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NOTE AND UNIQUE PHENOMENA

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Base temperatures affect accuracy of growing degree day model to predict emergence of bermudagrasses

M. Giolo[1] | R. Sallenave[2] | C. Pornaro[3] | C. Velasco-Cruz[4] | S. Macolino[3] | B. Leinauer[4]

[1] Council for Agricultural Research and Economics, Research Centre for Plant Protection and Certification, Lonigo, Vicenza, Italy

[2] Dep. of Extension Animal Science & Natural Resources, NM State Univ., MSC 3AE, Las Cruces, NM, 88003, USA

[3] Dep. of Agronomy, Food, Natural Resources, Animals, and Environment, Univ. of Padova, viale dell'Università 16, Legnaro, Padova, 35020, Italy

[4] Extension Plant Science Dep., NM State Univ., MSC 3AE, Las Cruces, NM, 88003, USA

Correspondence
S. Macolino, Univ. of Padova, Dep. of Agronomy, Food, Natural Resources, Animals, and Environment, viale dell'Università 16, Legnaro, Padova, Italy 35020.
Email: stefano.macolino@unipd.it

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Abstract

The germination of bermudagrass [*Cynodon dactylon* (L.) Pers.] under different temperature regimes has been extensively investigated, but a discrepancy remains between laboratory studies and field results. Thermal requirements calculated in growing degree days (GDD) have been found to differ within the same species depending on the location of the study. The accumulation of GDD may vary under different thermal conditions from seeding to seedling emergence and could depend on T_{BASE} used in the calculation. The most widely used T_{BASE} for bermudagrass is 5 ˚C. However, laboratory studies have suggested that a base temperature of 15 ˚C would more accurately predict seedling emergence. In this field study, we investigated the effect of using T_{BASE} 5 ˚C vs. T_{BASE} 15 ˚C on the estimation of GDD required by bermudagrass to emerge. Ten cultivars were seeded in northeastern Italy on three dates between 10 March and the end of April in 2013 and 2014. Number of emerged seedlings was counted weekly and soil temperature at 1-cm depth was recorded significant differences in seedling emergence between bermudagrass genotypes were found. Results demonstrated that the algorithm used to calculate GDD is strongly influenced by the T_{BASE} used and to include a T_{BASE} of 15 ˚C explains germination and emergence more accurately than a T_{BASE} of 5 ˚C.

1 | INTRODUCTION

Bermudagrass [*Cynodon dactylon* (L.) Pers.] is a warm-season turf species widely used in Mediterranean regions of Europe, most of which fall in the transition zone (De Luca et al., 2008; Rimi et al., 2011, 2013b; Schiavon et al., 2016; Severmutlu et al., 2011). Some bermudagrass cultivars produce viable seeds (seeded-type) while others are sterile hybrids derived from interspecific crosses between *C. dactylon* and African bermudagrass (*C. transvaalensis* Burtt Davy), which must be propagated vegetatively (Jennings et al., 2013). Hybrids have been the industry standard for high-quality turf for a long time because of the improved quality compared to seeded cultivars. However, these hybrid turfgrasses cost more to establish and maintain (Brosnan & Deputy, 2008). The quality of seeded cultivars has improved over the past 15 yr. Some of them are highly tolerant to cold temperatures and can be successfully used in transition zones where an early establishment is crucial to avoid cold damage during the first winter (Patton et al., 2008; Richardson et al., 2003, 2004; Schiavon et al., 2016). Transition zones are areas where neither cool nor warm-season grasses are completely adapted as summers are too hot for cool-season grasses, while winters are too cold for warm-season grasses (Dunn & Diesburg, 2004). In the

Abbreviations: DFS, days from seeding; GDD, growing degree days.

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northern areas of transition zone, early seeding is recommended to allow more time for the formation of stolons and rhizomes, which enhances winter hardiness and promotes early establishment (Patton et al., 2008; Schiavon et al., 2012).

