# Temperature requirements for the germination of alternative forage species for northern New Zealand climates and a prominent weed

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## Abstract

Ryegrass-clover pastures are increasingly facing challenges with reduced persistence and weed ingress, especially in northern New Zealand dairying regions. Seed germination is the first, and arguably most important step, to determine the successful establishment of pasture (or weed) species. Soil temperature and soil moisture are important factors for germination and therefore determining species-specific preferences for these parameters can indicate the environmental conditions facultative to their establishment. This study aimed to determine the cardinal germination temperatures of four forage cultivars: Haven tall fescue (*Lolium arundinaceum* (Schreb.) Darbysh.), Oakdon meadow fescue (*Lolium pratense* (Huds.) Darbysh.), berseem clover (*Trifolium alexandrinum* L.) and Fulkerson kikuyu (*Cenchrus clandestinus* (Hochst. ex Chiov.) Morrone) and one prominent weed: Madagascar ragwort (*Senecio madagascariensis* Poir.) relevant to northern pastures. Seeds were germinated across a range of temperatures for 28 days and cardinal temperatures were determined using broken-stick models. Cardinal temperatures and thermal time requirements are reported in the text. Kikuyu has a high base temperature for germination, which suggests a slow germination rate in spring compared to temperate forages, limiting its use in regions below the northern North Island. Madagascar ragwort has similar temperature requirements to ryegrasses and fescues. Further study of the interaction between soil temperature and moisture (hydrothermal constraints) would increase understanding of the germination behaviour of these species.

**Keywords:** cardinal temperature, *Senecio madagascariensis,* thermo-gradient, thermal time

## Introduction

Ryegrass-clover pastures are increasingly facing challenges with reduced persistence and weed ingress, especially in northern dairying regions such as Northland (Tozer et al. 2011; Teixeira et al. 2024). In response to this, alternative forage species are being evaluated for their suitability to northern conditions (McCahon et al. 2021; Teixeira et al. 2024). Research evaluating subtropical forage species for northern New Zealand has in fact been ongoing for many years (Arnold 1953; Taylor et al. 1976, Rumball and Lambert 1981, Crush and Rowarth 2007), but recent work has brought this back into focus (Dale 2025; King et al. 2025).

Seed germination is the first, and arguably most important step, to determine the successful establishment of pasture (or weed) species. To evaluate the germination requirements of alternative forages, cardinal temperatures: base/minimum ($T_b$), optimum ($T_o$), maximum/ceiling ($T_m$) and thermal time requirement values $T_t$ (often referred to as growing degree days) can be used to predict the seed germination of a species at certain temperatures. These data can be used to guide future sowing programmes and to parameterise models that may be used to explore future pastoral scenarios.

Tall fescue (*Lolium arundinaceum* (Schreb.) Darbysh.) is one of the leading cool-season grasses being considered for northern conditions (Teixeira et al. 2024; Dale 2025). Tall fescue has a higher tolerance to heat and drought stress when compared to ryegrass (Jiang and Huang 2001). Previous work has been done on the temperature conditions for germination for several cultivars (Moot et al. 2000; Monks et al. 2009; Zhang et al. 2013; Sharifiamina et al. 2016). The cultivar Haven is newer to the market than other tall fescue cultivars previously studied and is included in this study. Meadow fescue (*Lolium pratense* (Huds.) Darbysh.) is another species being considered and introduced to northern pastures, often in a mixture with tall fescue. The cultivar Oakdon meadow fescue is included in this study.

Kikuyu (*Cenchrus clandestinus* (Hochst. ex Chiov.) Morrone), is both a weed and an encouraged pasture species in Northland (Paton and Piggot 2009, McCahon et al. 2021). It was originally established in Northland by request from farmers, who planted cuttings (Percival 1978). After that, it appears to have spread into farms across Northland. Early research suggests that it has good germination between 19-29ºC with optimum germination at 29ºC (Blair et al. 1974). That study

did not state $T_b$ or $T_m$ values, but it was clear that germination started over 10ºC and declined sharply over 30ºC. Newer cultivars introduced from Australia are typically sown from seed rather than established from cuttings. The 'Fulkerson' cultivar with resistance to 'kikuyu yellows' and 'black spot' (Fulkerson et al. 2021), has increased persistence and palatability, and promises to have potential in New Zealand.

