ha/mm) were less efficient than most of the other treatments, but DE-DI was similarly efficient to DI (8.5 and 10.6 kg DM/ha/mm, respectively).

4.10 Rotational versus continuous grazing for persistence of tropical pastures

5.18.1 Rainfall

Rainfall was below average 2018-19 (50% of the LTA), but above average January 2020-October 2020 (139% LTA) and November 2020-April 2021 (143% LTA) when the experiments were conducted (Fig. 74).

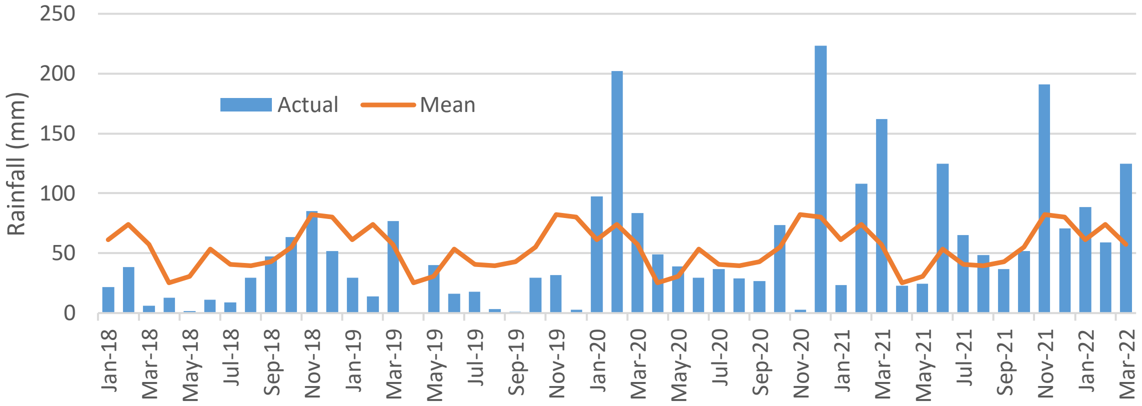


Fig. 74. Actual and long-term average (Mean) monthly rainfall (mm) at Tamworth, January 2018-June 2021. Data are from Bureau of Meteorology station 55325 (1992-2022).

5.18.2 Desmanthus-digit grass (2020-21 growing season)

Pasture growth and rest periods

There was ~2000 kg DM/ha pasture on all treatments when the experiment commenced on 4 November 2020 (Fig. 75). Sheep remained on the continuously grazed plots (T1) until 4 May 2021; a total of 180 days. The two rotational grazed treatments (T3 and T4) were grazed three times during the growing season (Fig. 76). The extended 'rest' periods in T2 and T4 were 10.5-11 weeks, during December 2020-February 2012.

Desmanthus was preferentially grazed by the sheep. Within 2 weeks of grazing commencing the sheep had grazed all desmanthus plants to ≤10 mm. On the continuously grazed plots, desmanthus plants remained short for the entire growing season. Desmanthus regrowth was slow taking up to 7 weeks to regrow to 0.25 m height.

Stocking rate matched pasture growth relatively well throughout November and December, however rainfall over the Christmas-January period resulted in strong pasture growth, which exceeded animal intake. Over this 4-5 week period herbage mass on the continuously grazed plots rose from 1.5 t DM ha to ~9.5 t DM/ha (with only ~5% green leaf). The tall pasture height (>1 m) and high digit grass stem density restricted sheep access, particularly in the plots that had been rested for seedset. Tracks were cut (~0.5 m wide with pasture cut to ~0.3 m high) across all plots using a whipper snipper in February to encourage sheep to move through the overgrown pasture.

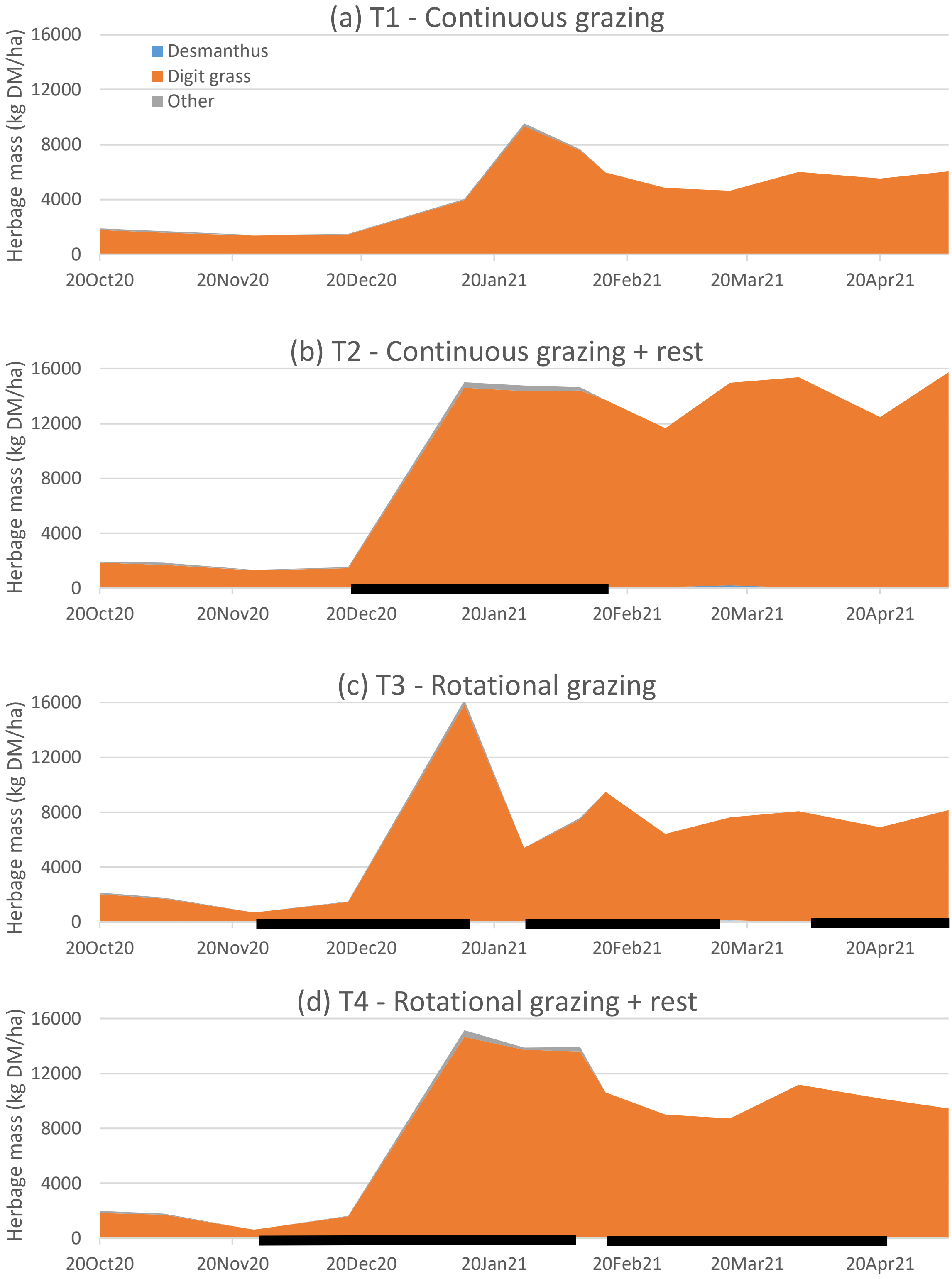


Fig. 75. Cumulative herbage mass (kg DM/ha) in the desmanthus-digit grass grazing experiment during the 2020-21 growing season. Periods when lambs were not grazing the plots are shown by black bars on each figure. The 'rest' periods (T2 and T4) resulted in large build-up of low quality digit grass material that could not be utilised later in the season.

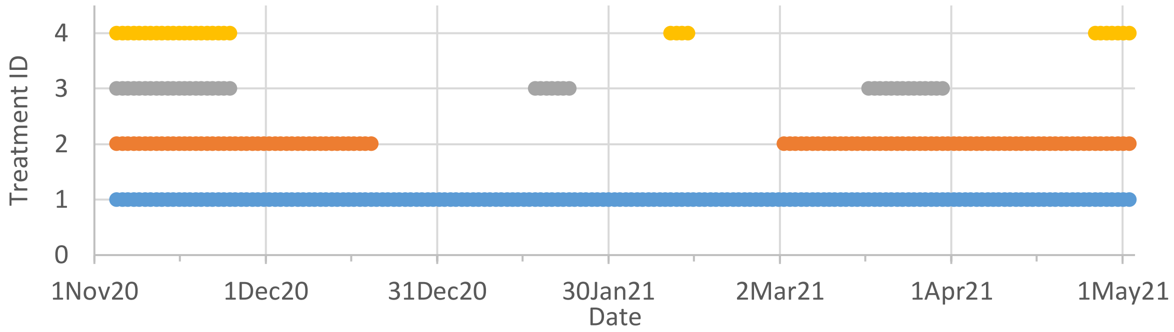


Fig. 76. Periods when the treatments in the desmanthus grazing experiment were grazed and rested from 5 November 2020 to 4 May. Treatment IDs are T1 (continuous), T2 (continuous + rest), T3 (rotational) and T4 (rotational + rest) and relate to treatments listed in Table 2a.

Desmanthus and digit grass persistence

Average frequency of occurrence of desmanthus and digit grass at the site at the start of the experiment (November 2020) were 5 and 19% respectively (Table 93). Desmanthus frequency was lower than preferred, but the experiment continued as planned.

When plant frequency was reassessed in October 2021, digit grass frequency had increased substantially to average 61%, while desmanthus had failed to persist; plant frequency declining to 0% in all fixed quadrats (Table 93).

During the 11 week rest period, seedling regeneration of both desmanthus and digit grass was noted, however, while digit grass set seed, desmanthus did not. During the rest period digit grass growth was extensive and pasture biomass estimated to be 14-16 t DM/ha (Fig. 75). Slow regrowth of desmanthus suggested that the bulk of digit grass shaded the desmanthus plants inhibiting their growth. Seedling recruitment of digit grass occurred in all treatments.

Table 93. Frequency of occurrence (%) of digit grass and desmanthus in October 2020, October 2021 and April 2022 for the four treatments. Treatment numbers 1-4 correspond with those in Table 2.

Treat-ment ID	October 2020				October 2021				April 2022			
	Digit grass		Desmanthus		Digit grass		Desmanthus		Digit grass		Desmanthus	
	Mean	se	Mean	se	Mean	se	Mean	se	Mean	se	Mean	se
T1	19	1.6	4	0.6	71	3.7	0	0.0	97	1.0	0	0.1
T2	17	1.4	4	0.8	51	4.0	0	0.0	91	1.8	1	0.6
T3	21	1.9	4	0.8	62	2.7	0	0.0	90	1.5	3	1.4
T4	18	1.9	7	0.8	61	3.8	0	0.0	88	2.2	2	0.7
Av	*19*		*5*		*61*		*0*		*92*		*1*	

Sheep grazing and production

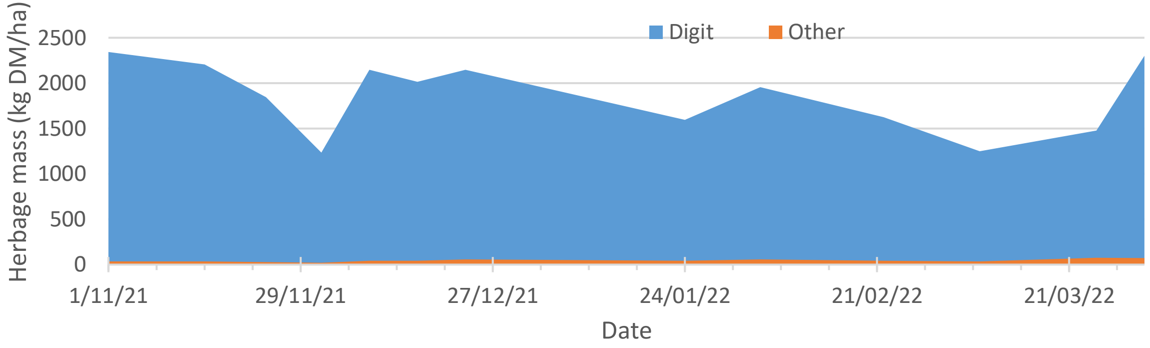
The number of sheep on the continuous grazed plots ranged from 2 to 13 (8–64 sheep/ha) over the growing season. On the rotationally grazed plots stocking rates were up to 452 sheep/ha to provide heavy stocking for short duration to graze digit grass without overgrazing desmanthus. Growth rates were highest early in the growing season (208 g/d), fluctuating as feed quality and quantity changed but generally declined as the growing season continued to average 106 g/d over growing season.

5.18.3 2021-22 growing season

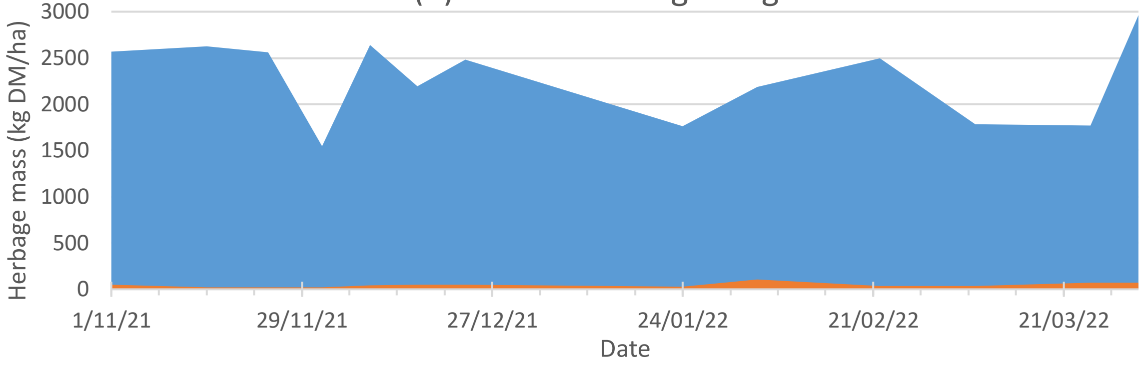
Pasture production

The growing season was conducted over 149 days and herbage mass was assessed 13 times. When the experiment commenced in November 2021, total herbage mass across the four treatments averaged 2359 kg DM/ha (Fig. 77) and consisted of 100% leaf (Fig. 78). As the season progressed herbage mass was maintained around 1000 kg DM/ha in the -N continuously grazed treatment, 1250 kg DM/ha in the -N rotationally grazed treatment plots, and 1700 and ~2000 kg DM/ha in the +N continuous and +N rotationally grazed plots respectively. The proportion of stem started to increase in the +N treatments from December. By the end of the growing season the +N treatments contained 32% green leaf while the -N rotationally and continuously grazed treatments contained 47 and 62% green leaf respectively; the +N treatments had a higher proportion of green and dead stem, but similar proportion of dead leaf (Fig. 78).

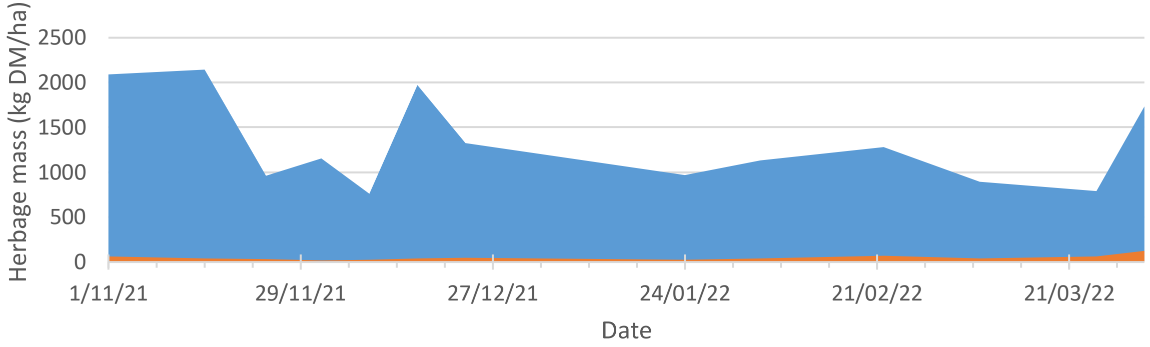
(a) +N continuous grazing



(b) +N rotational grazing



(c) -N continuous grazing



(d) -N rotational grazing

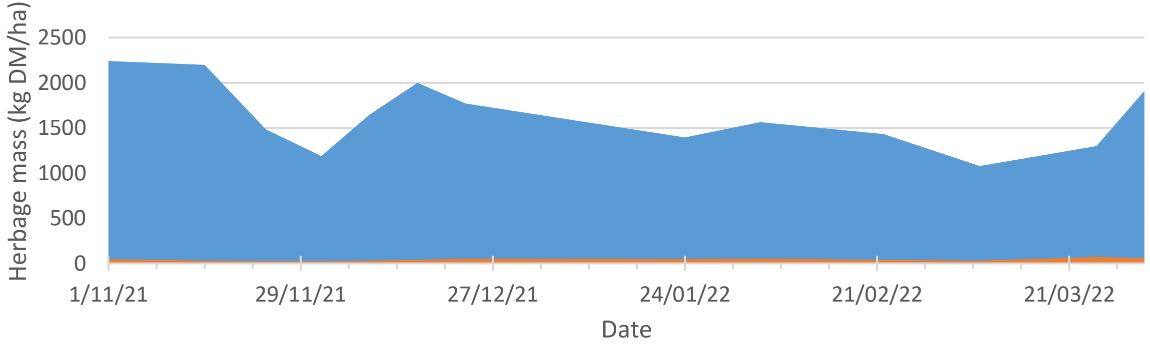


Fig. 77. Cumulative herbage mass (kg DM/ha) during the 2021-22 growing season for the treatments (a) +N continuous grazing, (b) +N rotational grazing, (c) -N continuous grazing, and (d) -N rotational grazing.