Due to the widespread use of indices such as "percentage of emerged seedlings" or "cover percentage", seedling emergence is often confused with germination, even though germination ends with the emission of the radicle (Bewley et al., 2013; Nonogaki et al., 2010), while seedling emergence is defined as the first appearance of a seedling at the soil surface (Forcella et al., 2000). Seedling emergence is often used in field trials to evaluate early stages of turfgrass establishment. The main factors controlling seed germination and seedling growth are temperature, air quality, light quality and intensity, and water potential. All these factors cannot be manipulated through management, with the exception of water potential that can be influenced by irrigation (Forcella et al., 2000). Therefore germination and seedling growth in the field are mainly influenced by temperature. Plant growth does not occur unless the temperature is above a minimum threshold value called $T_{BASE,}$ which, due to high spatial variability in the field, the T_{BASE} can only be accurately verified under controlled laboratory conditions, and it is always defined for seed germination not for emergence. Germination of bermudagrass under different temperature regimes has been widely investigated (Deaton & Williams, 2013; Giolo et al., 2014, 2019). Sandlin et al. (2006) documented no germination in chambers subjected to alternating temperatures of 15/5 ˚C (day/night; 12 h photoperiod). Giolo et al. (2014) reported the successful germination of several seeded bermudagrass cultivars under alternating temperatures of 20/10 ˚C (day/night; 8/16 h photoperiod) corresponding to an average base temperature of 15 ˚C. These results are in agreement with those reported by Shaver et al. (2006), who observed seedling emergence of two bermudagrass cultivars (Princess 77 and Riviera) in the field at lower temperatures than previously reported by others (Beard, 1973; McCarty, 2005). More recently, Giolo et al. (2019) reported T_{BASE} values ranging from 11.5 to 17 ˚C for the five bermudagrass cultivars Jackpot, La Paloma, Riviera, Transcontinental, and Yukon.

The time needed for turfgrasses to establish is typically calculated as the number of days from seeding to the achievement of coverage levels of 75–100% (Giolo et al., 2020; Leinauer et al., 2009; Patton et al., 2008; Pornaro et al., 2016; Schiavon et al., 2012; Severmutlu et al., 2011). Growing degree days (GDD) are a measure of heat accumulation (Bonhomme, 2000), and are used to determine the thermal requirements from seeding to the establishment of different species. The relationship between average daily soil temperature and time from seeding to establishment is well described by a sigmoidal curve, whereas the relationship between the same time period and GDD is linear (Todey & Taylor, 2019). The GDD algorithm uses only a limited number of variables, however a correct calibration is important because of their influence in the calculation of heat units. This aspect can partly explain why in different locations authors found different GDD for the establishment of the same species (Patton et al., 2004; Schiavon et al., 2012). Differences can also be the result of the fact that germination is commonly considered part of establishment. However, these are two separate growth stages with different thermal requirements.

Core Ideas

- The widely used T_{BASE} for bermudagrass is 5 ˚C.
- Laboratory studies found 15 ˚C is a more appropriate T_{BASE} for bermudagrass.
- Bermudagrass genotypes significantly differed in seedling emergence.
- A T_{BASE} of 15 ˚C provides more accurate seedling emergence estimation of growing degree days than 5 ˚C.

The algorithm used to calculate GDD takes into consideration soil daily maximum (T_{MAX}) and minimum (T_{MIN}) temperatures, and the base temperature (T_{BASE}) of the species. According to the algorithm, the accumulation of GDD should occur only when the average daily temperature is higher than $T_{BASE.}$ Using a T_{BASE} value that is too low could result in an overestimation of the number of GDD during periods when the average soil temperature is lower than the true T_{BASE}. An overestimation of heat units during the first period after seeding could also incorrectly estimate the GDD index from seeding to establishment, which is the parameter mainly used in agronomic practice. The use of an erroneous T_{BASE} could be problematic when attempting to compare GDD calculated under different temperature regimes or in different environments. Moreover, cold soil temperatures following seeding usually occur in early spring seeding when the period from seeding to seedling emergence can last longer than 50% of the overall period up to the establishment (Giolo, unpublished data, 2020).

