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Research Paper

Seedling emergence of tropical perennial pasture species in response to temperature used to determine sowing time recommendations

Emergencia de plántulas de especies de pasto perennes tropicales en respuesta a la temperatura utilizada para determinar recomendaciones de época de siembra

MARJA SIMPSON[1], SUZANNE PATRICIA BOSCHMA[2], YOHANNES ALEMSEGED[3], MATTHEW THOMAS NEWELL[4], MARK ROGER NORTON[5], WARREN JOHN SMITH[3], MARK ANDREW BRENNAN[2], NEIL MUNDAY[1], STEVE HARDEN[2] AND ANDREW PRICE[5]

[1] *NSW Department of Primary Industries, Orange Agricultural Institute, Orange, Australia.* dpi.nsw.gov.au
[2] *NSW Department of Primary Industries, Tamworth Agricultural Institute, Calala, Australia.* dpi.nsw.gov.au
[3] *NSW Department of Primary Industries, Trangie Agricultural Research Centre, Trangie, Australia.* dpi.nsw.gov.au
[4] *NSW Department of Primary Industries, Cowra Agricultural Institute, Cowra, Australia.* dpi.nsw.gov.au
[5] *NSW Department of Primary Industries, Wagga Wagga Agricultural Institute, Wagga Wagga, Australia.* dpi.nsw.gov.au

Abstract

Tropical pasture grasses and legumes can be highly productive and persistent and fill the summer-autumn feed gap typical of temperate pasture systems in southern Australia. However, more information is needed on optimum temperature range for seedling emergence because this will influence sowing time recommendations. A replicated field experiment was conducted at 5 locations in New South Wales over a 12-month period to determine the optimum temperature for emergence of a range of tropical species: Rhodes grass (*Chloris gayana* Kunth), Makarikari grass (*Panicum coloratum* L. var. *makarikariense* Gooss.), kikuyu grass (*Cenchrus clandestinus* (Hochst. ex Chiov.) Morrone), digit grass (*Digitaria eriantha* Steud.), panic grass (*Megathyrsus maximus* (Jacq.) B.K. Simon & S.W.L. Jacobs), paspalum (*Paspalum dilatatum* Poir.), *Urochloa* hybrid (*Urochloa decumbens* × *U. ruziziensis* × *U. brizantha*), 2 cultivars of *Desmanthus virgatus* (L.) Willd. (cultivars 'Marc' and 'JCU2'), *D. bicornutus* (S. Watson), *D. leptophyllus* (Kunth) and *D. pernambucanus* (L.) Thell.). Rhodes grass emerged satisfactorily over the longest time across all sites, exhibiting the greatest temperature range over which emergence occurred, while Makarikari grass and panic grass had the narrowest temperature range for emergence. The temperature for 50% emergence differed between the tropical species and whether the soils were warming or cooling. Rhodes grass had the lowest 50% emergence temperature (17 °C) while paspalum had the highest (22 °C). Results showed that temperature for 50% emergence is a useful indicator for determining sowing time in warming soils.

Keywords: C4 species, drought, heat, optimum emergence, pasture.

Resumen

Las gramíneas y leguminosas de pastos tropicales pueden ser altamente productivas y persistentes, llenando la falta de alimentos en verano y otoño típico de los sistemas de pasturas templadas en el sur de Australia. Sin embargo, se necesita más información sobre el rango óptimo de temperatura para la emergencia de plántulas, ya que esto influirá en las recomendaciones sobre la época de siembra. Con ese propósito se condujo un experimento de campo replicado

Correspondence: M. Simpson, NSW Department of Primary Industries (NSW DPI), Orange Agricultural Institute, 1447 Forest Road, Orange, NSW, Australia.
Email: marja.simpson@dpi.nsw.gov.au

en 5 ubicaciones en Nueva Gales del Sur, durante un período de 12 meses, para determinar la temperatura óptima para la emergencia de un grupo de especies tropicales: pasto Rhodes (*Chloris gayana* Kunth), pasto Makarikari (*Panicum coloratum* L. var. *makarikariense* Gooss.), pasto kikuyu (*Cenchrus clandestinus* (Hochst. ex Chiov.) Morrone), pasto pangola (*Digitaria eriantha* Steud.), pasto guinea (*Megathyrsus maximus* (Jacq.) B.K. Simon & S.W.L. Jacobs), paspalum (*Paspalum dilatatum* Poir.), híbrido de *Urochloa* (*Urochloa decumbens* × *U. ruziziensis* × *U. brizantha*), 2 cultivares de *Desmanthus virgatus* (L.) Willd. (cultivares 'Marc' y 'JCU2'), *D. bicornutus* (S. Watson), *D. leptophyllus* (Kunth) y *D. pernambucanus* (L.) Thell.). El pasto Rhodes emergió de manera satisfactoria durante un período más largo en todos los sitios, exhibiendo el mayor rango de temperatura en el que ocurrió la emergencia, mientras que el pasto Makarikari y el pasto guinea tuvieron el rango de temperatura más estrecho para la emergencia. La temperatura para el 50% de la emergencia difirió entre las especies tropicales y si los suelos se estaban calentando o enfriando. El pasto Rhodes tuvo la temperatura de emergencia del 50% más baja (17 °C), mientras que el paspalum tuvo la más alta (22 °C). Los resultados mostraron que la temperatura para el 50% de la emergencia es un indicador útil para determinar la época de siembra en suelos que se están calentando.