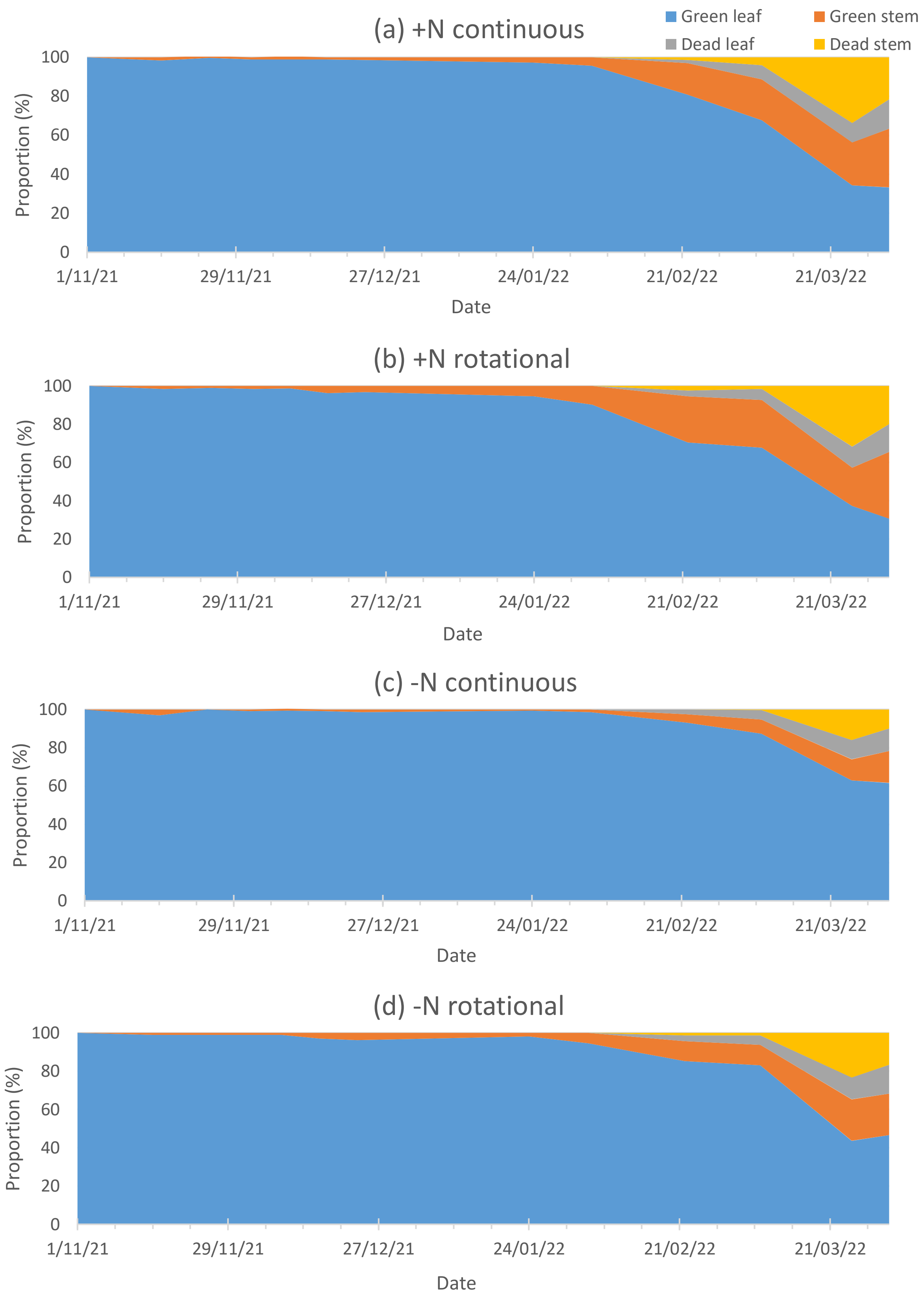


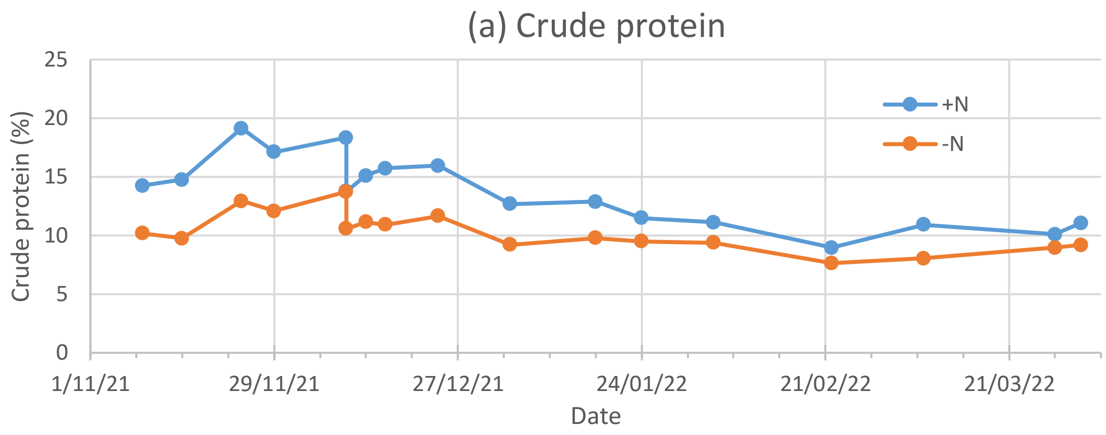
Fig. 78. Cumulative proportion (%) of green and dead leaf and stem of digit grass during the 2021-22 growing season for the treatments (a) +N continuous grazing, (b) +N rotational grazing, (c) -N continuous grazing, (b) -N rotational grazing.

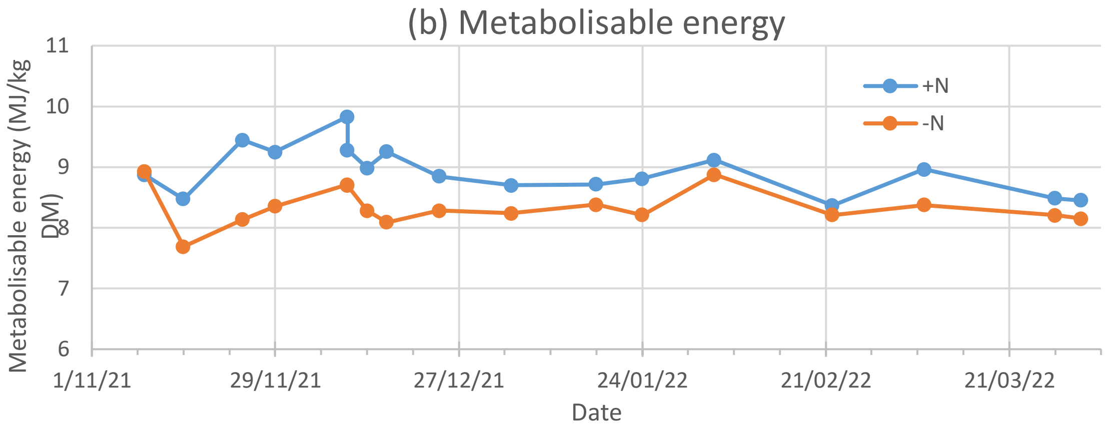
Pasture quality

The nutritive value of the N fertilised (+N) digit grass green leaf was higher than the unfertilised (-N) digit grass, the differences generally greater during spring, declining as the season progressed (Fig. 79). Crude protein levels were ≥10% for the unfertilised grasses from November until early January while the fertilised grass had crude protein levels ≥10% at all assessments except one. These values are suitable for livestock production.

Metabolisable energy levels were consistently higher in the +N than -N digit grass, the differences greatest in spring-early summer (up to 1.3 MJ), but only averaged 0.6 MJ difference over the whole growing season (Fig. 79b). These levels are only suitable for maintenance/moderate production.

NDF and ADF were lower in the fertilised (+N) than the unfertilised (-N) treatment plots (Fig. 79c). Over the growing season, NDF averaged 61 and 65% for +N and -N treatments respectively while ADF averaged 28 and 30% respectively.





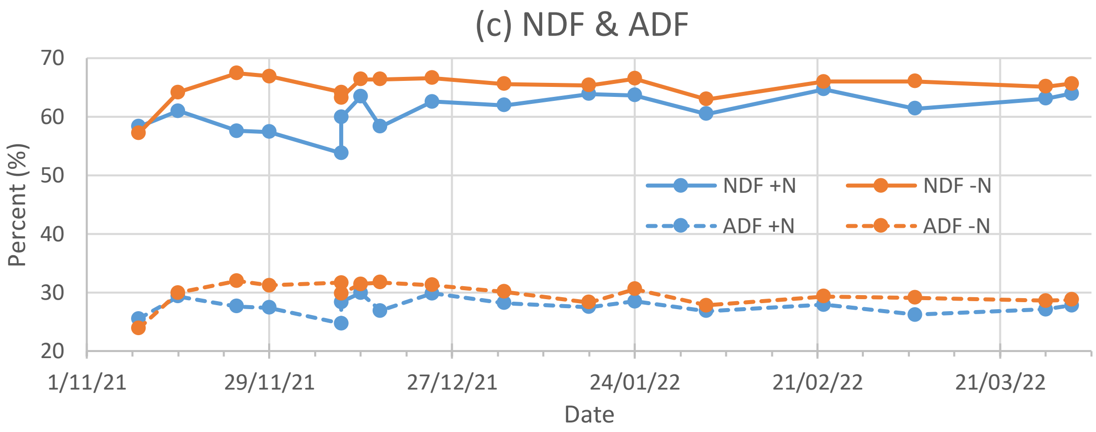


Fig. 79. (a) Crude protein (%), (b) metabolisable energy (MJ/kg DM) and (c) NDF and ADF of digit grass leaf in the +N and -N fertiliser treatments during the 2021-22 growing season.

Pasture persistence

Over the course of the growing season, plant frequency of digit grass increased in all treatments from an average of 61% in spring 2021 to 92% in April 2022 (Table 93). There was some recruitment of desmanthus over the growing season, but only small numbers (average plant frequency of 1%).

Animal production

Stock rates ranged from 108 sheep/ha (+N treatments) in November declining to 7 sheep/ha in March as growth rates declined (Fig. 80). The +N treatment area generally had higher stocking rates, especially during spring and early summer.

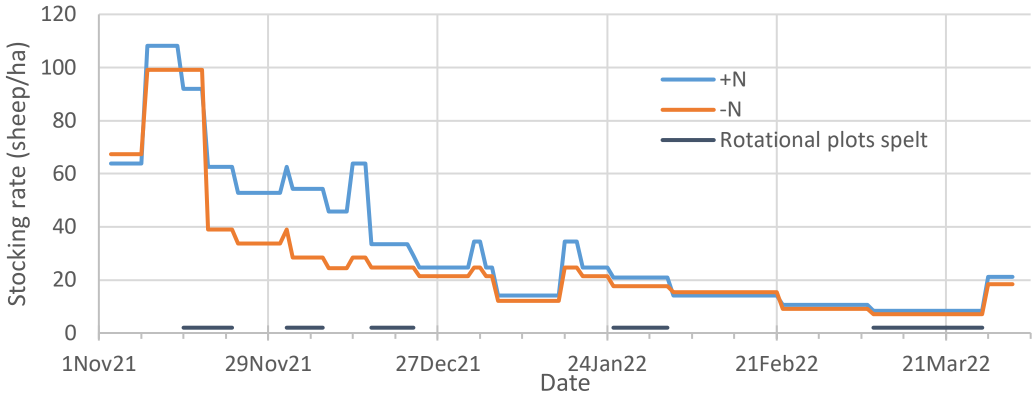


Fig. 80. Stocking rates (sheep/ha) on the nitrogen fertilised (+N) and unfertilised (-N) treatment plots 3 November 2021–1 April 2022. Periods when the rotationally grazed plots were closed for spelling are shown as black bars.

Sheep weights increased during the growing season. Over the 5 months of the growing season the average growth rate for sheep grazing the +N treatments was 111 g/d cf. 102 g/d for those on the -N treatment plots (Fig. 81). Interestingly, the average growth rate of the sheep used in our experiment (n = 50) grazing digit grass for the 5-month growing season exceeded (173%) those of the remainder of the flock (n = 268) they were removed from. The remained of the flock grazed a combination of forage oats, lucerne and native pasture over the same period.

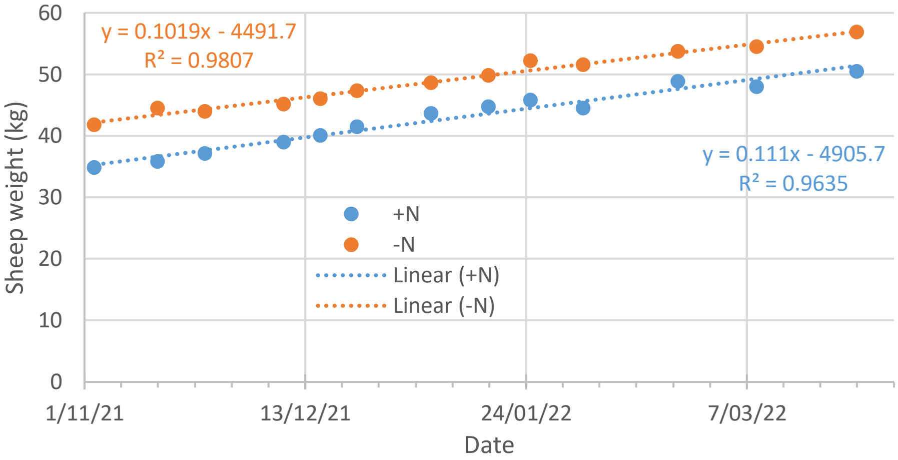


Fig. 81. Average weight of sheep that remained on the nitrogen fertilised (+N, n = 3) and unfertilised (-N, n = 3) treatment plots for the duration of the 2021-2022 growing season.

The total number of grazing days for the -N treatment area was 3876 d compared with 4741 days for the +N treatment area (+22%) (Table 94). The total liveweight gains were 383 and 528 kg/ha (+38%) equivalent to a daily weight gain of 1.62 and 2.23 kg/ha/d for the -N and +N treatment areas respectively.

Table 94. Stocking rate (kg/ha), Number of grazing days, total and daily weight gain (kg/ha and kg/ha/grazing day) of sheep which grazed the experiment for the duration of the growing season.