Madagascar ragwort (*Senecio madagascariensis* Poir.) has become a weed of major concern in Northland (Dymock and Winks 2024). It was considered constrained to parts of Northland above latitude 35.5 ºS but has recently been detected in southern Wairarapa (Ford and Shepherd 2026), and modelling suggests that it has a wide potential range across most of lowland NZ (Wijayabandara et al. 2022). In Australia, it commonly grows as a winter annual, with most germination in early autumn and growth throughout winter (Sindel 1989). While a contingent of seeds have physiological dormancy, a large proportion is immediately viable (Sindel and Coleman 2012). Optimum germination of populations under fluctuating temperatures in Australia is within the range 15-27ºC (Nelson and Michael 1982, Hooda and Chauhan 2024) and appears to cease at 35ºC. The base temperature for germination and thermal time requirement have not been determined for Madagascar ragwort.

The aim of this study was to determine the temperature requirements for the germination of four alternative forage species and one weed species of concern, for northern New Zealand climates.

## Materials and Methods

### Seed sourcing

Fulkerson kikuyu seed was sourced from Australian Seed Labs, Harristown, Australia. Oakdon meadow fescue and Haven tall fescue seed were sourced from Agricom, Lincoln, NZ. Berseem clover seed was sourced from Farmlands, Christchurch, NZ. Madagascar ragwort seed was collected from plants originating in the Far North, Northland, NZ that were grown in a contained glasshouse facility (PC1) at Ruakura Research Centre for seed collection.

### Thermogradient table set-up

The methods used for estimating cardinal temperatures for germination are similar to those of Dowsett et al. (2018) and Monks et al. (2009).

A GR-10 thermogradient table (Flohr Instruments, Nieuwegein, The Netherlands) was used to evaluate seed germination under a range of temperatures. The table consists of a 1 × 2 m plate, set at 7ºC and 35ºC on each end (vertically), with LED lights (Hi Lite F18T8 Cool-White Tubes) inside a glass compartment on the 'ceiling' of the table. The lights were on for 12 hours each day. Seeds were placed on one layer of germination blotter (Anchor Paper Company, St. Paul, Minnesota) on top of one layer of K-22 Kimpak® blotter paper (Anchor Paper Company, St. Paul, Minnesota) inside plastic petri dishes, with twenty-five seeds placed in each dish. Eleven petri dishes fit along the temperature gradient vertically and twenty horizontally (four replicates, five species) for a total of 220 dishes inside the thermogradient table. iButton temperature data loggers (iButtonLink Technology, Whitewater, Wisconsin) were placed in a vertical row of petri dishes to measure temperature. Those measured temperatures (7, 12, 15, 18, 20, 22.5, 24.5, 27, 29.5, 31.5 and 34ºC) were considered to be the true temperature that seeds were exposed to and were used in the analysis. Each dish initially received 4 mL of water, soaked into the paper, and was topped up as required to maintain moist germination conditions.

A seed was considered to have germinated immediately after its testa was broken and radicle emerged. There was no requirement for the size of the radicle (rather than counting seeds once their radicle was >5mm in length), as long as it had emerged the seed was considered germinated. Germination was recorded twice daily (every 12 hours) for the first two weeks, then daily for another two weeks. The experiment was terminated at 28 days. Seeds that did not germinate at the end of the experiment were assumed to either be non-viable or dormant (note that this may underestimate long-term germination potential). Any mouldy seeds or seeds visibly infected with pathogens were considered to be non-viable and omitted. No special steps were taken to break physiological or physical (hardseededness) dormancy, but all seed had been stored at room temperature for several months before the experiment.

### Data analysis

Data analysis was based on the method used by Monks et al. (2009). For comparison with that study the germination rate is defined here as the reciprocal of the number of days to reach 75% germination (days$^{-1}$). Germination rate was calculated using a three-parameter log-logistic model (LL.3) using the *drm* function from the *drc* package (Ritz et al. 2015) from the cumulative seed germination across temperatures. Data were pooled across replicates. Broken stick models, ascending from the base temperature ($T_b$) to the optimum temperature ($T_o$), and then descending from To to the maximum temperature ($T_m$), were fitted by using a linear model (*lm* function) to calculate base and maximum temperatures. The thermal time requirement ($T_t$; units of growing degree days, ºCd) is calculated from the reciprocal of the slope from $T_b$ to $T_o$ (for 75% germination). These calculations are the same used by Monks et al. (2009), who present the equations in their paper. Calculations for a 50% germination threshold

**Table 1** Estimates of the base (**Tb**), optimum (**To**) and maximum (**Tm**) temperatures (°C) for 75% germination, and thermal time (**Tt**) in degree days (°Cd; inverse of the slope for the ascending curve) for five species.