Palabras clave: Calor, emergencia óptima, especies C4, pasto, sequía.

Introduction

Tropical pasture grasses and legumes are an important component of grazing systems globally, due to their productivity and persistence within tropical and sub-tropical environments (Moser et al. 2004). In northern Australia, they are an integral part of livestock systems. Their higher production, nutritive value and longer growing season, compared with native grassland species, can significantly improve the productivity and profitability of northern Australian grazing enterprises (Quirk and McIvor 2006). Over recent decades adoption of these species has extended into the frost-prone summer dominant rainfall region in northern inland New South Wales (NSW) (Boschma et al. 2008, 2009; Nie et al. 2008) and the medium-low rainfall zone of southern Western Australia (Moore and Barrett-Lennard 2006; Moore et al. 2021). Over the last few years, there has been increasing interest in tropical grasses in temperate areas in southeastern Australia. In this region the growth pattern of tropical grasses allows them to utilise summer rainfall, with potential to assist with filling the traditional summer–autumn feed gap. Tropical pastures also reduce soil erosion and provide ground cover and competition to reduce weed invasion (Descheemaeker et al. 2014).

The success of pasture establishment is influenced by a range of factors including ground preparation, sowing depth and seed quality. The time from sowing until emergence is highly influenced by temperature (Angus et al. 1980), however, limited information is available on the optimal temperatures for sowing tropical pasture species in sub-tropical and temperate environments. Sowing when temperatures are optimal or near optimal will improve germination and, subsequently, success of establishment. In the absence of species-specific information, the recommended sowing temperature for forage sorghum (*Sorghum bicolor* (L.) Moench), when soil temperatures are above 15 °C, is sometimes used for tropical perennial pasture species (Cook et al. 2020). Field studies with tropical perennial grasses, such as, Rhodes grass (*Chloris gayana* Kunth cultivar 'Katambora'), kikuyu grass (*Cenchrus clandestinus* (Hochst. ex Chiov.) Morrone synonym *Pennisetum clandestinum*, cultivar 'Whittet'), Makarikari grass (*Panicum coloratum* L. var. *makarikariense* Gooss.), digit grass (*Digitaria eriantha* Steud.) and paspalum (*Paspalum dilatatum* Poir.) suggest optimal soil temperatures for germination in the range of >15–18 °C (Moore and Barrett-Lennard 2006; Nie et al. 2008) with day-time temperatures of 20 °C and night-time temperatures of 10 °C (Harris et al. 2014). Lodge and Harden (2009) investigated the effect of sowing time and depth on seedling emergence for several tropical grasses and recommended spring sowing when mean daily soil temperatures are >22 °C and mean maximum and minimum temperatures are >26 and >16 °C, respectively.

Several studies have shown that emergence temperature requirements of tropical forages differ between species. Watt and Whalley (1982) investigated optimum germination temperature using germination pads and found the optimum germination temperature range for Rhodes grass cultivar 'Katambora' was 20–30 °C while Makarikari grass ranged from 25–35 °C. Nichols et al. (2012) used a water agar medium and reported optimum germination temperature for kikuyu grass cultivar 'Whittet' ranged between 20–35 °C, Rhodes grass between 25–30 °C and digit grass cultivar 'Premier' between 20–25 °C. Egan et al. (2017) tested seedling emergence using a sand and peat mix in a growth cabinet and reported that optimum temperature for seedling emergence for Makarikari grass was between 24–35 °C, digit grass between 21–32 °C, panic grass (*Megathyrsus maximus* (Jacq.) B.K. Simon & S.W.L. Jacobs cultivar 'Gatton') between 24–32 °C and Rhodes grass between 24–35 °C. Egan et al. (2017) also identified temperatures for 50% of maximum emergence to determine recommended sowing time. These temperatures were between 12–14 °C for Rhodes grass and between 17–18 °C for digit grass and Makarikari grass. Angus et al. (1980) identified the base temperature for emergence for a range of temperate and tropical crop species under field conditions and found no emergence of tropical species below 10–14 °C.

Seedling emergence in the field is affected by several factors, including soil type, soil moisture content, wind and temperature. Controlled studies are highly effective at illustrating germination rates, however, the contrived conditions in which they are conducted have limited field application. Determining optimum temperatures for emergence under more variable conditions, such as in the field, are considered more robust for determining sowing times for specific localities. Therefore, an experiment was conducted at 5 locations, including novel growing environments, to quantify field emergence and determine optimum temperatures for emergence that could be used to recommend the earliest sowing time of a range of tropical species.