	+N fertiliser				-N fertiliser			
Date	Stocking rate (sheep/ha)	No grazing days	Weight gain (kg/ha)	Daily wt gain (kg/ha/grazing day)	Stocking rate (sheep/ha)	No grazing days	Weight gain (kg/ha)	Daily wt gain (kg/ha/grazing day)
9/11/21	64	383	32	0.083	67	404	90	0.222
15/11/21	108	649	54	0.083	99	595	132	0.222
19/11/21	92	368	54	0.148	99	396	-22	-0.056
24/11/21	63	313	46	0.148	39	195	-11	-0.056
2/12/21	53	422	52	0.122	34	269	21	0.078
3/12/21	63	63	8	0.122	39	39	3	0.078
9/12/21	54	326	40	0.122	28	170	13	0.078
13/12/21	46	183	26	0.143	24	98	12	0.119
16/12/21	64	192	27	0.143	28	85	10	0.119
23/12/21	33	234	50	0.214	25	173	33	0.190
2/01/22	25	246	38	0.155	25	248	24	0.095
4/01/22	34	69	11	0.155	25	50	5	0.095
6/01/22	25	49	8	0.155	21	43	4	0.095
17/01/22	14	155	14	0.091	12	134	14	0.106
20/01/22	34	103	15	0.146	25	74	22	0.292
25/01/22	25	123	18	0.146	21	107	31	0.292
4/02/22	21	209	-28	-0.133	18	177	-12	-0.067
22/02/22	14	253	61	0.241	15	275	33	0.120
9/03/22	11	158	-9	-0.056	9	137	8	0.056
28/03/22	8	159	21	0.132	7	135	17	0.123
1/04/22	21	84	-11	-0.125	18	73	-43	-0.583
Total		*4741*	*528*			*3876*	*383*	

4.11 Temperate legumes in tropical grass mixes in southern NSW

5.19.1 Cowra

Rainfall was well below average for over 6 months prior to sowing the experiment and during the 4-month period that the tropical grasses were establishing. Temperatures were also above average (up to 4.3^{o}C higher) during this period (Fig. 82). From March 2020, rainfall was more consistent with the site receiving average or above average rainfall for most months for the remainder of the experiment until February 2021. In the 12-month period from March 2020 to February 2021, rainfall was 140% of the long-term average. From March 2020, monthly temperatures tended to be below average during autumn and summer, and above average in winter and spring.

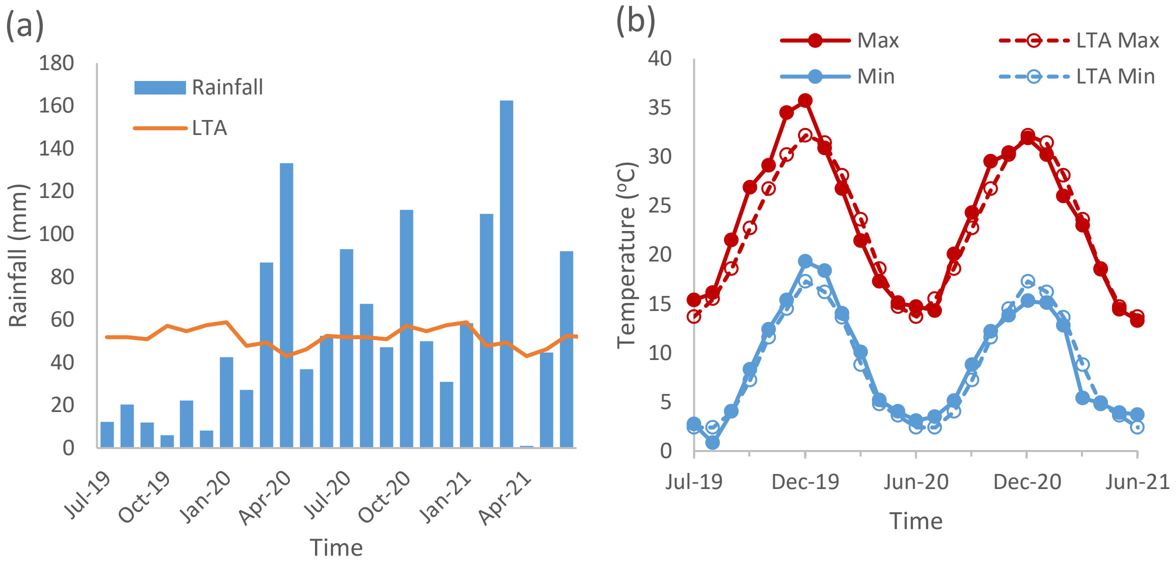


Fig. 82. (a) Monthly and long-term average (LTA) rainfall (mm) and (b) minimum and maximum monthly and LTA temperatures at Cowra, July 2019-June 2021

Establishment plant counts were conducted the first week of November 2019. Katambora Rhodes established well with an average of 12 plants/m^2. Premier digit grass had a lower plant density with an average of 5 plants/m^2 (Table 95). The seed supplied of the legume biserrula had unknowingly been scarified and established in high numbers (>300 plants/m^2) in November. which severely affected the establishment of digit grass. The other grass-legume combinations established at acceptable levels. All annual legumes senesced by the end of December 2019.

All of the annual legumes, except biserrula, germinated in sufficient numbers during autumn 2020. Legume density appeared to be higher in the digit grass treatments which reflected the greater density of the Rhodes grass which grew over summer.

Dry matter production was assessed six times from February 2020 to February 2021. At the February, April and May 2020 assessments, production was significantly higher for Rhodes grass than digit grass across all legume combinations (Fig. 83a). Rhodes grass suppressed the dry matter production of the companion legumes in contrast to digit grass, however productivity of legumes was low in all mixes (≤1000 kg DM/ha). Lucerne had the highest dry matter production combined with either Rhodes or digit grass (Fig. 83b).

Winter-spring productivity was assessed in October 2020. The better performing annual legumes were French serradella, bladder clover and gland clover with spring dry matter production averaging 5000 kg DM/ha (Fig. 83b). Lucerne produced 6400 and 4300 kg DM/ha in mixes with digit grass and Rhodes grass respectively. Biomass from the tropical grasses at this time was negligible.

The higher rainfall during winter and spring 2020, combined with increased temperate legume growth appeared to have a negative effect on the regrowth of Rhodes grass in the second summer period of the experiment (December 2020-February 2021). While there was little to no growth of Rhodes grass, herbage production of digit grass averaged 600 kg/ha in the same period, noting that the low density of this species reduced it potential production.

Table 95. Plant densities (/m²) for each combination of tropical grass and companion legume following establishment (November 2019) and regeneration (autumn 2020) at Cowra.

	Establishment		Regeneration
Companion legume	Legume	Grass	Legume
	Digit grass cv. Premier mixes		
Biserrula cv. Casbah	342	0	20
Bladder clover cv. Bartolo	68	8	86
French serradella cv. Margurita	34	7	256
Gland clover cv. Prima	70	8	116
Lucerne cv. Titan 9	56	2	56
Nil[1]	-	9	
Rose clover cv. Hykon	130	4	190
Yellow serradella cv. Avila	7	6	50
	Rhodes grass cv. Katambora mixes		
Biserrula cv. Casbah	380	11	33
Bladder clover cv. Bartolo	78	13	96
French serradella cv. Margurita	40	28	136
Gland clover cv. Prima	39	12	83
Lucerne cv. Titan 9	62	6	63
Nil[1]	-	6	
Rose clover cv. Hykon	113	8	193
Yellow serradella cv. Avila	4	12	83

[1] Pure grass sward

At the initial plant frequency assessment conducted in March 2020, digit grass and Rhodes grass had low but similar plant frequencies averaging 14 and 18% respectively. Plant frequency of digit grass in the mixture with biserrula was lowest in the experiment, evidence of the competition between the grass and legume during establishment. The temperate annual legumes had plant frequency values ≤26%. Lucerne had a plant frequency of 7 and 15% in mixes with digit grass and Rhodes grass respectively.

Plant frequency was assessed again in June 2020. There was little change in digit grass of the three-month period, but a three-fold increase in Rhodes grass due to stolon development, with average plant frequency increasing to 58%. Plant frequency of the annual legumes increased following their establishment after autumn rainfall; average increasing to 9 (biserrula-Rhodes grass)-70% (bladder clover-digit grass). Plant frequency of lucerne increased in mixes with both grasses however the difference in lucerne frequency was two-fold higher with digit due to the lower plant competition from this species over the time period (Table 96).

The 2020 winter-spring period at Cowra was wetter than average. This combined with the large amount of herbage produced by the sown legumes as well as background subterranean clover caused a decline in the plant population of both tropical grasses, especially Rhodes grass. In February 2021 when the plant frequency was measured no Rhodes grass had regenerated, and frequency of digit grass was <10 for all but one treatment (Table 96). We saw a similar decline in plant frequency across all Rhodes grass cultivars in the species evaluation experiment (Newell et al., unpublished data).

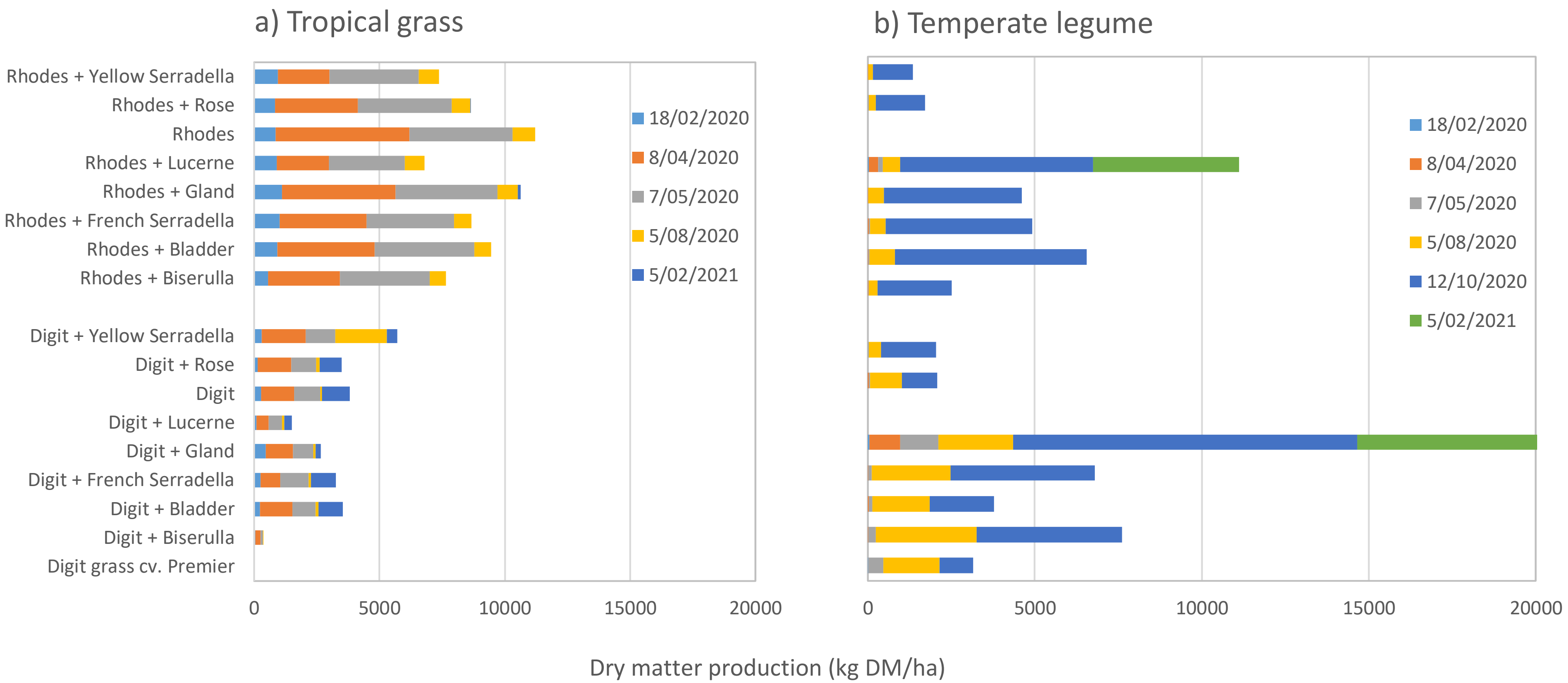


Fig. 83. Cumulative dry matter production (kg DM/ha) of (a) Rhodes grass and digit grass and (b) annual legumes in mixes at Cowra on six occasions, February 2020-February 2021.

Table 96. Frequency (%) for the tropical grass and temperate legume components of the mixtures experiment at Cowra

	17/03/2020		25/06/2020		19/02/2021	
Temperate legume	Grass	Legume	Grass	Legume	Grass	Legume
			Digit grass cv. Premier mixes			
Biserrula cv. Casbah	3.7	2.0	3.7	16.7	0.3	0.0
Bladder clover cv. Bartolo	24.7	3.7	22.3	70.3	22.0	0.0
French serradella cv. Margurita	15.3	25.7	14.7	61.7	4.0	0.0
Gland clover cv. Prima	18.3	11.7	17.0	52.3	3.3	0.0
Lucerne cv. Titan 9	7.3	15.7	6.7	34.0	1.7	33.7
Nil	13.7	-[1]	12.3	-	4.3	-
Rose clover cv. Hykon	16.3	2.3	18.3	9.7	7.0	0.0
Yellow serradella cv. Avila	15.0	5.0	17.3	20.7	7.0	0.0
			Rhodes grass cv. Katambora mixes			
Biserrula cv. Casbah	15.0	3.3	58.3	9.3	0.0	0.0
Bladder clover cv. Bartolo	18.7	9.7	58.0	58.7	0.0	0.0
French serradella cv. Margurita	14.3	13.7	58.0	31.3	0.0	0.0
Gland clover cv. Prima	22.3	8.3	58.7	17.0	0.0	0.0
Lucerne cv. Titan 9	15.0	7.0	51.7	9.0	0.0	21.0
Nil	20.7	-	69.7	-	0.0	-
Rose clover cv. Hykon	18.3	3.3	54.3	11.0	0.0	0.0
Yellow serradella cv. Avila	19.0	3.3	57.3	10.7	0.0	0.0

[1] No sown legume

5.19.2 Orange

Delaying sowing until January 2020 meant that rainfall was only below average for ~6 weeks following sowing. From March, rainfall was above average for three months, then fluctuated from well below average to well above average over the following 12-month period (Fig. 84a). Maximum temperatures were up to 4°C above average during the tropical grass establishment period. For the remainder of the experimental period, temperatures were generally within 1-2°C of the average (Fig. 84b).

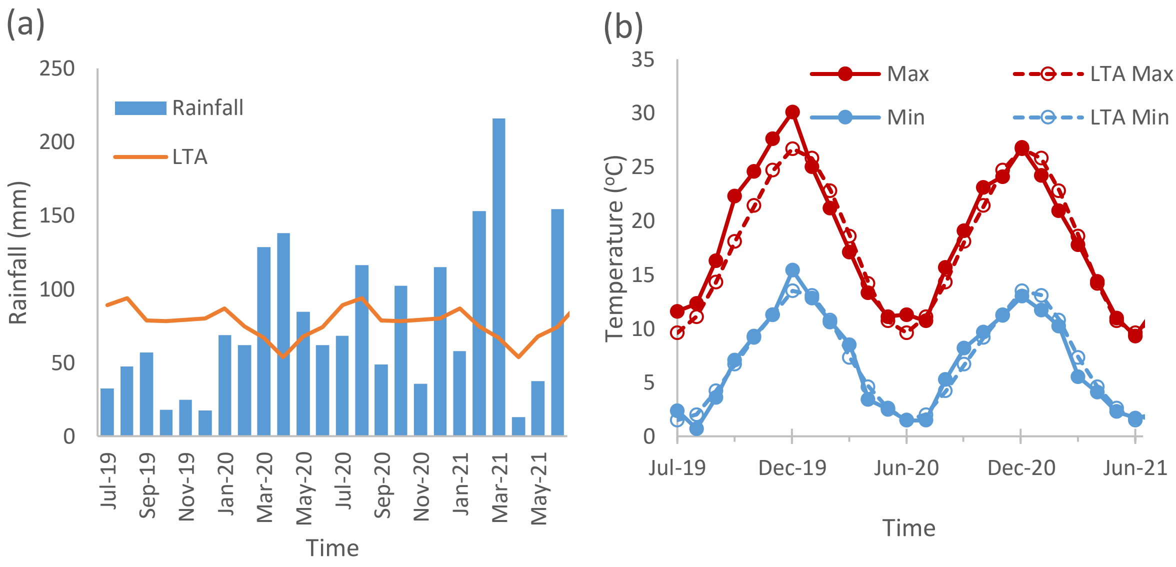


Fig. 84. (a) Monthly and long-term average (LTA) rainfall (mm) and (b) minimum and maximum monthly and LTA temperatures at Orange, July 2019-June 2021

The three tropical grasses established well (Table 97). Bambatsi panic established with the highest plant density (average 85 plants/m^2) compared to digit grass and Rhodes grass (average 57 and 50 plants/m^2 respectively). The companion legumes established with similar densities in mixes with Bambatsi panic and digit grass (average 44 plants/m^2), while Rhodes grass had less (average 23 plants/m^2).