The most widely used T_{BASE} for bermudagrass is 5 ˚C, although T_{BASE} values of 18.3 and 10 ˚C have also been considered (Deaton, 2012; Mittlesteadt, 2009). The T_{BASE} of 5 ˚C was first proposed by Unruh et al. (1996) who investigated vegetative bermudagrass cultivars. Subsequently, this value has been used for "seeded" cultivars as well (Patton et al., 2004, 2008; Pornaro et al., 2016; Schiavon et al., 2012; Severmutlu et al., 2011). Reported GDD needed to establish seeded bermudagrass vary widely. Patton et al. (2004) calculated that 950 GDD (T_{BASE} 5 ˚C) were required for 'Mirage' in Lafayette (Indiana) while Schiavon et al. (2012) reported that more than 2,000 GDD (T_{BASE} 5 ˚C) were required for

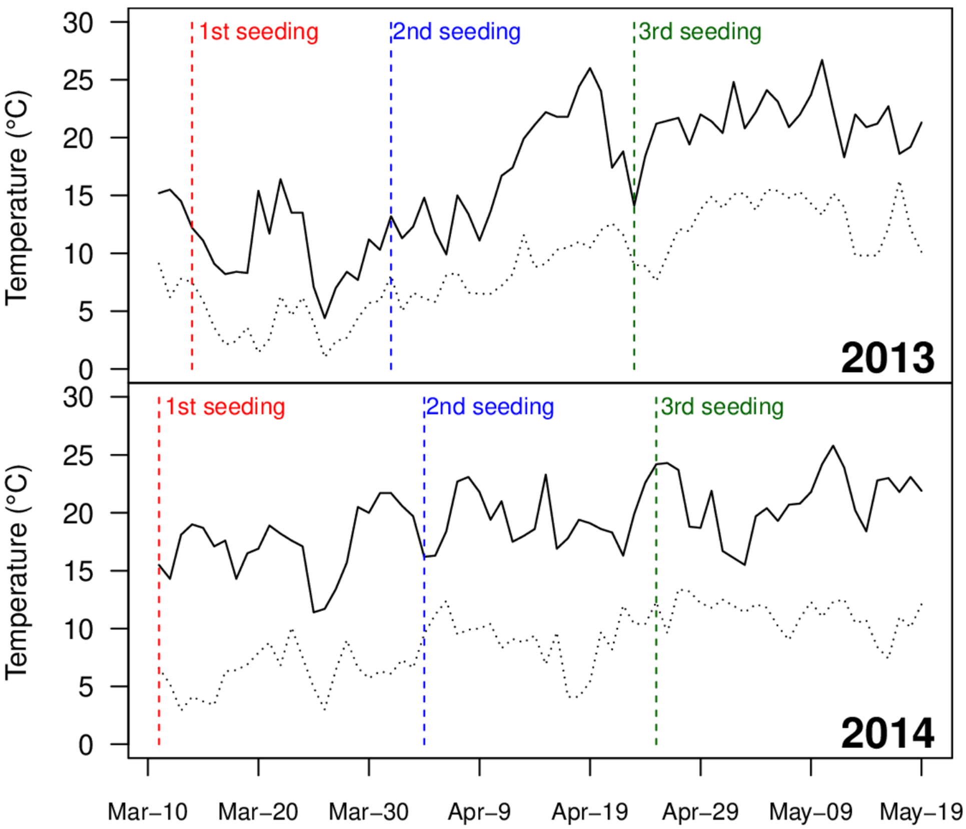

FIGURE 1 Daily maximum (straight lines) and minimum (dotted lines) mean soil temperatures at 1-cm depth from 10 March to 19 May 2013 and 2014. Dashed vertical lines indicate first, second, and third seeding