Materials and Methods

Experiments were conducted at 5 contrasting sites across NSW, which represent existing and potential areas of adaptation for the selected tropical pasture species. These sites were Tamworth, Trangie, Orange, Cowra and Wagga Wagga (Table 1). Four core species were sown at all sites with additional species sown at Trangie and Tamworth (Table 2). The species tested were included based on a distribution modelling study that indicated suitability at the selected study sites at current and future climate scenarios (Simpson et al. unpublished). The distribution modelling study was Australia wide and shows the extent of suitability for the continent. Horticultural seedling trays (330 × 280 × 50 mm deep) used at each site were filled with brown Chromosol soil (Isbell 2021) sourced from 0–50 mm depth at a single location at NSW Department of Primary Industries' Agricultural Research Institute, Trangie, NSW. This soil had a history of summer weed control with no residual herbicide. The soil was passed through a 5 mm sieve to remove large debris before filling trays. The filled trays were moistened to prevent soil from settling in the tray prior to sowing. Seeds were obtained from commercial suppliers, so their age and pre-treatment were unknown, with the exception of the desmanthus lines, which had been mechanically scarified. The same seed batch for each species was used for the duration of the experiment to avoid any potential differences in seed size and vigour between batches. A germination test was conducted in a growth cabinet with 12 hourly alternating 30/20 °C day/night temperatures each month to monitor any change in seed viability during the experiment. For each species, 50 randomly selected seeds were placed into petri dishes lined with filter paper moistened with distilled water with 3 replicates. Average germination of the species after 14 days ranged from 41% (panic grass) to 89% (kikuyu grass) over the 12 months of the experiment (Table 2). The exception was the *Urochloa* hybrid which had poor germination in the laboratory, although seedlings emerged when sown in soil (0% germination in the laboratory compared to 35% emergence in the field). The number of seeds sown were not adjusted for germination percentage due to the poor relationship between germination and emergence. Germination percentages were common for commercially available seed, except for the *Urochloa* hybrid.

Sowing of seeds in the trays commenced in August 2019. Rhodes grass was sown with spikelets from August until December 2019 and from January 2020 spikelets were removed and the seeds were passed through a 0.5 mm sieve. One hundred uncoated seeds of each species were placed in 1 or 2 rows per species. After sowing, soil was added to the trays so that all seeds were covered to a depth of 10 mm (equal to the height of the tray rim). This is the optimum sowing depth for several tropical grasses (Lodge and Harden 2009). This process was repeated at monthly intervals over the ensuing 12 months. The experiment at each site was a randomised complete block design with 3 replicates. Each tray represented a replicate, except at Trangie and Tamworth where additional species necessitated using 2 trays per replicate.

The trays were buried in the soil in the field 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. Micro-dataloggers (Thermochron iButon, Whitewater USA) were placed into each tray at a depth of 10 mm to monitor soil temperature. The soil surface was kept moist over the

14 days of the experiment by applying 80% of the daily potential evapotranspiration, recorded at the nearest Bureau of Meteorology site, using an automatic watering system with microsprays. Minimum and maximum air temperature was obtained from the nearest Bureau of Meteorology site. The number of emerged seedlings were counted on days 3, 7, 10 and 14 after sowing. The soil in all trays was then discarded.

Data analyses

Seedling emergence contour plots. The cumulative number of plants that emerged over the 14-day assessment period in each month from August 2019 to July 2020 were adjusted to a percentage of the maximum emergence achieved for each sown species at a given site. These emergence percentages were plotted to produce

Table 1. Location, elevation and long-term average (LTA) annual minimum and maximum temperature of the 5 experimental sites.

Location	Latitude	Longitude	Elevation (masl)	LTA annual minimum temperature (°C)	LTA annual maximum temperature (°C)
Tamworth	31°04’12” S	150°50’24” E	404	9.8	24.9
Trangie	31°59’24” S	147°57’00” E	215	10.9	24.7
Orange	33°19’12” S	149°04’48” E	922	6.2	18.4
Cowra	33°48’00” S	148°42’00” E	360	8.3	23.0
Wagga Wagga	35°03’00” S	147°21’00” E	219	9.1	22.2

Table 2. Tropical species sown at each site and their average laboratory seed germination range (%) over the 12 months of the study.

Species	Tamworth	Trangie	Orange	Cowra	Wagga Wagga	Lab germ (%)
Rhodes grass (*Chloris gayana* Kunth) cultivar ‘Katambora’	X	X	X	X	X	74±10.5
Digit grass (*Digitaria eriantha* Steud.) cultivar ‘Premier’	X	X	X	X	X	45±8.0
Makarikari grass (*Panicum coloratum* var. *makarikariense* L.) cultivar ‘Bambatsi’	X	X	X	X	X	75±8.2
Panic grass (*Megathyrsus maximus* (Jacq.) B.K. Simon & S.W.L. Jacobs[1]) cultivar ‘Gatton’	X	X	X	X	X	41±9.4
Kikuyu grass (*Cenchrus clandestinus* Hochst. ex Chiov.) Morrone[2]) cultivar ‘Whittet’		X				89±5.0
Common paspalum (*Paspalum dilatatum* Poir.)		X				53±5.5
Urochloa[3] hybrid (*Urochloa decumbens* × *U. ruziziensis* × *U. brizantha*) cultivar ‘Mulato II’	X					0±0.2[4]
Desmanthus (*Desmanthus virgatus* (L.) Willd.) cultivar ‘JCU2’	X					60±3.2
Desmanthus (*Desmanthus bicornutus* S. Watson) cultivar ‘JCU4’	X					71±4.0
Desmanthus (*Desmanthus leptophyllus* Kunth) cultivar ‘JCU7’	X					86±1.7
Desmanthus (*Desmanthus pernambucanus* (L.) Thell.) cultivar ‘JCU9’	X					88±4.7
Desmanthus (*D. virgatus* (L.) Willd.) cultivar ‘Marc’	X					49±6.3
Total number of species tested	10	6	4	4	4	