Table 97. Establishment plant densities (plants/m^2) for each combination of tropical grass and companion legume at Orange. Rhodes grass cv. Katambora was grown in a separate block to the other grasses.

Tropical grass	Companion legume	Legume (plants/m^2)	Grass (plants/m^2)
Bambatsi	Biserrula cv. Casbah	122	55
	Bladder clover cv. Bartolo	38	100
	French serradella cv. Margurita	13	101
	Gland clover cv. Prima	10	87
	Lucerne cv. Titan 9	28	80
	Nil	-[1]	101
	Rose clover cv. Hykon	121	93
	Yellow serradella cv. King	18	64
Digit grass cv. Premier	Biserrula cv. Casbah	112	59
	Bladder clover cv. Bartolo	33	50
	French serradella cv. Margurita	10	51
	Gland clover cv. Prima	10	65
	Lucerne cv. Titan 9	30	42
	Nil	-	85
	Rose clover cv. Hykon	124	42
	Yellow serradella cv. Avila	29	64
Rhodes grass cv. Katambora	Biserrula cv. Casbah	59	47
	Bladder clover cv. Bartolo	17	33
	French serradella cv. Margurita	7	54
	Gland clover cv. Prima	6	52
	Lucerne cv. Titan 9	22	66
	Nil	-	42
	Rose clover cv. Hykon	60	49
	Yellow serradella cv. Avila	11	60

[1] No sown legume

There was good legume herbage production in winter-spring 2020, although extensive regeneration of background legumes dominated production in spring, consisting predominantly of balansa clover in the Rhodes grass block and subterranean clover in the digit grass/Makarikari (Bambatsi) panic block. Herbage mass was assessed in March, August and October 2020. In March total herbage production averaged 4284 kg DM/ha. Rhodes grass was the most productive of the tropical grasses with 3806 kg DM/ha (89% of total biomass). In August total herbage production averaged 4059 kg DM/ha. Biserrula was the most productive legume with 3334 kg DM/ha (Fig. 85), constituting 67% of the total biomass present. Both tropical grasses were inactive at this assessment. In October total production averaged 9000 kg DM/ha; the majority of this growth from background and weed species. There was no growth of the tropical grasses. Lucerne was the most productive sown legume with 2084 kg DM/ha (22% of total biomass) followed by biserrula and yellow serradella (average 1608 kg DM/ha, 18% of total).

The experiment was mown after the March and August assessments and the growth of rose clover and biserrula was reduced after been mown in August. The experiment was not mown after the October assessment to allow the legumes to set seed. Both serradella species and biserrula flowered and formed pods while the other sown legumes had few flowers with negligible seed set. Some legume species maintained a little green leaf until late January 2021.

The tropical grasses did not recover in spring 2020 and upon closer inspection no grass crowns were found in January 2021. Plant frequency assessed in May 2021 confirmed plant death with only a few of the sown legumes recorded in a few plots; values ranging from 7-17%. The majority of plots that contained sown plants were mixes with lucerne. The large biomass produced by the background legume appeared to have been the issue, smothering the tropical grass plants.

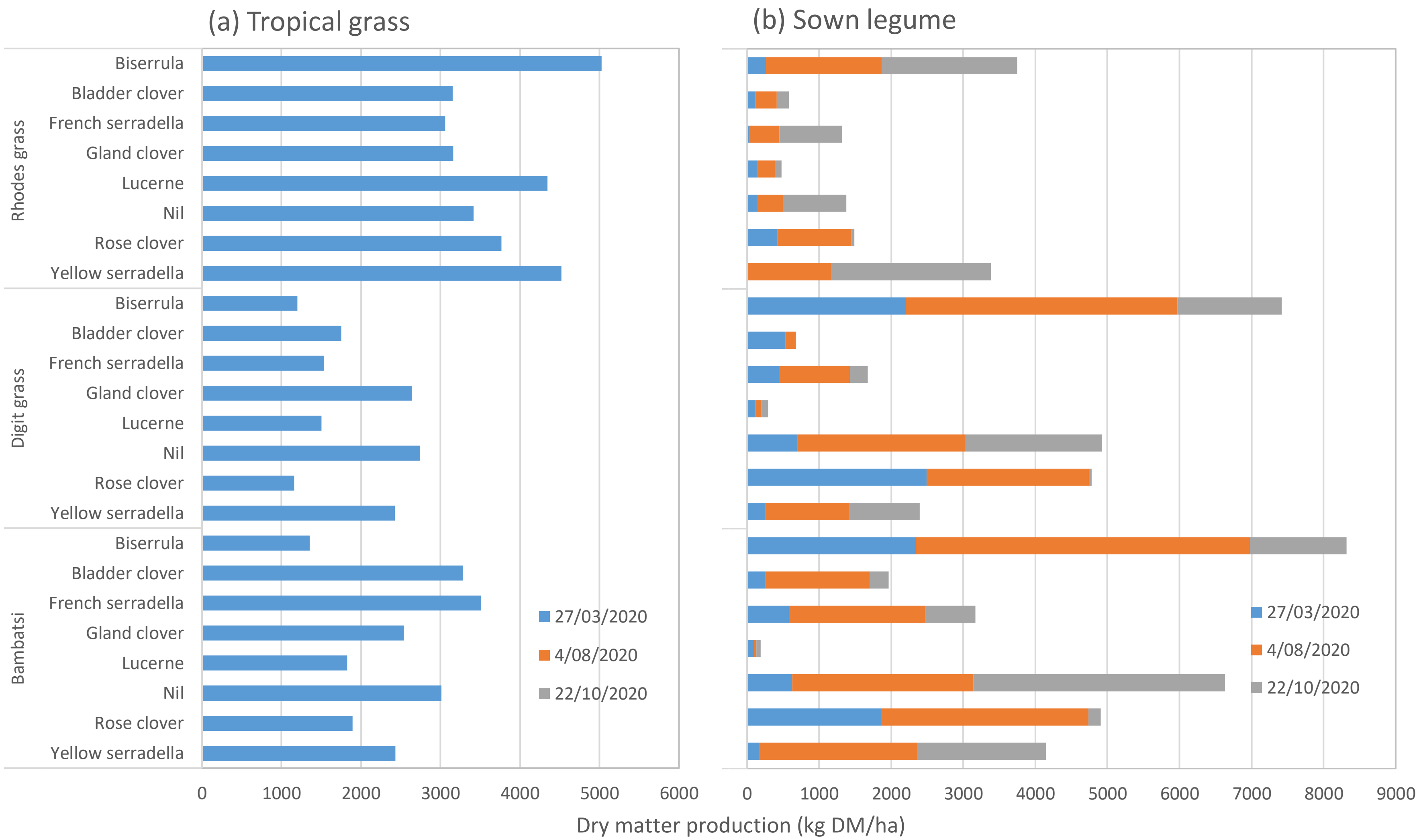


Fig. 85. Cumulative dry matter production (kg DM/ha) of the (a) tropical grasses and (b) annual legumes in mixes at Orange on three occasions, March 2020-October 2021.

5.19.3 Wagga Wagga

Rainfall was below average for 5 months following sowing, with the site receiving average or above average rainfall for 11 of the following 13 months (Fig. 86a). From April 2021 rainfall tended to be average to below average except for November 2021 and January 2022 when monthly rainfall was ≥4-fold greater than the average. Maximum temperatures over the first four months from sowing (September 2019 to January 2022) were above average as were those in the Spring of 2020. Conversely, minimum temperatures were slightly below average in the Autumns of 2020 and 2021 and again in the Spring of 2021 (Fig. 86b).

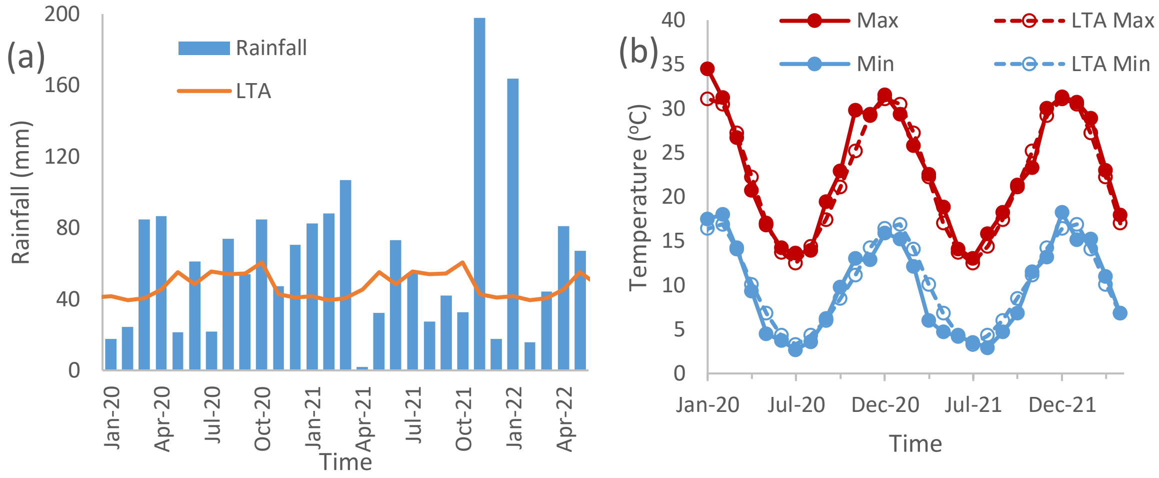


Fig. 86. (a) Monthly and long-term average (LTA) rainfall (mm) and (b) minimum and maximum monthly and LTA temperatures at Wagga Wagga, January 2020-May 2022.

No establishment plant counts were recorded but all grasses and most legumes established, an exception being lucerne which established with very few plants in any plot. The establishment of the hard-seeded legumes was better than expected from sowing in spring and most varieties were not as hard seeded as expected.

Productivity of both the tropical grasses and temperate legumes were low during winter 2020, generally being <1000 kg DM/ha for all mixes. In spring 2020 the most productive legumes were yellow serradella and biserrula in mixes with digit grass and Rhodes grass, respectively (Fig. 87). These two mixtures were also among the higher yielding at the next harvest in summer/early autumn 2021 along with the bladder clover-digit grass mix, albeit the absolute yields were low with no treatment having a combined yield greater than 2000 kg/ha. Yields at the subsequent harvest of late autumn/winter 2021 (April to early September) were legume dominant with the C4 grasses contributing little biomass. Interestingly, the legumes as a group were higher yielding at this time in mixes with digit grass rather than Rhodes grass. During this season the yellow serradella-digit grass, rose clover-digit grass and French serradella-digit grass were the highest yielding. The following season, spring 2021 (September to December 2021) returned the highest legume yields of the entire trial with little apparent effect of the tropical grass it was growing with. In this season the highest yielding mixtures were gland clover, bladder clover and French serradella in mixes with Rhodes grass and rose clover in a mixture with digit-grass. The following harvest conducted toward the end of summer in February 2022 had essentially no legume biomass as the annual species had senesced and the population density of lucerne too low to make a meaningful contribution. At the final assessment conducted in May 2022 average productivity of Rhodes grass was approximately double that of digit grass (Fig. 87). Legume yields were low (<1000 kg DM/ha); maximum for French serradella and biserrula, both in mixes with digit grass. Productivity of Rhodes grass exceeded digit grass at the majority of the assessments.

Plant frequency was assessed three times during the experiment: end of spring 2020 (December), end of autumn 2021 (May) and end of spring 2021 (December)(Fig. 88). In spring 2020, the average frequency for Rhodes grass and digit grass were ~70% and 25% respectively. Bladder clover had the highest plant frequency of the temperate legumes in association with both perennial grasses. Other good performers at that time were yellow serradella, rose clover and lucerne, all in mixes with digit grass. By May 2021, plant frequency of the grasses had increased significantly averaging ~95 and 80% for Rhodes grass and digit grass respectively. All legumes had greater presence in mixes with digit grass than Rhodes grass. This suggests that it may be a better companion grass for these legumes than Rhodes grass. The rhizomatous habit of Rhodes grass may make it more competitive than the more erect, non-rhizomatous digit grass. The final observations were undertaken in December 2021 by which time all the annual legumes had senesced so that only the presence of the companion grasses was recorded. Similar to the previous assessments, average plant frequency of Rhodes grass was higher than digit grass; values of both species declining significantly over the winter period. During this winter period the legumes were highly productive with rose clover producing more than 8000 kg DM/ha in the digit mix.

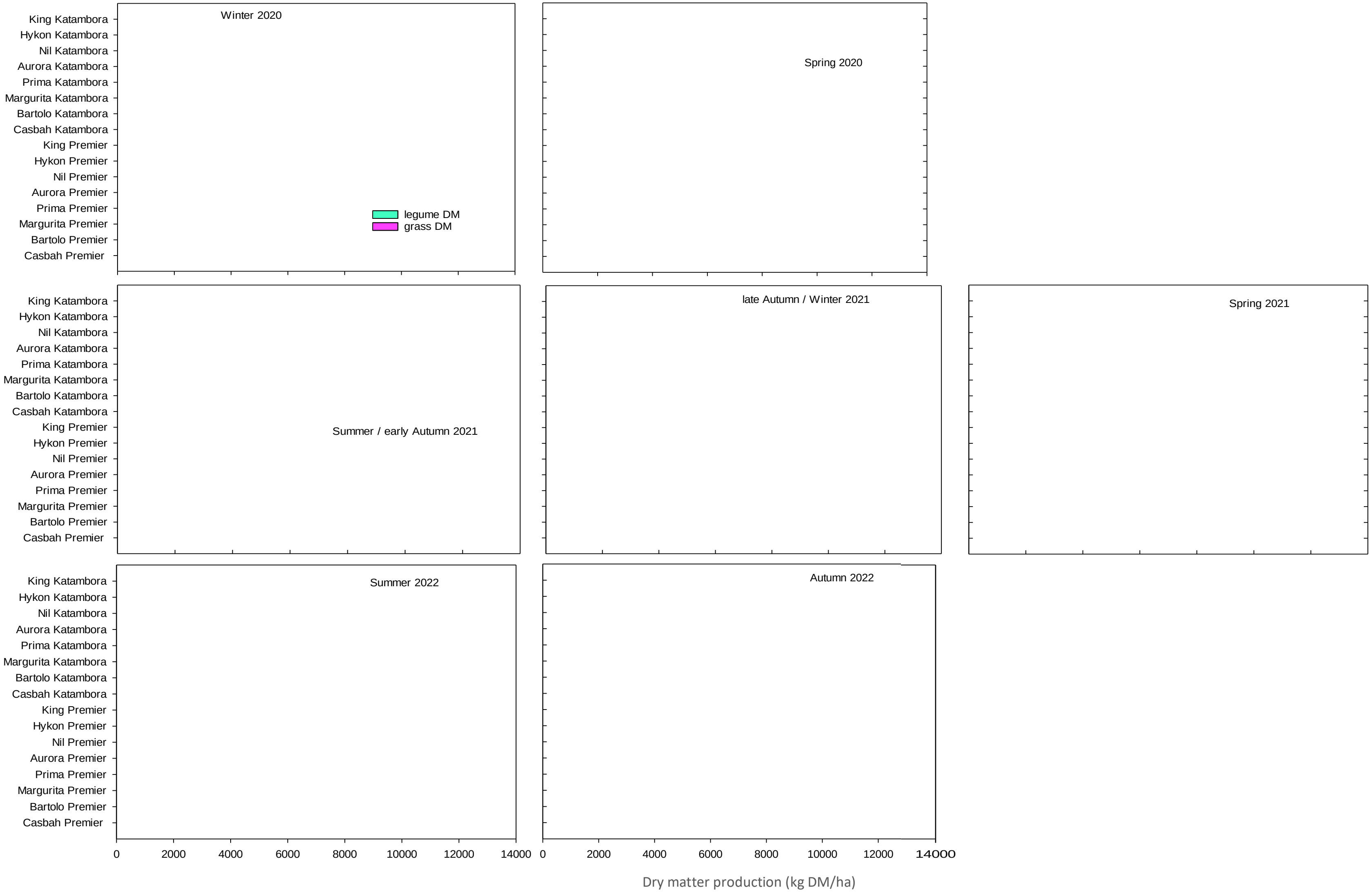


Fig. 87. Dry matter production of mixed grass/legume sward components on seven occasions from winter 2020 to autumn 2022 at Wagga Wagga. Full treatment details are provided in Table 29.