'Princess 77′in Las Cruces (New Mexico). Schiavon et al. (2012) used the soil temperature at 10-cm depth to calculate GDD, while there is no information on what depth was used by Patton et al. (2004). However, 4 yr of soil temperature data collected in Legnaro (typical transition zone in northeastern Italy) from 1 April to 31 July at two soil levels (0 and −10 cm) did not reveal any significant differences to justify the range in GDD values observed at the two locations (data not shown). Therefore, these differences could be partly due to genetic diversity among cultivars but also to the reference T_{BASE} used in the GDD calculation. Giolo et al. (2014, 2019) argued that the difference among T_{BASE} values of different bermudagrass cultivars may not justify significant modifications in the calculation of GDD. The base temperature of 15 ˚C was suggested as an average base temperature established from previous laboratory studies on different varieties (Giolo et al., 2014, 2019). The ability to accurately predict GDD required for the emergence of bermudagrass is useful in managing this species effectively. Information is currently lacking on the influence of different T_{BASE} values on GDD calculations. To address this, a 2-yr field study was conducted in northeastern Italy during spring 2013 and 2014 to compare the accuracy of the model used to calculate GDD in bermudagrass when base temperatures of 5 and 15 ˚C are used. In this study emergence of 10 cultivars seeded at different dates were recorded to determine which base temperature most accurately predicted the actual GDD observed for bermudagrass.

2 | MATERIALS AND METHODS

The study was conducted at the Experimental Agricultural Farm of Padova University in Legnaro, northeastern Italy (45˚20′ N, 11˚57′ E, and elevation 8 m). The area has a humid subtropical climate with an annual mean temperature of 12.3 ˚C and an annual rainfall of 823 mm. The soil at the site consisted of a sandy loam soil containing 63% sand, 31% silt, and 6% clay, with a pH of 8.2, 1.4% organic matter, C/N ratio of 15.3, 3.7 mg kg^{-1} available Olsen P, and 125 mg kg^{-1} exchangeable K (buffered $BaCl_2$ method). Ten bermudagrass cultivars, namely 'Gobi', 'Sunbird', 'SR9554', 'Princess 77′, 'Yukon', 'Riviera', 'Transcontinental', 'Casinò Royal', 'Savannah', and 'La Paloma' were compared in this study. Plots measuring 1 by 1 m were seeded at a rate of 4 g m^{-2} except for a 10 by 10 cm center area on which exactly 100 seeds were placed by hand. This number (100 seeds per 100 cm^2) corresponded to the seeding rate recommended by several authors (Macolino et al., 2010; Munshaw et al., 2001; Patton et al., 2004; Rimi et al., 2011, 2013a, 2013b). Certified seed was used and germination rates listed on labels ranged