[1]Synonym *Panicum maximum* Jacq.
[2]Synonym *Pennisetum clandestinum* Hochst. ex Chiov.
[3]Synonym *Brachiaria*
[4]Field emergence was superior to laboratory germination.

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 et al. 2022)] to smooth the contour plots, with the jitter option used to account for collinear points due to having 3 replicate emergence values for each sample day by month.

Emergence response to temperature. Day 10 cumulative emergence data were used to model response to temperature representing the period during which emergence is commonly observed. For each species at each site, total emergence on day 10 for each month was calculated as a percentage of the maximum emergence across all sites. These values were averaged to determine monthly emergence. The monthly soil temperature for days 1–3 at each site, hereafter called average soil temperature, was calculated by averaging the daily maximum and minimum temperatures for the 3 days following sowing. Emergence of each species was plotted against average soil temperature. Peak soil temperatures were recorded in January therefore each plot was divided into warming soil temperatures (August–January) and cooling soil temperatures (January–July). Combining all site data, provided a total of 30 and 35 data points in the warming and cooling temperature ranges respectively, for each species. Curves and standard errors were fitted to the data for warming and cooling soil temperatures using the "lowess" command from R (R Core Team 2020).

The same procedures were used to plot emergence for the additional species sown at Trangie and Tamworth. For each grass species, curves were fitted to warming and cooling soils using 6 and 7 data points, respectively. Data for the 5 desmanthus entries were pooled because usually species are blended to form regionally specific mixes (Gardiner 2016) and curves were fitted to warming and cooling soils using 30 and 35 data points.

To provide recommendations of the minimum temperatures required for sowing and to determine the emergence 'window' for each species, temperatures at which 50% of maximum emergence occurred in both warming and cooling soils were determined following the method of Egan et al. (2017).

Results

Emergence response surfaces

Rhodes grass had the widest emergence window of the 4 grasses, which were tested at all sites, emerging over the greatest number of months of the year at all sites (Figure 1A). Emergence occurred 11 and 12 months of

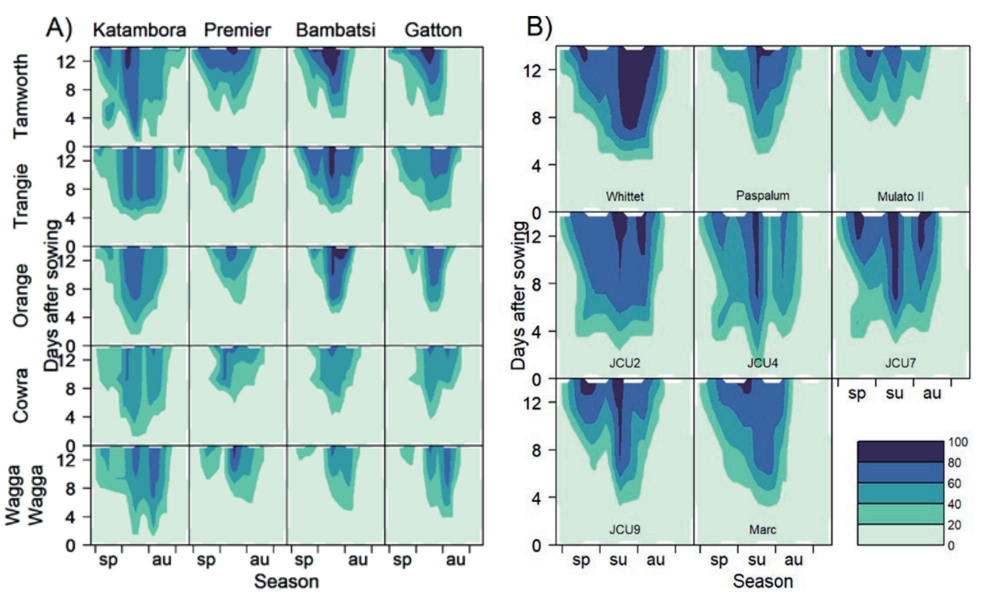

Figure 1. Plots of average cumulative seedling emergence (%) assessed 4 times over 14 days across the 12 months of the year from August to July for (A) Rhodes grass cultivar 'Katambora', digit grass cultivar 'Premier', Makarikari grass cultivar 'Bambatsi', panic grass cultivar 'Gatton' at 5 sites: Tamworth, Trangie, Orange, Cowra and Wagga Wagga, and (B) kikuyu grass cultivar 'Whittet' and paspalum at Trangie, *Urochloa* hybrid cultivar 'Mulato II' and desmanthus cultivars 'JCU2', 'JCU4', 'JCU7', 'JCU9' and 'Marc' at Tamworth. Emergence of each species was adjusted to the maximum achieved at any site. X-axis labels are spring (sp=September–November), summer (su=December–February), autumn (au=March–May) and winter (wi=June–August).