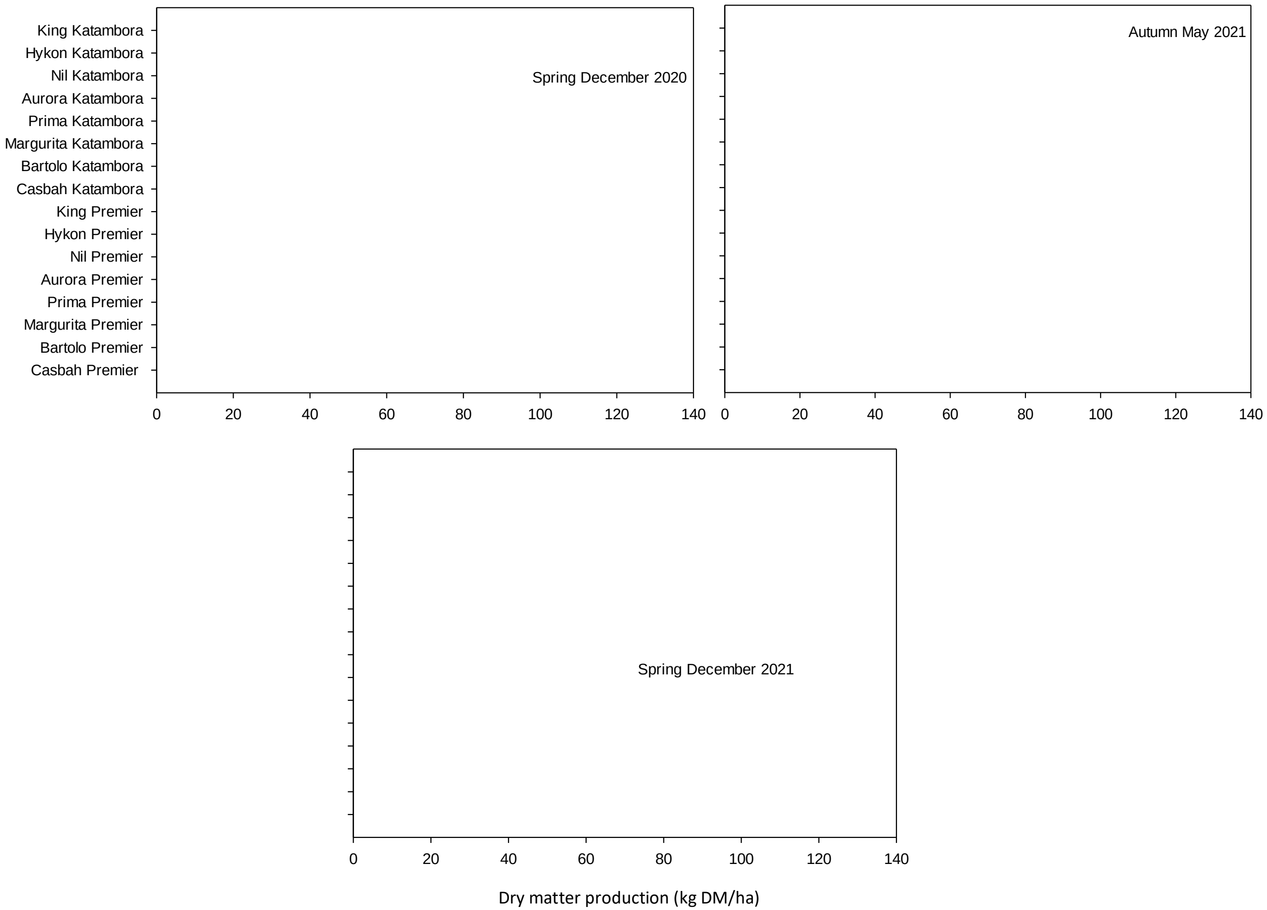


Fig. 88. Frequency (%) of the tropical grass (🟪) and temperate legume (🟩) components of the mixtures experiment at Wagga Wagga in December 2020, May 2021 and December 2021. Full treatment details are provided in Table 29.

5.19.4 Yanco

Rainfall fluctuated but was largely average for the 3 months following sowing, then more than double the long-term average during March-April 2020 (Fig. 89). From May 2020, rainfall tended to be below average, only exceeding the long-term average in 4 months over a 14-month period. Temperatures were generally within 1.5°C of the long-term average for the duration of the study.

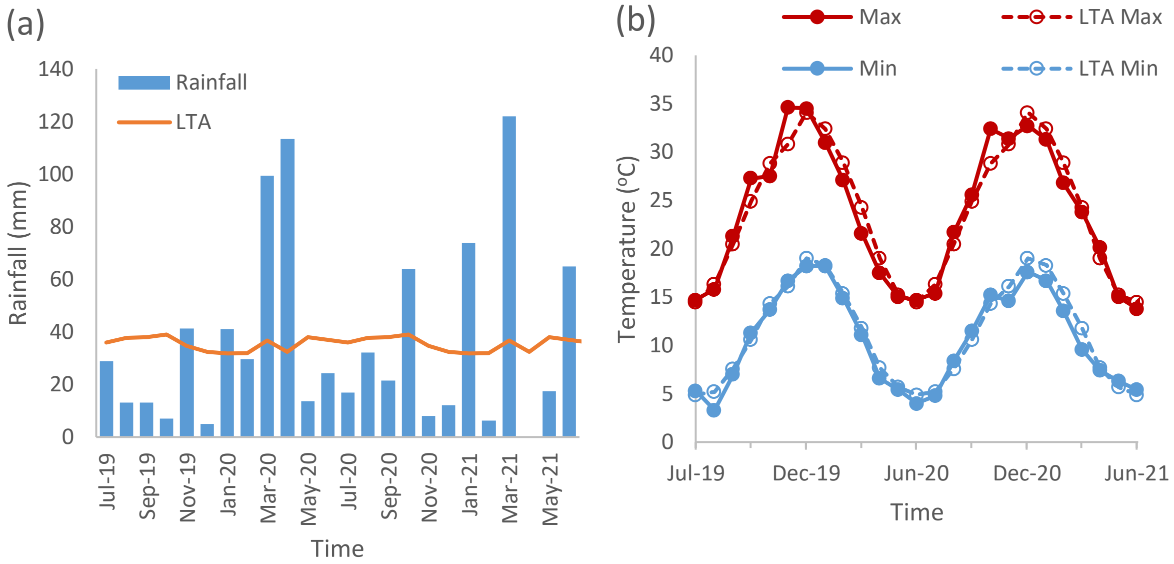


Fig. 89. (a) Monthly and long-term average (LTA) rainfall (mm) and (b) minimum and maximum monthly and LTA temperatures at Yanco, July 2019-June 2021

Both grasses established well. No sown legumes were ever observed in the two following years, so the experiment was discontinued in 2021.

4.12 Enablers and constraints to trialling and successful management of tropical grasses

4.12.1 Stage 1 – producer workshops

Experienced producer workshops

Producers at the Purlewaugh and Bingara workshops were confident in their ability to successfully establish and manage tropical grasses, some having 20-30 years of experience with these grasses. Although the producers at the Dubbo workshop had experience establishing and managing tropical grasses, they were less confident, especially those located in the more marginal areas west/southwest of Dubbo.

The most recognised value of tropical grass pastures identified by producers was improved feedbase stability and increased livestock carrying capacity. In the marginal areas (e.g., west of Dubbo) digit grass and Bambatsi panic have allowed increased pasture production on a broad scale. Other benefits included:

1. Highly responsive to late spring, summer and early/mid-autumn rainfall events, even rainfall events as small as 10 mm;
2. Ability to increase production on previously low productive country;

3. Effective control of difficult weeds (e.g., spiny burr grass, liverseed grass, blue heliotrope, Coolatai grass);
4. Drought persistence and resilience;
5. Can act as a drought reserve by providing a standing haystack in dry periods; and
6. Provides good ground cover and erosion control.

Challenges identified by producers included:

1. Less run-off available to flow into dams (offset by increased infiltration);
2. Difficult to manage when growth is rapid (requires smaller paddocks = increased cost for fencing and stock water);
3. How do you establish legumes into established tropical grasses?
4. When do you sow as you move further west and south?; and
5. Increased risk of establishment failure/poor persistence in lower rainfall areas and on different soil types.

Critical factors for successful establishment included:

1. Pre-sowing summer grass weed ‘clean-up’ phase;
2. Matching species/cultivar to soil type;
3. Checking germination and purity of seed;
4. Sow in spring ahead of rain if subsoil moisture is available and ground temperature is 16–18°C;
5. Sow seed shallow;
6. Soil test and correct for phosphorus, sulphur and nitrogen deficiency; and
7. Be patient. Establishment can be slow, especially in difficult years.

Important pasture management practices/factors included:

1. Keep the pasture short and green (using high stocking rates)
2. Allowing to flower and set seed in the establishment year;
3. Slash excess growth to promote higher quality vegetative regrowth or allowing the standing haystack for use over winter; and
4. Applying P and S in autumn for winter growing legumes and N in spring for tropical grasses to promote growth.

Producers regarded the extension support they received as critical to their trialling and, subsequent, successful adoption of tropical grasses. Many producers emphasised the role of networks and respected individuals to support their efforts in trialling tropical grasses.

Inexperienced producer workshops

Many of the producers at the Orange and Cowra workshops indicated they were preparing to trial tropical grasses in the coming spring. Several producers who had already trialled a small area indicated they were planning to increase the area sown.

The ability to provide a significant quantity of feed over the summer-autumn period was the most important benefit identified by the majority of producers. They recognised that this would provide the opportunity to trade and/or finish stock at times when the traditional annual pastures were not productive. From an analysis of their historical rainfall records, several producers indicated they were receiving increased summer rainfall and tropical grasses would allow them to productively utilise this moisture.

Benefits identified by the inexperienced producers included:

1. Reduced need for supplementary feeding during summer-autumn; potentially minimise the amount of grain required during summer; less labour intensive;
2. Competition against problem summer weeds;
3. Reduce the reliance on lucerne over summer;
4. Increased ground cover over summer = reduced wind and water erosion;
5. High quality bloat free feed;
6. Only need to sow once as they are perennials;
7. Ability to rest temperate perennial pastures over summer;
8. Potential for hay production outside the traditional late spring window; and
9. Productive use of poorer country (e.g., acid soils, light granite soils).

The highest priority information producers identified they would require to trial tropical grasses included:

1. Seed sources, availability, quality, purity and cost;
2. Cost of establishment, livestock performance and animal health issues;
3. Paddock selection and pre-sowing preparation;
4. Species selection, species mixes and legume options, matching species to soil type, rainfall and temperature requirements;
5. Growth rates and feed quality during the growing season;
6. Grazing management practices for pasture persistence and animal production;
7. Soil testing and fertiliser requirements; and
8. The possibility to harvest seed.

To support their decision-making to trial tropical grasses, many producers indicted they would like to have experienced advisors and/or growers with local experience. Several producers suggested group meetings to discuss with other producers their successes and failures with establishment and on-going management.

4.12.2 Stage 2 – Producer survey

There were many findings from the survey. Some key points include:

- About half of survey participants had sown tropical grasses.
- There is a high level of awareness of tropical grasses amongst inexperienced producers.
- Important economic and environmental benefits from growing tropical grasses identified included increased productivity, improved business performance and maintaining the resource base.
- Important issues include access to quality seed at a reasonable price, and evidence of tropical grass performance in their local environment.

Those setting out to engage producers about tropical grasses need to be aware of the extent of producer experience and the important drivers that can be used to foster practice change. For example, inexperienced producers need evidence of the economic benefits of tropical grasses; access to high quality seed at reasonable prices; and advice about how to establish and manage tropical grasses. That information and advice needs to be tailored to local contexts. For the experienced producers to take full advantage of growing tropical grasses there are several management topics that need to be addressed including integrating a legume, managing soil fertility and maintaining forage quality.

4.12.3 Stage 3 – Semi structured interviews

The interviews highlighted the enthusiasm of producers and agronomists towards tropical grasses and their role in grazing systems in southern NSW. Those producers who have already sown tropical grasses have done so without being fully informed about the key principles and practices for establishment and grazing management. The interviews identified producers have had mixed success integrating winter legumes with tropical grasses. The interviews reinforced the importance of using multiple sources to support producers in their decision-making around tropical grasses.

There is a groundswell of producers in southern NSW who have sown or are interested in trialling tropical grasses. There is a need to build on this momentum and support producers and their service providers. As indicated below the research team has responded by providing additional extension activities. Resources need to be developed appropriate for southern NSW to support these producers (and their service providers) in trialling tropical grasses.

5 Conclusion

This large multidisciplinary project has made significant progress in increasing our understanding of tropical pasture management and the role of companion legumes in northern NSW, but especially in identifying and understanding the potential of tropical pastures in SE Australia, in particular NSW.

5.1 Key findings

6.1.1 Tropical species occupy only a proportion of their potential, especially in southeast Australia

Distributions of the species modelled using the combined climate-soil pH-land use model were generally consistent with the known geographic distribution of the species in northern Australia, WA and NSW. They also indicate that these species occupy only a small proportion of their potential, especially in SE Australia. Our study showed, under a climate baseline a potentially highly suitable area (combined model) in Australia for tropical species ranges from 57.07 M ha for panic grass to 19.6 M ha for kikuyu, with digit grass having the largest potential in SE Australia (total 16.33 M ha in NSW, ACT, Victoria and Tasmania). Future climate scenarios suggest that the potential distribution of these species will decrease in northern Australia (Queensland, NT and northern WA). However, in SE Australia, suitability will increase if temperatures increase (MIROC-H) but decrease if rainfall declines significantly (CSIRO-MK 3.0).

Our study used two GCMs. The CSIRO Mk3.0 model predicts a mean temperature increase of 2.11°C while MIROC-H predicts an increase of 4.31°C by 2100 (Kriticos et al. 2012). Rainfall projections also vary with the CSIRO Mk3.0 and MIROC-H models predicting a decline in mean rainfall of 14% and 1% respectively. The greatest impact of the GCMs on potential tropical species distribution is declining rainfall, not increasing temperature. In general, the distribution of tropical species in areas where they are currently grown in northern Australia was not greatly affected by increasing the temperature (MIROC-H model), however reducing the rainfall (CSIRO Mk3.0) significantly reduced the suitable area, particularly in NT. In southern Australia, the area potentially suitable for tropical species increased when temperatures increased (MIROC-H), but only those states with higher rainfall (e.g., Victoria and Tasmania) were projected to have an increase in suitable area when a slight temperature increase was coupled with a significant reduction in rainfall (CSIRO Mk3.0). However, the reduction in suitability of temperate species is likely to be greater, and hence the role of tropical species more prominent. In southern Australia, under both models, tropical species were least suited to the lower rainfall states of SA and WA. The major difference between the 2 models was their effect on NSW.

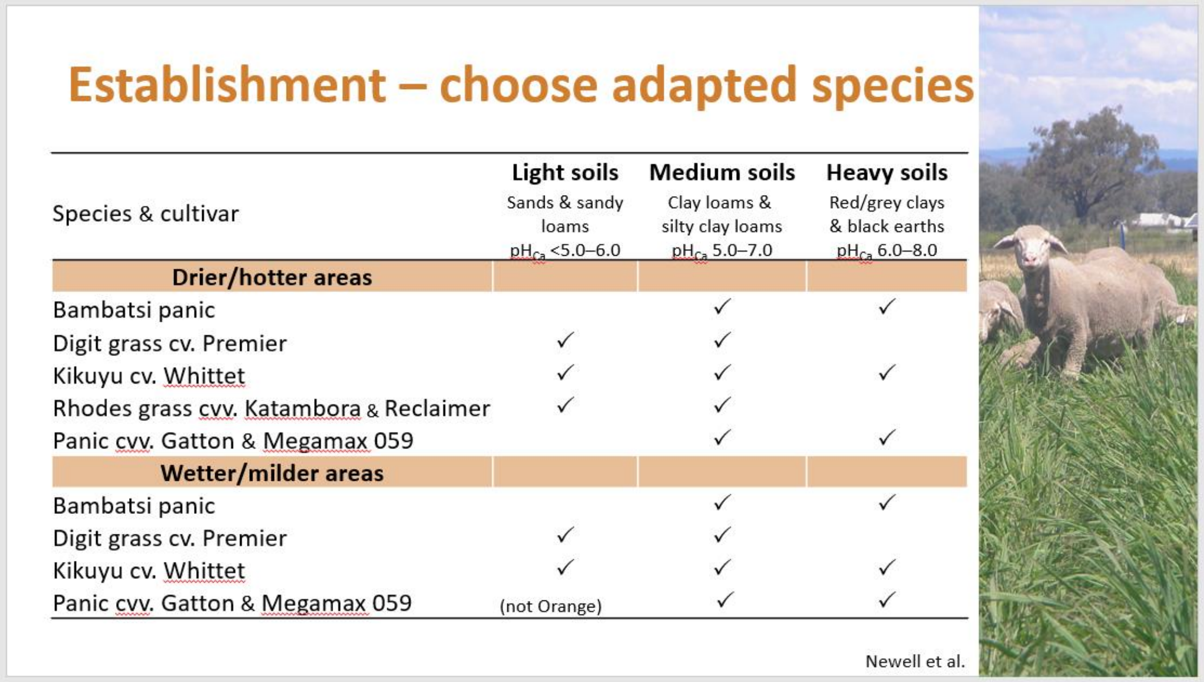
6.1.2 Tropical grasses species can be persistent and productive in central and southern NSW

Modelling is a tool. It can be effective for providing generalisations and assisting decision making, but it is not exact (Kriticos and Randal 2001; Lawson et al. 2004). We used our preliminary maps, developed early in the project to guide location of our field evaluation experiments to test the suitability of tropical species in areas currently considered marginal (e.g., Central West NSW) or unsuitable (e.g., Northern and Central Tablelands) by conventional wisdom, but modelled as potentially suitable. Our species evaluation studies validated the models and confirmed that tropical grasses have potential in the tested areas.