| Species | Cultivar | $T_b$ | $T_b$ 95% CI | $T_o$ | $R^2$ (≤To) | $T_m$ | $T_m$ 95% CI | $R^2$ (≥To) | $T_t$ (°Cd) |
|---|---|---|---|---|---|---|---|---|---|
| kikuyu | Fulkerson | 14.8 | 10.4-19.2 | 29.3 | 0.98 | 40.7 | -1.2-82.6 | 0.98 | 24.5 |
| tall fescue | Haven | 3.9 | -1.4-9.2 | 20.0 | 0.98 | 40.1 | 28.8-51.5 | 0.86 | 69.9 |
| meadow fescue | Oakdon | 0.8 | -8.2-9.7 | 24.2 | 0.81 | 37.4 | 9.6-65.1 | 0.72 | 95.1 |
| berseem clover | Alexandria | 4.4 | 1.5-7.3 | 22.5 | 0.98 | 37.1 | 11.1-63.1 | 0.72 | 21.7 |
| Madagascar ragwort | - | 1.4 | -5.4-8.2 | 21.4 | 0.93 | 34.5 | 19.4-49.6 | 0.87 | 74.1 |

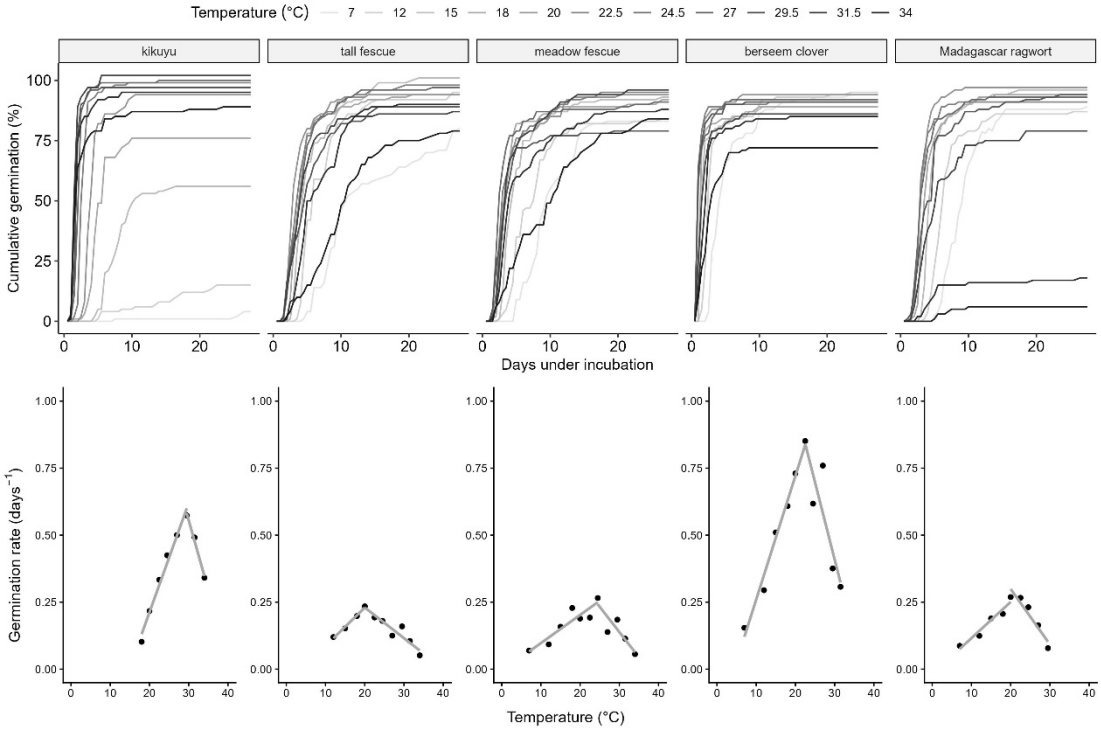



**Figure 1** Cumulative germination and estimated germination rate (inverse of days to 75% germination) for Fulkerson kikuyu, Haven tall fescue, Oakdon meadow fescue, Alexandria berseem clover and Madagascar ragwort across temperatures 7-34ºC over 28 days.

were also done and are available on Figshare (doi: 10.57935/AGR.33579961).