the year at Trangie and Tamworth, respectively, albeit only in low proportions in the final days of assessment during the coolest months of the year. Across all sites, Makarikari grass and panic grass had the smallest emergence window, emerging over the fewest months of the year, while digit grass was intermediate. Of the 5 sites, seedling emergence for all species generally occurred over a greater period of the year at Tamworth, and least at Orange and Cowra. Maximum total emergence also tended to occur at Tamworth, the most northerly site, while lowest emergence was at Cowra and Wagga Wagga, the 2 most southerly sites.

Kikuyu grass and paspalum sown at Trangie had an emergence window similar to Makarikari grass and panic grass respectively, both emerging from September–October until May (Figure 1B). Paspalum emergence peaked in January while kikuyu grass peaked in January–March. At Tamworth, *Urochloa* hybrid cultivar 'Mulato ll' emerged between September to April, similar to Makarikari grass. Seedlings of the cultivar 'Mulato II' were also slower to emerge than the other species at this site, with the first seedlings generally emerging >7 days after sowing. The 5 desmanthus cultivars sown only at Tamworth emerged from September until April, with peak emergence generally occurring in December and seedlings of all 5 cultivars emerging within 4 days of sowing in January.

Emergence response to temperature

There was no seedling emergence of Rhodes grass after 10 days when average soil temperatures were ≤11 °C (Figure 2A). After the temperature peak (>28 °C) in January, emergence was variable, ranging from 50–100% of maximum emergence as soils cooled to about 23 °C. Emergence then declined linearly, ceasing when soil temperatures were ≤12 °C (Figure 2A).

There was no emergence of digit grass in either warming or cooling soils when temperatures were ≤14 °C (Figure 2B). Emergence of digit grass was linear in warming and cooling soils, with maximum emergence occurring in January across all sites.

There was no emergence of Makarikari grass seedlings when soil temperatures were <12 °C. Rate of emergence increased as soil temperature increased (Figure 2C). In cooling soils, decline in emergence of Makarikari grass was linear with emergence ceasing when temperatures were ≤15 °C.

There was no emergence of panic grass seedlings when soil temperatures were <14 °C and seedling emergence response in warming soils was linear (Figure 2D). The change in slope when soil temperatures were 18–20 °C corresponded with highly variable emergence across the sites ranging from 10–100% of maximum. The response in cooling soils, was also linear, with emergence ceasing when temperatures were below 15 °C.

Due to the limited number of data points and being sown at only 1 site, emergence responses for kikuyu grass, paspalum, *Urochloa* hybrid and desmanthus were less instructive (Figure 2). Kikuyu grass did not emerge when average temperatures were ≤14 °C, however 70% of maximum emergence occurred when soil temperatures had increased to 20 °C. Emergence was high (>90%) in cooling soils when soil temperatures were >21 °C but declined rapidly below this temperature (Figure 2E).

Highly variable emergence (5–45% of maximum) was observed for paspalum when soil temperatures were ~20 °C at Trangie. Emergence peaked when soil temperatures were ~27 °C, declining rapidly in cooling soils. Emergence was low when soil temperatures had fallen to 19 °C and ceased when soil temperatures were 15 °C (Figure 2F).

No seedlings of the *Urochloa* hybrid emerged when soil temperatures were below 15 °C. In warming soils, emergence was variable when soil temperatures were ~22 °C ranging from 55–100% of maximum. In cooling soils, emergence declined rapidly as temperatures fell below 25 °C. The limited data points when soil temperature was 15–20 °C resulted in large standard errors for emergence at low temperatures in cooling soils. Nil emergence was observed when soil temperatures were below 19 °C, compared to ~10% modelled by the response curve (Figure 2G).

Pooled data for desmanthus cultivars provided more data points but are from only 1 site (Figure 2H). No seedling emergence of desmanthus was observed in warming soils when temperatures were 11 °C, and minimal emergence (2%) occurred when temperatures were 15 °C. However, emergence was greater than 60% of maximum emergence when temperatures were ≥22 °C. At this temperature (October–December), emergence of the 5 entries was variable, ranging from 65–100%. There was also significant variation in emergence in cooling soils when soil temperatures ranged from 19–25 °C. In cooling soils, emergence ceased when temperatures reached 13 °C.