In the current climate, the tropical perennial grass species we evaluated had a competitive advantage over temperate perennial species in environmental zones which where warmer and drier (e.g., Condobolin and Goolgowi). In these locations the tropical grasses proved to be persistent and more productive than many of the temperate pasture species included as comparisons, and present as potential viable perennial alternative where none of the temperate grasses were able to persist. Further testing is required to confirm this finding.

At the wetter/cooler sites of this study (e.g., Orange and Cowra) a number of tropical grasses were productive and persistent but were outperformed by tall fescue and Phalaris. In these areas in current climates, tropical pastures potentially only play a complimentary role in grazing systems, however increasing temperatures and variable rainfall in these areas is likely to increase their use in pastures of the future. This result was consistent with our systems modelling findings.

Tropical grass species/cultivars which ranked high and are suitable for central and southern NSW are summarised in Fig. 90.



Establishment – choose adapted species

Species & cultivar	Light soils Sands & sandy loams pH_{Ca} <5.0–6.0	Medium soils Clay loams & silty clay loams pH_{Ca} 5.0–7.0	Heavy soils Red/grey clays & black earths pH_{Ca} 6.0–8.0
Drier/hotter areas			
Bambatsi panic		✓	✓
Digit grass cv. Premier	✓	✓	
Kikuyu cv. Whittet	✓	✓	✓
Rhodes grass cvv. Katambora & Reclaimer	✓	✓	
Panic cvv. Gatton & Megamax 059		✓	✓
Wetter/milder areas			
Bambatsi panic		✓	✓
Digit grass cv. Premier	✓	✓	
Kikuyu cv. Whittet	✓	✓	✓
Panic cvv. Gatton & Megamax 059	(not Orange)	✓	✓

Newell et al.

Fig. 90. The best performing species/cultivars of those tested in the evaluation studies and their known soil type/pH preference.

All tropical pasture cultivars had adequate mineral concentrations of Ca, Mg and P to meet the needs of grazing ruminants. The exception was the Na deficiency found in digit grass, kikuyu and bahia grass. For stock grazing these forages, provision of a supplement containing Na would be recommended to increase forage intake and subsequent growth rates.

The oldest sites in this study have only been monitored over 4 summer periods and were not grazed, therefore continued evaluation under grazing would allow their persistence and productivity to be monitored longer term. Upscaling from small plot studies will assist growers to build confidence in tropical species and help foster adoption.

We suggest that the next step to extending the distribution of tropical grasses in SE Australia is to conduct more extensive field testing including some of the species used in this study to get a better understanding of their true persistence and productivity, interaction with soils and position in the landscape in these areas.

6.1.3 Tropical perennial grass pastures can maintain or improve gross margins in central and southern NSW farming systems

Our systems modelling showed tropical pastures have a role to improve feed during summer-autumn, reduce supplementary feeding and maintain or improve farm profitability, in most locations studied. Inclusion of subterranean clover and/or annual ryegrass in the tropical grass pasture provided winter growth which is important for extending the growing season of the pasture providing feed for the majority of the year. In higher rainfall locations where lucerne can provide summer and autumn growth (e.g., Cowra and Wagga), the benefits of adding a tropical pasture were reduced. However, in lower rainfall regions there is a greater role for tropical grasses to improve profitability. This finding supported our species evaluation findings.

In recent years the climate has become more variable. This has increased variability in gross margins and reduced profitability and indicates that further adaptations to the feedbase and grazing systems will be required if this trend continues.

We improved the tropical grass parameters set used in AusFarm using comparisons with long-term data, however the revised set still underestimated pasture growth rates and digestibility and therefore animal production. During periods of peak growth the revised model was predicting only 25% of the maximum growth compared to experimental data used to validate the parameter set. This underestimation means that the modelled supplementary feed requirements for tropical grass pastures will most likely be overestimated and thus underestimating the positive effect of introducing tropical grasses.

Supplementary feed declined when tropical perennial grasses replaced a winter growing annual (average 25%). The benefit was less (6-12%) when a lucerne based pasture was replaced. One of the main benefits of tropical pastures to grazing systems will be where lucerne cannot be grown. The winter growing companion species in mixes with the tropical grass provided significant growth through winter and helped provide continuity of feed throughout the year.

Under increased temperatures and more variable rainfall, the role of tropical pastures is likely to increase, particularly where temperate perennial species fail to persist. Using a reference site approach (https://www.climatechangeinaustralia.gov.au/en/projections-tools/climate-analogues/analogues-explorer/), in 2050 (RCP 4.5 emissions scenario) the Cowra site would be represented by the Tamworth results, Wagga represented by somewhere between Condobolin and Cowra, and Condobolin would be on the wetter end of scenarios for Leeton. These highlight the continuing trend in profitability loss and increasing value of tropical grass mixed pastures in central and southern NSW production systems.

The potential to increase or maintain gross margins with tropical grass pastures is summarised by site as follows:

1. Tamworth – the highest gross margins occurred when at least 3 of the 4 paddocks were sown to tropical grasses.
2. Cowra and Wagga Wagga – there was benefit in replacing annual based pastures with 25-50% or 75% tropical at Cowra and Wagga respectively, but little difference in gross margin by replacing lucerne.
3. Condobolin – having a winter component in the summer growing pasture was important, such that there was minimal effect on gross margin by replacing lucerne-winter annual pasture with a tropical grass-winter annual mixed pasture. However, replacing pure lucerne with a tropical-clover pasture improved gross margin, with 100% tropical-clover the most profitable.
4. At Leeton, there was minimal effect of replacing annual winter pasture or lucerne with winter species with a tropical grass-annual winter species pasture. However, where lucerne was a pure stand, gross margins were improved by incorporating a tropical grass-based pasture.

Tropical grasses also provide a range of additional benefits to farming systems that have not been accounted for in this modelling. These factors, identified by producers in our social research studies, include year-round ground cover, reduced erosion and competition against difficult to manage summer growing weeds.

6.1.4 New knowledge for successful establishment of tropical pastures

Know the risk and use strategies to maximise success

There was a clear north-south gradient of emergence success evident; Tamworth in northern NSW had the highest frequency of years when emergence would occur (≥94%), reduced opportunities at Condobolin and Cowra in central NSW (71–87%) and low success at Leeton and Wagga Wagga in southern NSW (16–48%). This gradient largely reflects anecdotal experience, that the risk of establishment failure increases the further south tropical grasses are sown. Improvements to management, mainly through improved groundcover, will improve establishment success.

While the number of years with successful emergence was lower further south, the length of each emergence event increased. On average, there were similar number of days of emergence at Wagga and Leeton compared to Tamworth. Dry sowing in front of a rainfall event would likely lead to longer period suitable for emergence within the sowing window and increase the likelihood of success.

We divided historical records into two time periods to identify differences and see if there was a trajectory of change. While some locations (Cowra and Leeton) showed a relatively large increase to more favourable conditions for emergence during the recent period, on average there was only a marginal benefit, and in some locations (Condobolin and Wagga), emergence frequency declined slightly. The high year-to-year variability potentially masked any difference at these locations that may have been present.

In northern and central NSW, tropical pastures are often successfully sown in lighter soil types (R. Freebairn, pers. comm.), however, in southern NSW soil water-holding capacity appeared was an important factor determining the success of pasture emergence. As such it would appear that sowing these pastures into heavier soils in southern NSW is more likely to lead successful establishment (compared to the risk of establishment failure is high on lighter soils), being careful to avoid locations that could be exposed to winter waterlogging.

Maximise establishment success by sowing tropical grasses when soil temperatures are warming and above the recommended minimum

We recommend sowing tropical perennial grasses in spring when soils are warming with a minimum temperature of 17°C for Rhodes grass, 18°C for kikuyu, 19°C for the *Urochloa* hybrid and desmanthus, 20°C for digit grass, panic and Bambatsi panic and 22°C for paspalum. While emergence will occur at lower temperatures, at these temperatures, seedling emergence will be faster. Sowing in spring as sowing temperatures are increasing provides more opportunities for suitable rainfall to achieve successful establishment and sufficient time for establishing plants to mature before the onset of frosts.

Indicative months when these grasses could be sown at each site is shown in Table 69. While the rate of emergence and total emergence was often higher in late summer–early autumn we suggest that autumn sowing should be opportunistic, and only considered when there is (a) a very high likelihood of good rainfall over a period of ~4 days, (b) soil temperatures are several degrees above the 50% maximum emergence temperature for cooling soils determined in this study, and (c) there is a minimum of 2.5 months before the first frost likely. It is also recommended that only species with known ability to overwinter are sown, e.g., digit or Rhodes, not Bambatsi.

Ground cover can aid establishment but there’s no benefit in high rainfall years

In a year where there was good spring rainfall (129 mm rainfall and irrigation over 33 days), stubble type and tillage treatments did not affect establishment of Bambatsi panic.

For successful pasture establishment, moisture is needed in the top 10–25 mm of soil where seed is placed during sowing (Smith and Johns 1975; Lodge and Harden 2009; Harris et al. 2014a) with several days following rainfall being critical. Conditions at or near the soil surface can change quickly, especially during summer so the use of mulch or residual cereal crop stubbles that help maintain soil temperature and moisture at suitable levels are important especially in hot, lower rainfall environments. Repeating this study over multiple years which would provide a more representative range of seasons which occur in the Central west NSW is recommended to quantify the effect of stubble and tillage on tropical perennial grass emergence. The results would also be applicable to all of NSW.

Sowing time and stored soil moisture levels affect establishment

Establishment with high seedling densities can be achieved when tropical perennial grasses are sown in either spring or autumn. While establishment in summer can also be achieved it’s likely to be at a reduced rates with poorer seedling survival. Survival of seedlings into the second year was affected by the level of stored soil moisture highlighting the importance of sowing grasses into a full soil profile in spring-summer for successful pasture establishment. High levels of stored soil moisture is of less importance for autumn sown.

Stored soil moisture is less important for successful establishment in autumn because cooler season rainfall is more effective (lower evapotranspiration) and reliable than warm season rainfall, however winter survival requires plants of some species to be mature before the onset of frosts.

The following summer when all plants can be considered mature, pastures sown with high levels of stored soil moisture had greater productivity, especially the panic grasses and kikuyu. It is also interesting to note that despite the poor establishment and seedling survival of the grasses sown in summer, those that persisted provided some productivity (0.6-8.1 t DM/ha), although generally less than those sown in spring.

6.1.5 Herbicide options to control broadleaf weeds in desmanthus based pastures

To support adoption of desmanthus in NSW, ability to control broadleaf weeds in desmanthus pastures is important. Our studies identified a range of herbicides that can be used:

- Pre-emergent –imazethapyr and trifluralin
- Seedling pastures – bromoxynil and flumetsulam
- Established pastures – bromoxynil, imazethapyr and terbuthylazine. Plants also regrew well after application of paraquat.

There may also be an opportunity to use 2,4-DB in established pastures in some situations, for example, to salvage a desmanthus pasture. While 2,4-DB caused extensive distortion of the plants and reduced productivity, we observed no plant losses with no ongoing adverse effect on growth 1 month after cutting.

Our findings and those of others (e.g., Cox and Harrington 2005) will be used to prepare a minor use permit for submission to APVMA for use in NSW and Queensland.

6.1.6 Well managed tropical pastures can be successfully ensiled

Good fermentation of tropical grasses can be achieved if the pasture is vegetative (or just commencing stem elongation), wilted rapidly to 350 g/kg DM content or higher and inoculated with a bacterial inoculant.

Ensiling provides a strategy for farmers to better utilise tropical grass pastures as both a grazing and conserved forage option. The lower WSC levels and quality of tropical pastures make them more difficult to ensile than temperate species. We showed that fertilised tropical pastures in the vegetative growth stage (or just commencing stem elongation) can be successfully ensiled. For effective ensiling, the cut pasture must be wilted rapidly to 350 g/kg DM content. Adding a commercially available bacterial inoculant suitable for summer growing grass forages is also a cost-effective means to maximise opportunity for WSC to be efficiently utilised and fermentation improve. Baled silage will have lower fermentation quality than chopped silage, however, the practical implications for livestock will be minor, provided the wilt is rapid and effective, and a bacterial inoculant is used (Piltz et al. 2022).

6.1.7 Productivity of unfertilised digit grass can be increased to be equivalent to pastures fertilised long-term with moderate, but not high rates of nitrogen

Productivity of fertilised digit grass (100 and 200 kg N/ha) exceeded unfertilised digit grass (0 kg N/ha) within 1 year of sowing, while digit grass fertilised with 200 kg N/ha exceeded that fertilised with 100 kg N/ha after 3.5 years. During low rainfall seasons, the productivity of digit grass fertilised with 100 and 200 kg N/ha was similar, but once higher rainfall returned, the grass fertilised with 100 kg N/ha lagged that fertilised with 200 kg N/ha.

Productivity of digit grass with a history of nil fertiliser can be increased with moderate levels of fertility (100 kg N/ha) to be equivalent to pastures fertilised long-term with the same rate. However, for higher rates of N (200 kg N/ha), productivity lagged those continuously fertilised.

Nutritive value of unfertilised digit grass immediate after drought was high, but not maintained. In contrast fertilised digit grass (100 and 200 kg N/ha) maintained higher nutritive value with the pastures continuously fertilised being higher than those with the changed regime. This suggests consistent N application has a legacy buffering effect, especially at high rates.

We are still waiting for more soil analysis results to understand the effect of N fertiliser regime on soil N and C levels over the full 10-year period which included both severe drought and above average rainfall. However, there was a notable decline in total N% during the initial 2 years as digit grass extracted N from the soil system. There was also a net decline in N with an increasing C:N ratio, suggesting that N present in grazed or harvested material was removed from the system.

Nutritive value of these pastures following drought also showed the benefit of applied N. Immediately after the drought, initial growth of the unfertilised digit grass (nil N) was high potentially reflecting the mineralised soil N that would have been available for plant growth, but once this had been utilised, growth rates and nutritive value declined compared with the fertilised pastures. Interestingly the treatments with a continuous N application regime (i.e., 100 and 200 kg N/ha applied annually) had higher nutritive value (all components) compared to the changed regimes (i.e., nil N for 5 years then annual application of either 100 or 200 kg N/ha) for the three assessments conducted suggesting a legacy buffering effect of consistent N application.

6.1.8 Tropical perennial grass pastures have potential in central west NSW

Collectively our studies conducted in this project have provided insights into the successful establishment and ongoing productivity of tropical perennial grasses in CW NSW system. In brief:

1. Emergence success is moderate; successful emergence frequency was ~ 71–87%.
2. Establishment of most species was highest when sown in spring with high stored soil moisture. Success from autumn sowing varies with species and was only successful if plants are sufficiently mature to overwinter.
3. Perennial pastures can respond quickly to rainfall when temperatures are suitable for growth, in contrast to annual forages that need to be sown annually.
4. Long growing season; ~7 months compared with ~4-5 months for an annual forage. This means that the window to accumulate soil water over the winter period is short.
5. Deep rooted with the ability to extract water from >1.6 m depth.
6. Capable of high productivity when adequate fertilised.
7. High water use efficiency with values similar to those reported in northern NSW
8. High soil refill efficiency during winter months when the pasture is inactive (average 40%) compared with an annual forage (27%) and lucerne (18%).