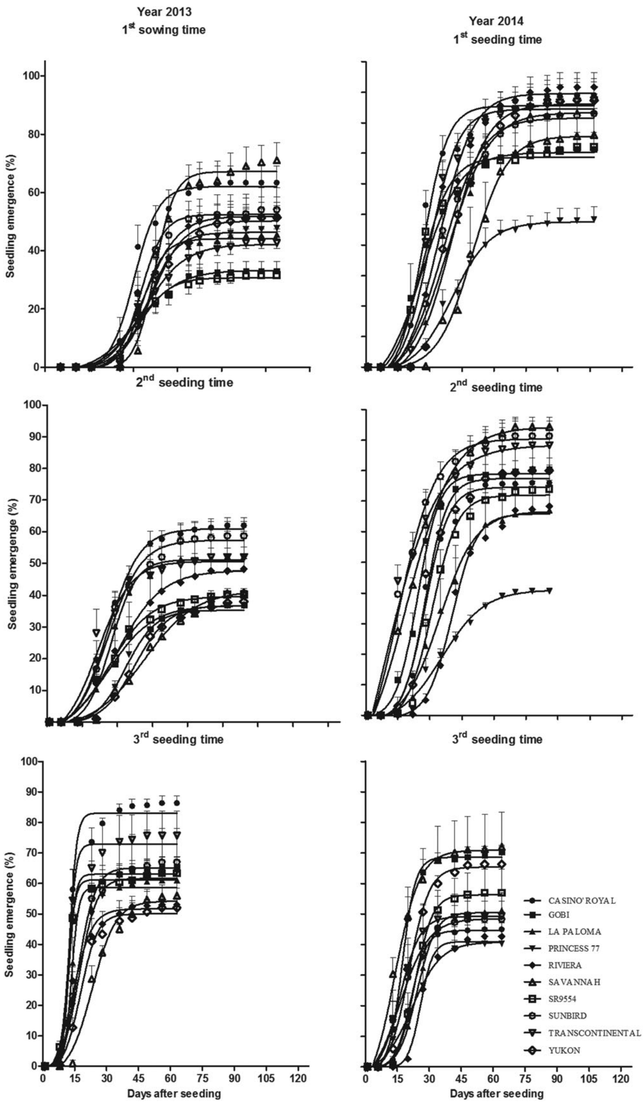

FIGURE 2 Cumulative emergence percentage at a 7-d interval of 10 seeded bermudagrass cultivars at three seeding dates in 2013 and 2014. Vertical bars represent the upper bound standard error

from 75 to 87%. The experiment was carried out from March to June in 2013 and 2014. During each year there were three different seeding dates, 13 March (D1), 3 April (D2), and 24 April (D3) in 2013 and 10 March (D1), 31 March (D2), and 22 April (D3) in 2014. Before seeding, seeds were stored at 5 ˚C for 1 mo to break seed dormancy. After seeding, seeds were covered with a 2-mm layer of washed river sand and were irrigated daily with 5 mm of water. The experimental design was a randomized complete block with three replications.

Soil temperatures at 1-cm depths were measured every 5 min using thermocouples connected to a datalogger (CR10X; Campbell Scientific) and soil T_{MAX} and soil T_{MIN} were selected from recorded values and averaged over 1 d. The average daily air temperature measured 2 m aboveground correlated highly with the soil temperature (R^2 = .95*** in 2013; R^2 = .90*** in 2014). The minimum and maximum daily soil temperatures recorded during the experiment are shown in Figure 1.

Emerged seedlings from the center area of each plot were counted weekly and then removed without disturbing the soil. Counting was stopped when no new seeds emerged for 2 wk. Growing degree days (GDD) from seeding were calculated using the equation first suggested by René-Antoine Ferchault de Réaumur in 1730 and again published by McMaster (1997) and Moore and Remais (2014):

$$\mathrm{GDD} = \frac{(T_{MAX} + T_{MIN})}{2} - T_{BASE}$$

where if $T_{MAX} < T_{BASE}$, then $T_{MAX} = T_{BASE}$, and if $T_{Min} < T_{BASE}$, then $T_{Min} = T_{BASE}$

Growing degree days were calculated using two T_{BASE} values. The first T_{BASE} used was 5 ˚C (GDD5) because it has been used in several published studies (Patton et al., 2008; Pornaro et al., 2016; Schiavon et al., 2012; Severmutlu et al., 2011). The second T_{BASE} used was 15 ˚C (GDD15) as reported by Giolo et al. (2014, 2019). A non-linear sigmoidal model (El-Kassaby et al., 2007) was identified to best describe cumulative seed emergence (GraphPad Prism 5.0 for Windows; GraphPad Software).

$$\text{The equation is, y} = \frac{A_{min} - A_{max}}{1 + \exp^{V_{50} - x}/slope} + A_{max}$$

where A_{min} is the minimum value, A_{max} is the maximum value, V_{50} is the value at which the fitted curve is halfway between minimum and maximum, and slope describes the steepness of the curve.