## Results

Final germination percentages were ≥79% across the entire temperature range for both fescue cultivars (Figure 1). Germination rates declined slightly when temperatures were above 34ºC for berseem clover (72% germination at 34ºC) and declined substantially at temperatures above 29.5ºC for Madagascar ragwort (79% at 29.5ºC, 18% at 31.5ºC, 6% at 34ºC; Figure 1). Kikuyu had high final germination rates (≥94%) above 20ºC, declining substantially below 15ºC (56% at 15ºC, 15% at 12ºC, 4% at 7ºC) and slightly above 34ºC (89%; Figure 1).

Base temperature ($T_b$) estimates overlapped (95% confidence intervals) with 0ºC for all species except kikuyu and berseem clover (Table 1). Optimum temperatures ($T_o$) ranged between 20-24.2ºC for the fescues, berseem clover and Madagascar ragwort, and 29.3ºC for kikuyu (Table 1). For most species the maximum temperature for germination was above 37ºC, except Madagascar ragwort ($T_m$ = 34.5ºC; 95% CI 19.4ºC-49.6ºC), however 95% confidence intervals were high for maximum temperature estimates, and the fit for the descending model was worse than the ascending model for all species except kikuyu (Table 1).

## Discussion

### $C_3$ forage grasses

The cardinal temperatures reported here for Haven tall fescue are within the range of previously reported temperatures for other tall fescue cultivars (Moot et al. 2000; Monks et al. 2009; Zhang et al. 2013; Sharifiamina et al. 2016). There is a large confidence interval for the Tm of Haven (40.1ºC; 95% CI: 28.8-51.5ºC) that overlaps with estimates for Flecha (35.8ºC) and for Advance (>35ºC; Monks et al. 2009). While it is difficult to compare thermal time requirements between studies, base temperature estimates of tall fescue cultivars are similar, and therefore it may be true that Haven (Tt = 69.9ºCd) will germinate faster than Roa (Tt = 120ºCd), but slower than Flecha (Tt = 39ºCd) at the same temperature. Comparing the speed of germination between cultivars could be done by calculating the number of days to reach Tt requirements above Tb with measured soil temperatures. Oakdon meadow fescue falls within the range of cardinal temperatures seen in tall fescue cultivars.

Cardinal temperatures of other fescue species are similar to those of meadow fescue (Lonati et al. 2009) and ryegrass (*Lolium* spp.) cultivars, though fescues tend to have higher Tb values (Moot et al. 2000; Monks et al. 2009). Phalaris (*Phalaris aquatica* L.), prairie grass (*Bromus catharticus* Vahl) and cocksfoot (*Dactylis glomerat*a L.), all species considered suitable for future climates in Northland (Dale 2025), all have higher Tt requirements than fescues and ryegrasses (Moot et al. 2000; Monks et al. 2009). However, their Tb values are lower, so germination would be able to start at colder temperatures. Also, Tt (and cardinal temperatures) varies with cultivar, with the Tt for Vision cocksfoot much lower than Apanui or Wana cocksfoot (Moot et al. 2000, Monks et al. 2009).

### $C_4$ forage grasses

In this study, the $T_o$ of kikuyu (29.3 ºC) is consistent with an Australian study that reported a $T_o$ of 29 ºC for the Whittet and Breakwell cultivars (Blair et al. 1974). However, unlike that study, $T_b$, $T_m$ and $T_t$ values are reported here as well, though the $T_m$ estimate is not reliable, with a large error range (Table 1). Although kikuyu has a relatively low $T_t$ (24.5 ºCd), this is only accumulated above its (relatively) high $T_b$ value of 14.8ºC. Soil temperatures in Northland are below this threshold in September, rising above it in November and dropping again in May (Chappell 2014), indicating November as the earliest viable sowing period for Northland. By using the cardinal temperatures reported here, and monthly mean earth temperatures (NIWA 2026), the number of days for 75% germination in November in Kaitaia would be 17.3 days, but only 6.8 days in December.

By contrast, vegetative growth can occur at lower temperatures; kikuyu has a $T_b$ of 4 ºC for regrowth (Acero-Camelo et al. 2021). Therefore, propagation from fragments could be done earlier in the season, or in areas where establishment from seed is not possible. There are many other $C_4$ grasses being considered for use in Northland (McCahon et al. 2021; Teixeira et al. 2024; King et al. 2025). There is limited information published on the temperature requirements for germination for many of these species. Base temperatures for germination of other $C_4$ forage grasses are usually above 10ºC (Jordon and Haferkamp 1989; Egan et al. 2017; Giolo et al. 2019), and many are typically propagated using vegetative fragments rather than seed (Davies and Hunt 1983; Woods et al. 1996).