Tropical grass pastures maintain greater levels of ground cover compared to lucerne and annual forages.

6.1.9 Companion temperate legumes in mixes tropical perennial grass mixes in central and southern NSW

Temperate legumes will be an important component for tropical grass pastures in central and southern NSW – providing winter feed for livestock and N for the tropical grass. This was highlighted in our farm systems modelling. We were not able to identify legumes that were best suited as companion legumes. Our study did, however, highlight the challenges for tropical perennial pasture establishment if annual temperate legumes establish at the same time, and persistence in years when there is large temperate legume production. Additionally, the challenge at drier sites such as Yanco where sown legumes simply failed to emerge. Further studies are required to understand establishment and management of these mixes. This is a priority issue identified by producers.

The three tropical grasses sown in mixes with temperate annual legumes died at the Orange site. This is contrary to the species evaluation experiment at Orange where both digit grass and Bambatsi panic were among the most persistent grasses (Newell et al., Appendix 3). This suggests that when companion temperate legumes are sown with tropical pastures, the legume biomass needs to be controlled through winter as excessing growth can cause the death of tropical pastures.

Further studies are required to understand the population dynamics of tropical grasses and temperate legumes. This will require determining the optimum time to sow each species for successful establishment (e.g., sow the legume before, with or after the tropical grass is sown/established) and how to manage to ensure the persistence of both components of the mixture (e.g., minimum residual of the grass for overwintering and legume grazing management to reduce biomass but allow seedset).

6.1.10 Understanding and manipulating species competition in mixes to achieve successful establishment in northern NSW

To realise the potential of tropical legumes, indeed mixed pastures in northern NSW, we need to be able to successfully establish legumes in mixes in new pastures and existing tropical grass or native pastures. Several studies have contributed to understanding the competition between grasses and legumes and testing strategies to manipulate the competition to achieve successful establishment.

Tropical grasses are competitive against tropical legumes in seedling mixes

In seedling mixes, all tropical grasses tested were more competitive than the desmanthus and stylo species and cultivars tested with desmanthus as a group being more competitive than the stylos. Strategies will be required to overcome this competitiveness such as adjustments to sowing rates and spatial or temporal separation as a means to reduce competition in establishing mixtures.

Our study showed that mixtures of tropical legume seedlings with tropical grasses were more likely to result in tropical grass seedling dominance potentially leading to grass dominance over the life of the pasture.

For desmanthus and stylo species to be effective companion legumes in tropical grass-based pastures sowing strategies will be required to overcome the competitiveness of the tropical grass. These strategies could adjustments to sowing rates to achieve higher plant densities of the less competitive species (e.g., reducing the tropical grass and increasing the legume), and spatial or temporal separation (e.g., sow the legume in year 1 and the grass the following year) and warrant investigation.

Spray fallows and Group 1 herbicide support successful establishment of legumes into native and sown tropical perennial grass pastures

To accumulate soil water in winter-spring for sowing tropical legumes in early summer, an 8- to 12-week fallow period appears adequate, while in summer-autumn, a 12 to 16-week period is likely necessary for sowing temperate legumes in autumn. The spray fallow needs to be effective for accumulation of soil water but maintain greater than 65% ground cover.

While final assessments are still to be made, results indicate that delaying sowing of desmanthus until early summer (December) assists its establishment. The delay allows the spray fallow to also control the tropical grass reducing its competitiveness against the establishing legume. After desmanthus has emerged, the addition of a Group 1 herbicide further checks the competitive ability of the grass pasture allowing the tropical legume to mature.

The major challenges to sowing legumes into existing perennial grass pastures is the amount of available soil water to support establishment and competition posed by perennial grasses. Spray fallows are effective for accumulating stored soil water before sowing, but should not extend beyond the duration that allows ground cover to decline below >65%.

Our spray regime did not kill the tropical perennial grass pasture, so it could potentially be conducted over a whole paddock rather than the 3 m strips we applied. This would make overall management of the paddock (e.g., grazing management) easier, but remains to be tested.

Establishing a tropical legume in spring-summer is inherently riskier than a temperate legume in autumn-winter. We had two attempts and found delaying sowing in December following an 8-12-week fallow period allowed for greater control of the tropical perennial grass. This was due to later applications of glyphosate were applied to growing plants in spring achieved a better control rate rather than application of glyphosate to dormant grasses in winter. Better suppression of the grasses provided more space and resources for the seedling desmanthus to grow. Application of a Group 1 herbicide post-desmanthus emergence provided additional and effective tropical perennial grass control in the longer spray fallow treatments. By the end of the growing season desmanthus plants were larger and more mature when sown in tropical grass pastures that had been spray fallowed and a Group 1 herbicide applied post desmanthus emergence. In the 0-week treatment, no plants were flowering, and in minus Group 1, plants were indistinguishable. Regeneration will to be assessed in summer 2022-23.

6.1.11 Characterising legume seed softening patterns to assist management recommendations

The tropical and temperate legumes tested showed a range of initial hard seed levels and breakdown patterns in northern NSW (Table 98) with management recommendations to maintain a seed bank for persistence of the legume in a long-term or permanent pasture developed:

1. *Slow breakdown (>2 years)*. This breakdown pattern in conjunction with high initial hard seed levels is highly suitable for long-term or permanent pastures. A slow breakdown pattern requires a large seed bank to ensure that there are sufficient numbers softening each year for recruitment, but only infrequent large seed set (e.g., every 3-4 years) would be required to maintain the seed bank.
2. *Moderate breakdown (1-2 years)*. To maintain a large seed bank, these systems would benefit from set seed every 2 or so years. This breakdown pattern is suitable for medium and long-term/permanent pastures, but more 'active' management would be required to ensure the legumes set seed more regularly.
3. *Rapid breakdown (<1 year).* Legumes with this type of breakdown pattern would ideally need to set seed annually. In a long-term perennial pasture these legumes would need to set seed most years to maintain a large a seed bank. Alternatively, these legumes may be better suited as a component in an annual fodder crop or a short-term perennial pasture, possibly in a cropping rotation.

Table 98. Hard seed breakdown pattern matrix for tropical and temperate legumes

Breakdown pattern	Initial hard seed levels		
	High	Medium	low
Slow (> 2 years)	Desmanthus cv. Marc Barrel medic cv. Caliph		
Intermediate (1-2 years)	Desmanthus cv. JCU2 Bladder clover cv. Bartolo Biserrula cv. Casbah Snail medic cv. Silver	Caatinga stylo cv. Primar	
Rapid (<1 year)	Fine stem stylo Arrowleaf clover cv. Cefalu Yellow serradella cv. Santorini	Siratro cv. Aztec Burgundy bean cv. B1 Subterranean clover cv. Clare and Dalkeith French serradella cv. Margurita	Butterfly pea cv. Milgarra Woolly pod vetch cv. Haymaker

Local experience and anecdotal evidence indicate that seed banks of some of these species last longer than our data suggest, for example, burgundy bean, serradella and arrowleaf clover. Large desmanthus seedling recruitment observed in the field also suggests that patterns of hardseeded breakdown may also be faster than our results indicate. These differences could be due to a range of factors including environmental conditions (Kirchner and Andrew 1971; Fairbrother 1991; Taylor 2005; Howieson and Hackney 2018), seed placement (Revell and Taylor 1998; Loi et al. 1999; Taylor and Revell 2002), and ground cover that affects ground temperatures (Quinlivan 1965; Lodge et al. 1990).

6.1.12 Equal proportions of digit grass and lucerne in mixes maximise production, water use and nitrogen fixation

Over the 4 years of the study, 50% lucerne had the most consistent annual herbage production, plus the highest overall water productivity and N fixation (assessed 1 year only). The N fixation study suggested that lucerne densities of 50–75% were required to better meet the demands of digit grass in a mixed pasture. At 25%, lucerne did not fix sufficient N to meet the demands of the mixture while lucerne growing on its own fixed less N, because it had exclusive access to any mineralised N.

This study experienced two periods of contrasting weather conditions; the first was hot and dry, and the second was mild and wet. The hot and dry conditions favoured digit grass, and mixes with ≥50% digit grass (i.e., ≤50% lucerne) were the most productive and had the highest water productivity. In contrast, the mild and wet conditions favoured lucerne, and mixes with ≥50% lucerne were more productive. In mixtures of tropical perennial grasses and legumes, the species whose growth is favoured by temperature at the time of rainfall or water availability, dominates the soil water balance (Murphy et al. 2022).

N_2 fixation varied during the growing season as the plant demand for N changed due to (a) moisture conditions favouring growth, (b) moisture and temperature conditions favouring mineralisation of soil organic matter to yield available mineral N, and (c) moisture and temperature conditions favouring the competition for soil mineral N from digit grass.

Lucerne shoot N in our samples was 3.7% compared with 3.4% (average of 77 Australian studies, Unkovich *et al.* 2010). The %Ndfa in our study was also slightly higher than for previous studies (67%, range 34–95% cf. 60%, range 17–90%) which have focussed on pure stands rather than mixed swards. The total amount of N fixed by the lucerne component (153 kg N/ha) was also above average for cumulative total fixed shoot N compared to other Australian research (2–284 kg N/ha, mean: 91). Assuming a typical shoot:root ratio for grazed/mown lucerne of 1:1 (Unkovich *et al.* 2010), the total amount of N fixed by the lucerne in this environment would be ~300 kg N/ha. This is well above the 100 kg N/ha applied as fertiliser to the pure digit sward. Additionally, the contribution of lucerne root material to soil organic N would add to the pool of readily mineralisable N for following seasons.

6.1.13 New knowledge for successful management of desmanthus in mixed pastures

Our studies conducted during this project have provided multiple learnings for the management of desmanthus in tropical pastures:

1. Sow desmanthus in warming soils at a minimum of 19°C for rapid seedling emergence. Sowing in autumn is not recommended as there is insufficient time for the plants to set seed before frosts commence. In northern NSW, select early flowering cultivars for use in perennial pastures.

2. Desmanthus cultivars are hard seeded (≥79%) but have different hard seed breakdown patterns. Cultivar Marc has a slower breakdown pattern than JCU2
3. Desmanthus is not as productive as lucerne but can provide useful a contribution in mixed pastures.
4. A rest period of ~11 weeks was suitable for recruitment of both desmanthus and digit grass but only seed set of digit grass. During the extended rest period, digit grass growth was extensive (14-16 t DM/ha) with flowering stems growing to >1 m height shading desmanthus sufficiently to have inhibited plant growth.
5. Digit grass has higher growth rates and is highly competitive towards desmanthus in establishing and established stands.
6. Digit grass commences spring growth earlier than desmanthus. The grass therefore gets first and uninhibited access to mineralised N and stored soil water.
7. Desmanthus (cv. Marc) can extract water to 1.8 m soil depth.
8. Desmanthus is highly palatable to livestock and sheep are more proficient at selective grazing than cattle. Tall pastures are also better suited to cattle. These features collectively suggest that digit grass-desmanthus pastures may be better suited to cattle than sheep because the stocking rates and intensity required to maintain the pasture in the range suitable for sheep is not conducive to desmanthus regrowth.
9. Slashing frosted desmanthus plants which have large woody stems in late winter may have been detrimental to their persistence. We observed that crowns of plants had been broken. This possibly left plants vulnerable to infection.

6.1.14 Leucaena is persistent with sustained production over variable rainfall years

Northern NSW had traditionally been considered unsuitable for leucaena. Our 10-year study has demonstrated leucaena can be persistent in northern (>80% plant survival) and less so central NSW (≥50%). Once established leucaena can maintain productivity over variable rainfall conditions. While it is not as productive as either lucerne or desmanthus, leucaena was the only pasture species that continued to grow during drought, highlighting its potential as a drought fodder option.

Despite its potential, NSW DPI will not be recommending leucaena due to it weediness but look forward to the opportunity to evaluate the sterile/seedless lines that are being developed in NSW.

All commercial cultivars of leucaena were highly persistent (>80%) at the two Northern Inland NSW sites Bingara and Manilla with no plant losses after 2015 (2 years after establishment). Leucaena persistence at Trangie was more variable, but the majority of losses occurred in the establishment year with some small losses in plant numbers towards the end of the experimental period. Persistence of the commercial cultivars was ≥50%.

In our genotype by environment study, total herbage mass production, was variable across sites being highest at Bingara (50.2 t DM/ha), followed by Manilla (34.1 t DM/ha) and Trangie (17.7 t DM/ha). Over the three sites cvv. Wondergraze and Cunningham ranked the highest for persistence and production (Bingara and Manilla) or production (Trangie). The higher herbage production at the Bingara site in comparison with the similar Manilla site, may be attributed to higher fertility at the Bingara site (Harris et al. 2019), timing of rainfall, or lack of grass competition as digit grass failed to establish in the alley between the rows.

Leucaena is frosted most years in this environment, requiring plants to recommence growth in spring as fresh buds from the plant crown. During one winter (2016), the leucaena plants were not frosted resulting in strong growth the following spring with the first graze occurring in early November instead of December-January. In this year, leucaena accumulated its maximum annual yields up to 10.3 t DM/ha, double the productivity of the other years (Murphy et al. 2022). This slow growth and therefore need to delay grazing should be take into consideration when sown (e.g., higher in the landscape to avoid frost and/or with a north facing aspect) as well as being considered within the structure of a productive livestock enterprise.

Leucaena seedlings are slow to establish and respond poorly to competition (Dalzell et al. 2006), hence the best management practice in Queensland to establish the grass after the leucaena, rather than simultaneously (Dalzell et al. 2006). However, establishing the mixed pasture over 2 years was not successful in this environment (Harris et al. 2019). Our results clearly showed that while competition from digit grass sown at the same time and 1 m from the leucaena rows did not affect plant establishment or persistence, yield was negatively impacted. If both leucaena and digit grass are simultaneously established, then a wider grass-free buffer is required (e.g., a minimum of 3 m). The grass could set seed in the first year and encroach on leucaena without ill effect.

During drought, leucaena remained green and continued to grow in all of our experiments when other species, such as tropical grass and lucerne, had ceased. In these challenging growing conditions, leucaena in both mixed and pure swards was the most productive pasture tested (Murphy et al. 2022). This continued productivity highlights the potential of this legume as a fodder reserve during drought.

Despite our increased confidence on the adaptation of leucaena to Northern Inland NSW and to a lesser degree Central West NSW, NSW DPI will not be recommending the legume to producers until sterile cultivars have been evaluated and are available to mitigate the weed risk.

6.1.15 Understanding producer perceptions to develop quality targeted extension programs

There is a groundswell of producers in southern NSW who have sown or are interested in trialling tropical grasses. This provides an opportunity to build on this momentum and support producers and their service providers. Those setting out to engage producers about tropical grasses need to be aware of their experience. They also need to be aware of the important drivers that can be used to foster practice change as this may not always be association with maximising production or financial gain.

Our study showed that for producers with limited experience with tropical pastures, the initial learning opportunities should focus on the principal and practices critical to successful establishment. These should be tailored to local contexts. They should also demonstrate how tropical grasses could contribute to the feedbase and increase the livestock carrying capacity. It will also be important to provide the economic costs and returns of incorporating tropical grasses from credible sources.

For experienced producers, focusing on activities that support their management of tropical pastures will assist them to take full advantage of the opportunities that tropical grasses present. These include the ability to integrate a legume, grazing strategies to maintain forage quality and managing soil fertility to ensure critical macro elements are non-limiting. These important post establishment issues are relevant also to the inexperienced producers.

Our approach was particularly valuable for understanding the personal characteristics of producers, the context in which they operate, their perceptions of and knowledge about these grasses. We have identified current drivers and constraints to the adoption of these grasses, particularly for inexperienced producers. It has provided evidence on which to base effective extension planning and targeted delivery rather than making assumptions about what information and learning producers ought to have to support their decisions about tropical grasses.

Across NSW, producer experience with sowing and managing tropical grass pastures is variable therefore 'fit for purpose' extension plans and activities are required. With increasing interest in tropical pastures in central and southern NSW, future extension should focus on approaches that will engage substantial numbers of producers.