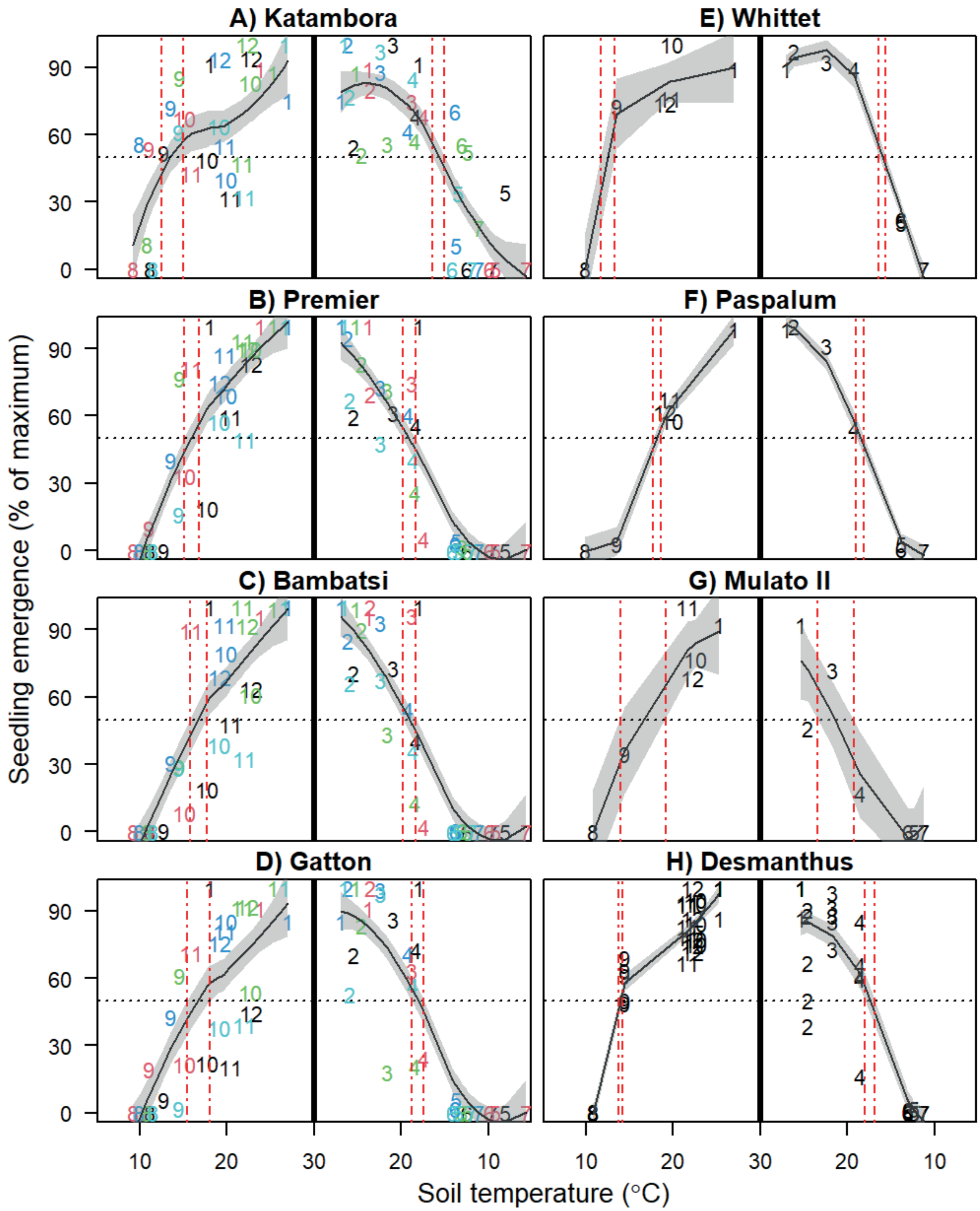

Figure 2. Smoothed mean seedling emergence response to soil temperature for 12 months from August to January as soil temperatures increased (left panel of each subfigure) and January to July (right panel) as temperatures decreased for (A) Rhodes grass cultivar 'Katambora', (B) digit grass cultivar 'Premier', (C) Makarikari grass cultivar 'Bambatsi', (D) panic grass cultivar 'Gatton', (E) kikuyu grass cultivar 'Whittet', (F) paspalum, (G) *Urochloa* hybrid cultivar 'Mulato II' and (H) desmanthus cultivars 'JCU2', 'JCU4', 'JCU7', 'JCU9' and 'Marc'. Sites for pooled figures (A-D) are: Cowra (■), Orange (■), Tamworth (■), Trangie (■) and Wagga Wagga (■). Numbers on each figure indicate the month of the year, (1=January to 12=December). Grey shading represents the standard error of the mean. The black dotted horizontal line represents 50% of maximum seedling emergence while the red lines indicate the upper and lower temperature ± standard error to achieve 50% maximum emergence.