### Legumes

Berseem clover has a higher Tb (4.4; 95% CI: 1.5-7.3ºC) and To (22.5ºC) than most other annual clover species (Moot et al. 2000; Lonati et al. 2009; Monks et al. 2009; Nori et al. 2014; Teixeira et al. 2020). Berseem clover's maximum temperature for germination (Tm) estimate is not precise (Tm = 37.1; 95% CI: 11.1-63.1ºC), but is likely to be within the range of other annual clover species, which range from 24-45ºC (Moot et al. 2000; Lonati et al. 2009; Monks et al. 2009; Nori et al. 2014; Teixeira et al. 2020). While berseem clover has a low thermal time requirement of only 21.7 degree-days to reach 75% germination, so too do other annual clover species, which range from 22-30ºCd (Lonati et al. 2009; Monks et al. 2009; Nori et al. 2014); subterranean clover (Trifolium subterraneum L.) is the exception, with a much higher Tt (26-78ºCd, average 49ºCd). Lotus (Lotus pedunculatus Cav.), birdsfoot trefoil (Lotus corniculatus L.) and sainfoin (Onobrychis viciifolia Scop.) have higher Tb requirements than clovers, with values of 6.4ºC, 2.7ºC and 3.7ºC, respectively (Blumenthal et al. 1996; Allahmoradi et al. 2013). Other annual legumes have similarly low Tb and Tt requirements to annual clovers (Brunel et al. 2009; Hu et al. 2012; Renzi et al. 2014).

Cardinal temperatures for perennial clovers are similar to that of annual clovers (Moot et al. 2000; Lonati et al. 2009; Monks et al. 2009), but typically have higher Tt values (35-77ºCd), indicating possible slower germination than annual species. Lucerne (Medicago sativa L.) has Tb values similar to that of other legumes, but a Tt of 39 degree-days (Moot et al. 2000), which is lower than most white clover (Trifolium repens L.) cultivars. Subtropical perennial legumes considered candidate species for northern pastures (King et al. 2025) have Tb estimates between 6.9-9.1ºC, To estimates from 32.3-34.7ºC, and relatively low Tt requirements between 25-47ºCd (McDonald 2002, Mahendraraj et al. 2021).

While this study did not measure hardseededness directly, physical dormancy of berseem clover decreases

significantly during dry room-temperature storage (Hussey et al. 1993). High final germination in this study (germination between 89-95% in temperatures from 7-27ºC) suggests minimal residual dormancy in the seed used. As no post-experiment viability tests were conducted, the 5-11% of ungerminated seed cannot be definitively attributed to either persistent dormancy or non-viability.

**Madagascar ragwort**

Results from this study identify the optimum temperature for germination for Madagascar ragwort of 21.4ºC, which is in the middle of the optimum temperature range 15-27ºC determined by previous studies (Nelson and Michael 1982; Hooda and Chauhan 2024). The study by Nelson and Michael (1982) did not specify a $T_m$ but implied a value close to 35ºC (with no germination recorded above that temperature); the $T_m$ value of 34.5ºC observed here is close to that temperature ceiling (although with a large confidence interval of 19.4-49.6ºC).

The temperature requirements for Madagascar ragwort estimated from this study fit with observations by Northland farmers that it germinates most rapidly in autumn. The range of temperatures that it can germinate at, and the range of soil temperatures recorded in Northland (Chappell 2014), suggests continuous regeneration from seed is possible year-round in Northland, though would be predicted to be considerably slower in winter. For example, considering the 10 cm mean soil temperature of 10.6ºC in July in Kaitaia (Chappell 2014), Madagascar ragwort would take 8 days to reach 75% germination based on $T_b$ and $T_t$ estimates. By contrast, between October and May it would take 4-6 days.

Rather than temperature, the factor that will most likely limit its germination in Northland is soil moisture, which is often limited in the Far North during summer and early autumn (Chappell 2014). Hooda and Chauhan (2024) recorded a reduction in germination with decreasing osmotic potentials, with germination 46-59% at -0.4 MPa. There may be variations between populations in their response to the osmotic stress of drier soils (Hooda and Chauhan 2024). Burial depth, soil salinity, light availability and soil disturbance are also important factors for Madagascar ragwort germination (Hooda and Chauhan 2024).