Across central and southern inland NSW, there is the need for/to:

1. *Quality extension activities*. A multifaceted approach is required but could include a network of commercially sown tropical grass pastures located across different geographies. These sites can be a base to promote engagement with producers, provide opportunities for knowledge and skill development, and for producers to share their knowledge and experience with their peers. These sites should be located across the state and evaluate species under grazing conditions.
2. *Upskill service providers*. Engage with local service providers to build their technical knowledge and confidence to deliver quality advice. This includes government extension staff, private consultants, seed companies and retail agronomists to effectively promote tropical grasses and ensure consistent advice is provided across the different client bases.
3. *Conduct research to address important unaddressed issues*. These could be conducted as discrete studies (pot or field) or larger on farm larger plots, for example, integrating suitable legumes with tropical grasses; soil type x species/cultivar evaluation; validating soil temperature to refine optimum time of sowing for different geographies; and economic and animal production case studies for sheep and beef enterprises.
4. *Resources*. Develop specific tropical grass resources to meet the information and learning needs of producers and their advisors in these regions. Resources should consist of different learning materials which could include comprehensive booklets (in print and electronic format) which provide agronomic information, economic analyses and local producer case studies/testimonials; glovebox guides/mobile phone apps for principles and practices for establishment and management; and short videos providing key technical information and local producer case studies.

A streamlined approach to understanding a target audience to develop a quality extension program – a recommendation

We suggest that the information required to conduct an effective extension program can be gathered using a mix of qualitative and quantitative methods. We recommend conducting a series of workshops with purposefully selected participants followed by in-depth interviews with purposefully selected interviewees. The quantitative outputs from the ADOPT tool can complement the qualitative findings from the workshops and interviews. This process will provide cost-effective and timely evidence to effectively employ a structured rather than an ad hoc approach in engaging and delivering extension

Due to time and financial constraints, as well as specialists with expertise in social research, it is not realistic or practical for all projects to be undertaken with extent of social research that we have in this project to understand our target audience. For a modified approach to develop a high-quality extension program within a research project, we recommend:

1. Use the ADOPT tool (https://adopt.csiro.au/) at the beginning of a research project to make some estimates about the extent and rate of adoption of the new practice. It can be used to identify gaps in knowledge of the potential drivers and challenges that could influence producers' decisions about adopting the practice.
2. Collect data about property, personal and social factors influencing the decision-makers perceptions about the new practice; their knowledge about the new practice and their interest in trialling the new practice.
3. The information developed and the location of field sites must be 'fit for purpose' for producers to have confidence the new practice will perform in their location.

Tropical perennial grass seed quality and price – a restriction to adoption

To realise the significant investment in tropical grass RD&E producers need access to quality seed at reasonable prices.

Both experienced and inexperienced producers consistently identified seed quality and price as an issue with tropical grasses. Inexperienced producers concerned about the issue are significantly less likely to trial these grasses over the next three years. This is a constraint to increasing the rate and extent of adoption. Conversely, those inexperienced producers more concerned about the poor persistence of traditionally sown temperate species are significantly more likely to trial tropical grasses.

To keep this issue in context, it is important to remember that the majority of this project was conducted during a severe drought. The length of the drought meant that seed stocks were low with high quality seed hard to find. Additionally, the seed quality of many tropical grasses is commonly lower than temperate grasses.

5.2 Benefits to industry

With highly variable and changing climates, and projections for further increases in temperature and changing rainfall distribution, we have provided data that quantifies the potential of tropical species in grazing systems. Based on our work on a novel group of tropical grasses and legume our results provide evidence that assist producers in grazing systems of SE Australia make informed decisions before trialling these species. Our social research highlighted that evidence is an essential requirement for successful adoption to occur.

Our project provided a focal point for producers in central and southern NSW interested in tropical pastures. This has allowed us to simultaneously raise both awareness and provide support based on quality evidence-based findings for both producers and advisors. We have successfully drawn together many parties involved in the grazing industries (producers, advisors, seed companies) and provided quality technical information and available resources to these parties. We also assisted in the development of new networks among southern and northern agronomists. We have gained momentum in southern NSW which places MLA in prime position to support producers in adopting these new technologies.

For red meat producers who have experience with tropical pastures we have provided new knowledge to support their decision choosing suitable companion legumes for tropical grass pastures, plus evidence-based strategies to better utilise these pastures via fodder conservation.

We have had an integral role increasing awareness and interest in tropical pastures among red meat producers in NSW. Moreover, the drought in 2020 highlighted the resilience of these pastures – their drought persistence and the speed with which they could respond to the summer rainfall. This inspired producers across the red meat zone, including northern NSW where there is experience sowing and managing these species, and southern NSW where they are a novel group of species.

6 Recommendations and future research

7.1 Practical implications

Our collective findings provide largely practical knowledge that can assist the development and/or improvement of technical information to support adoption and utilisation of tropical pastures. They will be key resources for those engaging with and supporting producers trialling tropical pastures in their systems and improve their management and utilisation to maximise their pastures

7.2 Future R&D

We have identified two main areas for future RD&E. These project areas build on our findings supporting the red meat industry preparing for future challenges, including changing climate, and reducing and mitigating emissions.

7.1.1 Increasing livestock production by integrating tropical pastures into farming systems II

Our current project has shown the potential of tropical pastures in southern NSW and developed a significant awareness of these species. Phase II of this project will build on the momentum we have gained, bringing together producers, their advisors and other interested parties (e.g., seed companies, agribusiness, and societies and groups). We will support trialling and build further knowledge in a co-learning environment. We will also address issues which have been identified as barriers to adoption.

Capitalising on the interest and trialling that has already commenced by early adopters of this technology, we are well positioned to conduct activities that facilitate adoption. This will need to be a multifaceted approach tailored to suit different areas and will vary depending on the interest, experience, level of understanding, and challenges in the target areas. This will be predominantly a development and extension program with the primary objective of adoption. The project will also contain a research component to investigate known issues but with the flexibility to address issues that are identified during the project within the design led thinking framework. For example, a major issue still to be addressed is the establishment and management of companion legumes to provide stable grass-legume pasture mixtures.

This project led by NSW DPI, would have three target zones which will have different needs and require different approaches for engagement:

1. Central and southern NSW

There is already awareness and increasing interest in tropical pastures in this region with producers currently trialling these species championing their use in grazing systems. Our activities will primarily focus on resource/package development and extension, with a small component of research to address known deficits in knowledge (e.g., compatible temperate legumes) with the flexibility to address issues as they are identified.

We will form groups consisting of farmers, advisors, extension specialists and scientists to plan priorities and activities. These activities may include:

- Develop material and conduct on-farm demonstrations and support groups that have current MLA PDSs e.g., Holbrook Landcare Network. As groups like this do not occur across the state, a more coordinated approach with agencies, agricultural/agronomical service providers (e.g., Elders, Nutrien), seed companies, and/or other relevant agencies or organisations could be undertaken.
- On farm demonstrations and monitoring to validate species productivity and persistence and optimum sowing time for successful establishment.
- Economic case studies for a range of livestock enterprises (breeding, fattening, sheep and cattle) showing the benefits and challenges of tropical pastures in grazing/mixed farming systems.
- A small research component that is flexible and provides opportunity to conduct issues already identified as priority, plus others that are identified during the project using design led thinking practices.
- Tropical grass species evaluation packages (‘species kits’) available to groups and advisors across SE Australia plus kits in collaboration with other agencies (state government agencies, universities and/or Grassland Societies).

2. Low rainfall western environments

Our species evaluation showed the ability of tropical grasses to persist in low rainfall areas of Goolgowi, Condobolin and Yanco. Producers in these low rainfall areas are interested in tropical pastures; some travelling 2 hrs to participate in our field days. Further work is required to determine their long-term persistence across a broader area in this rainfall zone, also management (e.g., establishment and fertility) and economic viability (return on investment). Activities in this area could include a series of species evaluation experiments (i.e., species kits) that contribute to a larger SE Australian network, case studies and field days.

3. SE Australia beyond NSW

Our modelling indicated that areas in SE Australia beyond NSW could sustain tropical pastures. This project would provide an opportunity to evaluate a range of species in collaboration with producers, advisors and other interested organisations. Species kits could be distributed for sowing in a range of locations. These would be replicated to produce a genotype x environment network across SE Australia.

7.1.2 Sequestering carbon and reducing methane emissions with tropical legumes in southern latitudes

Red meat producers are looking for pasture species and mixes which offer multiple benefits for their grazing systems. They are seeking pastures that are adapted to variable and changing climates, reduce methane emissions, and are capable of sequestering carbon while maintaining or improving animal production. Tropical pastures that are drought and cold persistent, containing species with lower methane potential and a legume to provide N, that also provide a longer-term more stable source of carbon sequestration have merit. Red meat producers in the frost-prone summer dominant rainfall zone have a range of commercial grasses they can utilise. While two legumes have been identified, low growth rates, poor competitiveness against grasses, and limited frost tolerance restrict their productivity. Additionally, weediness of leucaena severely restricts its potential in NSW. A study of species used in northern Australian grazing systems showed there is significant species and seasonal variation in *in vitro* methane production among both tropical grasses and legumes (Durmic et al. 2017). Little is known of the methane production of tropical pasture species utilised in frost prone regions of the summer dominant rainfall zone. Nitrogen fixation and cycling in mixed tropical pastures is not well understood and poor rhizobia survival has been identified as an issue (e.g., McInnes and Date 2005). The ability of more fibrous/woody legumes such as leucaena and desmanthus in mixed tropical pastures to sequester carbon also warrants investigation.

This 5-year RD&E project will involve three components conducted concurrently:

1. *Quantifying methane production and carbon sequestration of tropical species*. New and elite lines and commercial cultivars of tropical legumes and grasses will be evaluated for seasonal methanogenic potential, nutritive value, growth rate, C sequestration and persistence in northern NSW. Examples of material/species that will be included in the evaluation:

   a) Sterile/seedless leucaena. These lines offer potential for NSW red meat producers to utilise this persistent legume. The material developed by University of Queensland and Department of Primary Industries and Regional Development (DPIRD), WA require field evaluation to test their productivity and persistence.
   b) Elite *Stylosanthes* material developed in Southern Queensland are suited to lighter soils and likely have greater cold tolerance than the commercial cultivars. This material warrants testing in northern NSW.
   c) Species/accessions identified as having potential in previous R&D programs conducted in Southern Queensland (e.g., CoPE, NAPLIP) and untested germplasm collected from environments and/or latitudes similar to northern and central NSW (e.g., *Desmanthus tatuhyensis* [B. Pengelley, R. Clem and B. Reid, retired CSIRO and DAFQ scientists, pers. comm.])
   d) Tropical legumes for acid soils (pH_{Ca}<6.0). There are no tropical legumes available for acid soils. This is a significant gap identified by red meat producers and advisors in inland and coastal regions.

2. *Component studies to address identified knowledge gaps*. Studies will investigate N fixation in tropical grass-tropical legume mixes to quantify and maximise fixation in mixed pastures, also the transfer of N from the legume to the grass. Other studies will include screening current cultivars and elite *Desmanthus* spp. for susceptibility to alfalfa mosaic virus, soil water use dynamics in tropical legume mixes.

3. *Extension and adoption*. Adoption of new technologies, such as desmanthus as a persistent companion legume for tropical grasses in northern NSW, requires ongoing support provided to producers and their advisors. In the last 5 years the number of commercially available cultivars of desmanthus has expanded from several to ~14. Testing these cultivars on farm under commercial grazing regimes is required to give producers confidence in the cultivars suited to their system. On farm monitoring of these pastures would also inform and validate establishment and management recommendations. Case studies would also highlight the benefits and challenges of using these species.

This project would be led by NSW DPI and be a collaborative project with at least one seed company. This would provide a pipeline for delivery of any elite germplasm that may be identified for development. Findings from this project, especially productive persistent germplasm would also be suitable for southern Queensland. This project links with other projects in the MLA CN30 program.

7 Acknowledgements

We gratefully acknowledge the following:

1. Technical support which was integral to the management of experiments and data collection provided by Mark Brennan, Geoff Bevan, Kylie Cooley, Susan Langfield, Karen Lowien, Neil Munday, Cameron Murray, Peter Preferment, Andrew Price, Warren Smith, Ian Toole, Lance Troy, Peter Tyndall, Binbin Xu, Daryl Reardon and Scott Richards.
2. Expert advice and/or support provided by Steven Harden (NSW DPI, biometrics), Allan Curtis (CSU, social research), Chris Gardiner (JCU, CLIMEX maps), Paul Sandford (DPIRD, CLIMEX maps), Geoff Moore (DPIRD, CLIMEX maps), David Lloyd (retired, formerly DAFQ, CLIMEX maps), Kendrick Cox (DAFQ, CLIMEX maps), and Neville Herrmann (CSIRO, AusFarm).
3. Our collaborating farmers who generously provided land for experiments: Phillip and Annette Butler, 'GlenAyr', Bingara; Robert and Lea Bowman, 'Fairfield', Manilla; Ian, Faye and Gavin Heywood, 'Marathon', Manilla; Ray and Michele Cheers, Goolgowi; Chris Dedes, Guyra; John, Laurie and Tom Chaffey, 'Werona', Attunga.
4. Seed supplied for experiments by Barenbrug, DLF Seeds, Agrimix, Selected Seeds and Upper Murray Seeds.
5. Bacterial inoculants for ensiling studies donated by Lallemand and Pioneer.

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9 Appendices

While several of the studies described in this report have been published, the majority are being prepared for submission to scientific journals. To avoid jeopardising publication they are unable to be published as part of this report. For further information on any of the studies conducted in this report the Project Leader can be contacted: Suzanne Boschma, suzanne.boschma@dpi.nsw.gov.au.

The following appendices are available for MLA internal use with links to published results provided for general use:

1. Modelled potential distribution of tropical perennial pasture species in current and future climates for Australia with special reference to SE Australia. Preliminary results published: Simpson et al (2019); Conference 2019 | Grassland Society of NSW (grasslandnsw.com.au)
2. The potential of tropical perennial grasses in grazing systems in NSW – Modelling. Preliminary results published: Broadfoot et al. (2022); http://agronomyaustraliaproceedings.org/images/sampledata/2022/Pastures/ASAbroadfoot_k_400s.pdf
3. Herbage mass, persistence and forage mineral content of tropical grasses grown in eight contrasting sites across NSW.
4. Expected emergence of tropical grasses in southern Australia. Preliminary results published: http://agronomyaustraliaproceedings.org/images/sampledata/2022/Soil/ASAbroadfoot_k_402s.pdf
5. Quantifying seedling emergence response of tropical perennial pasture species to temperature to determine sowing time recommendations.
6. Seedling establishment and persistence of six tropical grasses. Preliminary results published: Alemseged and Smith (2019), Conference 2019 | Grassland Society of NSW (grasslandnsw.com.au)
7. Impact of cover on tropical perennial grass establishment and survival.
8. Herbicides for control of broadleaf weeds in desmanthus (*Desmanthus virgatus*) pastures.
9. Fermentation quality of silages produced from wilted sown tropical perennial grass pastures with or without a bacterial inoculant. Published: https://doi.org/10.3390/agronomy12071721
10. Quantifying the response to nitrogen fertiliser of herbage productivity and soil nitrogen levels over 10 years
11. Tropical pasture water use and production in Central West NSW. Preliminary results published: Uddin et al. (2021), Conference 2021 | Grassland Society of NSW (grasslandnsw.com.au)
12. Replacement series study – seedling competition of tropical legumes sown with tropical grasses.
13. Establishing legumes into existing perennial grass pastures.
14. Hard seed breakdown patterns of temperate and tropical legumes in northern inland NSW.
15. Rotational versus continuous grazing for persistence of tropical pastures.
16. A lucerne-digit grass pasture offers herbage production and rainwater productivity equal to a digit grass pasture fertilized with applied nitrogen. Published: Murphy et al. (2022), https://doi.org/10.1016/j.agwat.2021.107266
17. Potential of temperate legumes suitable as companion species for tropical perennial grasses in central and southern NSW – a preliminary study.

18. Long-term persistence and productivity of leucaena in Northern Inland, and Central West NSW. Publication on the initial productivity and persistence: Harris et al. (2019), https://doi.org/10.17138/tgft(7)120-126
19. Digit-lucerne density replacement series competition experiment. Preliminary results published: Murphy et al. (2019), Conference 2019 | Grassland Society of NSW (grasslandnsw.com.au)
20. Digit-lucerne density replacement series competition experiment – Legume nitrogen fixation.
21. Enablers and constraints to trialling and successful management of tropical grasses. Preliminary results published: Sinclair et al. (2019), Conference 2019 | Grassland Society of NSW (grasslandnsw.com.au) and Sinclair et al. (2021), Conference 2021 | Grassland Society of NSW (grasslandnsw.com.au)