Soil temperatures to achieve 50% maximum seedling emergence

Rhodes grass required the lowest temperature to achieve 50% emergence in warming soils (17 °C), followed by digit grass, Makarikari grass and panic grass (19–20 °C) (Table 3). Of the additional species assessed at Trangie, the 50% emergence temperature for kikuyu grass was similar to Rhodes grass (18 °C). Paspalum required the highest temperature of the tested species and reached 50% emergence at 22 °C. Species ranking for temperatures to achieve 50% of maximum seedling emergence in cooling soils was slightly different to warming soils (Table 3), with Rhodes grass and kikuyu grass having the lowest temperature requirement (17 °C) followed by desmanthus (19 °C). Panic grass, Makarikari grass and digit grass were intermediate (20–22 °C). Paspalum and the *Urochloa* hybrid had the highest temperature requirement (23 °C) to achieve 50% of maximum seedling emergence. The temperature range from warming to cooling soil temperatures, an indicative 'window' for effective emergence, was widest for Rhodes grass, then kikuyu grass. Desmanthus was intermediate. The effective emergence window for digit grass, Makarikari grass and panic grass was relatively narrower, but not as short as paspalum which required soil temperatures to be >22–23 °C in both warming and cooling soils.

Table 3. Predicted soil temperatures (°C) for 50% of maximum emergence for the pasture species tested in warming and cooling soils.

Species	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
Makarikari grass	20.5±0.9	21.2±0.7
Panic grass	20.1±1.4	20.1±0.8
Kikuyu grass[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[1,2]	19.3±0.3	18.5±0.7

[1]Values are based on emergence at 1 site.
[2]Values are based on pooled data for the 5 cultivars.

Discussion

This study is the first to quantify emergence of tropical perennial species across multiple locations representing a range of temperatures at temperate latitudes and therefore increasing the applicability of results to other temperate regions of the world where tropical pasture plants are increasingly being used. The species tested differed in their emergence response in warming and cooling soils. Their temperature requirements to achieve 50% maximum emergence also varied which is useful information to develop sowing time recommendations.

Maximum emergence for each species recorded at all sites occurred at Tamworth, the site with the most northern latitude while the slowest emergence tended to occur at the 3 most southern latitude sites (Orange, Cowra, Wagga Wagga). All species included in this study are known to persist in frost prone northern NSW, except for the *Urochloa* hybrid cultivar 'Mulato II' which has not been tested in inland NSW to our knowledge, although it is reported as suited to high rainfall tropical/lowland subtropical environments (Cook et al. 2020; Hare at al. 2007). Each of the 4 core grasses persisted to varying degrees in central and/or southern NSW for 2–3 years, with digit grass and Makarikari grass consistently persistent at all sites (Newell et al. unpublished). Despite their cold tolerance as mature plants, the species had varied emergence responses to temperature.

Rhodes grass, kikuyu grass and paspalum have a wide geographical distribution and are sown and/or naturalised in many locations across the world (Cook et al. 2020). Kikuyu grass and paspalum were early introductions to southern Australia and were evaluated for their potential as pasture species (Reed 2014). Kikuyu grass is now widely sown and naturalised across large areas of eastern Australia and south-west Western Australia (Morris 2009; Moore and Barrett-Lennard 2006). Paspalum has long been recognised as a persistent pasture species in cooler climates and while it is naturalised in many areas, it is not widely sown (Reed 2014).

Urochloa hybrid had the slowest emergence of the species tested and a narrower emergence temperature range than the other grasses sown at Tamworth. This may be due to 'Mulato II' being suited to high rainfall tropical and lowland subtropical environments

(Pizarro et al. 2013; Cook et al. 2020). The temperature, humidity and soil moisture regime at the site would have been suboptimal. Additionally, as there was no information whether any seed treatments had been applied, it may be that seed was dormant. This would also account for the low emergence of this grass compared with the other species tested. The common practice is for seed to be acid-scarified for successful germination (Hare et al. 2007; Pizarro et al. 2013). 'Mulato II' was included in the study at Tamworth because it was an opportunity to gather some fundamental information on emergence response in a temperate, summer dominant rainfall environment.

Emergence temperatures for the tropical species determined from the current study were 3–6 °C higher than previously reported. Based on the 50% emergence method using growth cabinet emergence data, Egan et al. (2017) suggested Rhodes grass could begin to be sown when temperatures were 12 °C and increasing, while McDonald and Bowman (2002) suggested 14 °C; 3–5 °C lower than the temperature recommended from this study. Similarly, for Makarikari grass, previous studies have suggested 17 °C (McDonald and Bowman 2002) and 18 °C (Egan et al. 2017); 2–3 °C lower than the temperature recommended from this study. Both of those studies were conducted in controlled environments. In other field studies average soil temperatures >22 °C have been recommended for sowing tropical pastures (Lodge and Harden 2009) which aligns with the current study. Germination has been reported to be similar under constant and alternating temperatures when the temperatures are within the optimum range for the species. However, when either the minimum and/or maximum temperatures were outside this optimum range, the rate of germination and total gemination achieved are reduced (McDonald and Bowman 2002). This helps to explain the higher temperature recommendations in both field studies. Additionally, this study was conducted under conditions where daily temperature fluctuations were inconsistent, which may have influenced emergence. Other environmental factors, such as wind, could also have influenced emergence, especially at the southern sites that are at latitudes considered marginal for the growth of tropical species. In this study, maintaining a moist soil surface for emergence was difficult during windy periods, which can adversely impact germination and emergence. Maintaining the required moist soil surface over several days, let alone for extended periods like 10 days during summer, is challenging. Summer rainfall commonly falls in high intensity storms, hence management practices that leave organic matter on the soil surface should maintain conditions suitable for germination over a longer period. The cover reduces maximum soil temperature on hot days and holds moisture nearer the soil surface for longer, thereby assisting germination and emergence (Ward 1993; Unger 1978).