The germination rate of Madagascar ragwort is similar to that of ryegrasses and fescues, which have similar Tb and Tt estimates. White clover also has a similar Tb and lower Tt, suggesting that it will germinate quicker than Madagascar ragwort. However, Tt parameters for seedling germination and seedling establishment do not always correlate (Moot et al. 2000). Additionally, Wardle et al. (1992) found that pasture plots consisting of legumes were less effective than plots consisting of grass swards in inhibiting the growth of nodding thistle (*Carduus nutans* L.) and Scotch thistle (*Cirsium vulgare* (Savi) Ten.). This likely applies to other broadleaf weeds including Madagascar ragwort. Therefore, it should be grasses that are evaluated for suppression of Madagascar ragwort germination rather than legumes despite their faster germination rate. While most ryegrass and fescue cultivars have germination that is slower, or similar to Madagascar ragwort, some cultivars such as Ariki hybrid ryegrass and Flecha tall fescue have low Tt requirements (Moot et al. 2000; Monks et al. 2009) and may be better options to sow for early competition to mitigate Madagascar ragwort emergence. Nonetheless, the similarity in germination requirements of Madagascar ragwort to cool-season forage grasses suggest that this weed will compete directly with them even at the germination stage and will require a management plan when sowing new pastures in infested paddocks.

Many other weeds have studies published on temperature requirements for their germination (Ivens 1983; Monks et al. 2009; Guillemin et al. 2013; Dowsett et al. 2018), but also a large number of common weeds surprisingly do not have these estimates published.

**Other factors to consider for seed germination**

While temperature could be considered the most important factor for germination when light, nutrients and moisture are not limiting, it is not the only factor important for establishing pasture species, nor predicting weed germination. Seed characteristics (e.g., size, after-ripening requirements, dormancy), external abiotic factors (e.g., light availability, water availability, presence of nutrients), external biotic factors (e.g., pathogens, microbiome, mycorrhiza) and management factors (e.g., sowing depth, sowing rate, sowing date) will all affect seed germination rates (Lamichhane et al. 2018).

Investigation of the effect of fluctuating temperatures and the relationship between temperature and moisture ('hydrothermal time') would improve understanding of the germination of these forages and weeds (Leon et al. 2004; Guillemin et al. 2013; Sharifiamina et al. 2016). Most plant species have some type of seed dormancy (Baskin and Baskin 2004). This is typically more important to consider for weeds (James and Rahman 2013), but is prominent in some leguminous forages, including berseem clover, as a trait known as 'hardseededness' (Taylor 2005). This is a type of physical dormancy, which can in theory be beneficial for persistence, but in practice has challenges with attaining a consistent level of regeneration across seasons (Faulkner et al. 2025). Additionally, the paper by Moot et al. (2000) shows that thermal time requirements for germination cannot be extrapolated directly to seedling emergence (in the context of sowing

species mixtures). Studies of seedling emergence and tracking plants beyond germination would additionally improve understanding of the interactions between sown forages and weeds.

## Practical implications

Temperature requirements for germination have been revealed in this study for the first time for meadow fescue, berseem clover and for a new tall fescue cultivar (Haven). Additionally, $T_b$, $T_o$, $T_m$ and $T_t$ values, are now available for kikuyu and Madagascar ragwort. Exploration of future pastoral systems is often conducted *in silico* using process-based modelling tools such as APSIM. For these models to be accurately parameterised, germination temperature metrics (including $T_b$ and $T_t$) are essential inputs. By combining local temperature records with the measured base temperature ($T_b$) and thermal time ($T_t$) requirements, it becomes possible to predict the likely timing of seed germination under field conditions.

In contrast, many $C_4$ grasses and several promising forage legumes being considered for northern climates lack data on their base temperature requirements for germination. If these species are to be considered to be viable candidates for warmer climate pasture systems, it would be valuable to quantify their germination temperature responses. Understanding the base temperature requirements of other weed species could also provide valuable information to guide crop planting and management strategies and enabling predict the possibility and direction of potential range expansion under changing climatic conditions. One potential use for these data could be in comparing germination requirements of common weed species to pasture (or crop) species to determine which weeds are of highest threat during different sowing windows.

## ACKNOWLEDGEMENTS

The authors would like to thank Angee Nagra (Agricom), Steven Payne (Foundation for Arable Research) and Tracy Dale (BSI) for supplying seed; Kayley Rowell for helping set the experiment up and count seeds; Trevor James (BSI) and Craig McGill (Massey University) for providing advice on using the thermogradient table; Joanne Jensen (BSI), Nigel Bell (BSI) and Warren King (BSI) for providing advice on the species selection and manuscript. Funded by MBIE (through the SSIF fund), BSI (Axel Heiser) and NZ dairy farmers through DairyNZ.

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