The 50% emergence threshold in warming and cooling soils provides a theoretical 'time window' to develop recommendations for soil temperatures for sowing. Warming soil temperatures for 50% emergence can be used as an indicator for the earliest time to sow. Temperatures in cooling soils are more problematic to estimate because the rate of plant development following establishment and the ability of immature plants to survive the coming winter varies (Lodge et al. 2010).

Based on the current study it is suggested tropical grasses be sown in spring when soil temperatures are rising and when the 3-day average soil temperature at 10 mm depth is at least 17 °C for Rhodes grass, 18 °C for kikuyu grass, 19 °C for *Urochloa* hybrid and desmanthus, 20 °C for digit grass, panic grass and Makarikari grass and 22 °C for paspalum. Autumn sowing should be opportunistic, and only considered when there is a very high likelihood of good rainfall over a period of about 4 days and soil temperatures are several degrees above the 50% maximum emergence temperature for cooling soils. Additionally, it is suggested sowing should be at least 2 months before frost to allow the seedlings to establish. It is also recommended that only species with known ability to overwinter are sown in autumn (kikuyu grass, digit grass or Rhodes grass) and not Makarikari grass. This follows the recommendation by Lodge and Harden (2009) where sowing in autumn should not be conducted in northern inland NSW because insufficient autumn rainfall has the potential to result in poor emergence, which is confounded by potentially low winter survival if seedlings are small and weakened due to weed competition (Descheemaeker et al. 2014). Poor persistence and subsequent low productivity have been reported for autumn-sown Makarikari grass (Jones 1969; Lodge et al. 2010), although neither digit grass nor Rhodes grass were affected (Lodge et al. 2010). Small plant size and low foliage cover due to defoliation at the onset of frosts/winter have been suggested as reasons for the poor overwintering ability of some grasses (Jones 1969). A study in northern NSW also noted that plants sown in autumn were smaller (<0.1 m) and vegetative compared to those sown in the previous spring and summer (>0.5 m and flowering) at the time of the first frost (late May, 75 days after autumn sowing) (Lodge et al. 2010).

Central and southern NSW also receive summer rainfall, albeit with even greater variability and less reliability than northern NSW. Based on rainfall data from Wagga Wagga for the period 1990–2022, the occurrence of more than 25 mm falling over a 7-day period in any single month from December to March averaged 55% (range 48–61%). However, by sowing early in the emergence window, for example by sowing on 1 December, the likelihood of receiving 25 mm over a 7-day period increased to 94% of years (31 of 32 years) compared to 52% if the pasture was sown on 1 February (17 of 32 years) (climateapp.net.au).

Peak seedling emergence in this study tended to occur in summer with high emergence continuing into early autumn in some species. Other studies have also reported this (Lodge and Harden 2009; Lodge et al. 2010) and suggested it was due to average temperatures masking the large variation between minimum and maximum temperatures that occurred at this time (Lodge and Harden 2009). These results support this suggestion because the range in daily air and soil temperatures was greater in spring than autumn. For example, average soil temperatures at Wagga Wagga in October and March were similar, both being ~20 °C, however, October average minimum and maximum temperatures were 10 °C and 38 °C (range 28 °C) while in March temperatures were 12 °C and 33 °C (range 21 °C). This variation also helps explain the highly variable germination of panic grass and Rhodes grass between October to December when average 3-day soil temperatures ranged from 17–22 °C.

Desmanthus virgatus is the most widely sown species of the desmanthus genus with several cultivars commercially available, although several other species have also been commercialised in Australia (Gardiner 2016). These can be blended to provide regionally specific mixes (Gardiner 2016), therefore a single sowing temperature recommendation has merit. There was variation between the entries tested which might represent species differences, but further testing would be required to confirm this because desmanthus cultivars were only studied at Tamworth. Further regional studies investigating different sowing times in different soils with and without cover in central and southern NSW will refine localised recommendations.

Conclusions

Results support the recommendation to sow tropical perennial species in spring when soils are warming, beginning at a minimum temperature of 17 °C for Rhodes grass, 18 °C for kikuyu grass, 19 °C for both *Urochloa* hybrid and desmanthus, 20 °C for digit grass, panic grass and Makarikari grass and 22 °C for paspalum. Sowing at these times provides more opportunities for suitable rainfall to achieve successful establishment and sufficient time for establishing plants to mature to survive the following winter. Although the rate of emergence and total emergence were often higher in late summer–early autumn than spring, the likelihood of receiving adequate rainfall to promote emergence is lower and the timeframe for plant development is shorter, with increased risk of establishment failure. Sowing in late summer–early autumn may be an option if sowing can occur before a rainfall event that has a high probability of delivering significant rainfall over multiple days. Species with superior cold tolerance, such as Rhodes grass and digit grass, could be sown in autumn, while sowing those with lower tolerance, such as Makarikari grass, should be avoided.

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