Following El-Kassaby et al. (2007), the model was used to compute the time at maximum germination rate. Then, the GDD were computed up to that time. Models were fitted for different T_{BASES} from 5 to 20 ˚C at 1 ˚C increments. Subsequently, an analysis of covariance was conducted using the two-way factorial design with cultivar (10 levels) and seeding time (three levels) and GDD at different T_{BASES} as covariates (Supplemental Table S1). The response variable for this analysis is the logarithm of the maximum germination rate. The analysis marginalized the effect of year, and it was conducted using SAS statistical software (version 9.4; SAS Institute). Residual log likelihood (−2 Res Log-Likelihood), Akaike's Information Criterion (AIC), corrected Akaike's Information Criterion (AICC), Bayesian Information Criterion (BIC), Comparison of Akaike's Information Criterion (CAIC), Hannan–Quinn Information Criterion (HQIC), Pearson's chi-Square test (Pearson chi-square), and Pearson's chi-square test over degrees of freedom (Pearson chi-square/df) (Littell et al., 2006) were used to select the best fitting model. When AIC is used to compare two models, it is mathematically equivalent to the Odds ratio (Jaynes, 2003), the Odds ratio was also calculated.

TABLE 1 Number of days from seeding (DFS) and growing degree days calculated with a base temperature of 5 ˚C (GDD5) and 15 ˚C (GDD15) in 2013 and 2014 to reach 25% emergence (mean of 10 bermudagrass cultivars)

Seeding date	DFS	GDD5	GDD15
2013			
13 Mar.	48	130.1	38.8
3 Apr.	34	110.9	60.5
24 Apr.	15	49.9	43.3
2014			
10 Mar.	31	161.3	49.6
31 Mar.	25	124.2	71.9
22 Apr.	21	98.7	78.2

TABLE 2 Number of days from seeding (DFS) and growing degree days calculated with a base temperature of 5 ˚C (GDD5) and 15 ˚C (GDD15) in 2013 and 2014 to reach 38% emergence (mean of six bermudagrass cultivars)

Seeding date	DFS	GDD5	GDD15
2013			
13 Mar.	53	148.4	54.6
3 Apr.	42	138.3	84.0
24 Apr.	18	59.6	51.9
2014			
10 Mar.	36	183.7	62.2
31 Mar.	28	138.0	82.2
22 Apr.	25	119.5	97.3

3 | RESULTS AND DISCUSSION

Sigmoidal regression curves of cumulative emergence percentage of the 10 cultivars tested are shown in Figure 2.

Cumulative seed emergence was lower than the labeled germination rate. Indeed, field germination is affected by high variability in environmental factors (seed burial depth, water availability, oxygen deficiency presence of pathogens, etc.) that usually reduces the emergence rate compared to controlled laboratory conditions (Hardegree et al., 2000). Most of the cultivars tested reached an emergence of 70% but only on the first two seeding dates in 2014 (Figure 2). In both experimental years, all 10 cultivars reached 25% emergence at each seeding date, but only six of them reached 38% emergence at each seeding dates.

These values were used as maximum emergence rate in further analysis. With the exception of ‘Princess 77′, emergence was higher in 2014 than in 2013 for cultivars seeded on the first two seeding dates.

Cultivars that were seeded on the third seeding date achieved greater percentage emergence in 2013 than 2014. The number of days from seeding (DFS) to reach maximum emergence rate of 25 and 38% based on the non-linear sigmoidal regressions are listed in Tables 1 and 2 together with GDD5 and GDD15. Differences in GDD5 and GDD15 among seeding dates are mainly related to differences in DFS and maximum temperatures during the period from seeding to maximum emergence rate. The high GDD15 observed on 22 Apr. 2014, was due to low maximum temperatures recorded at the end of the month, which probably also caused a lengthening of time from seeding to reach maximum emergence rate (Figure 1). Because of higher maximum daily temperatures from the beginning of April in the first experimental year, GDDs in 2013 were generally lower than GDDs in 2014 for both 25 and 38% emergence.

The results of the analyses of variance are listed in Table 3. Analyses indicate that GDD significantly affect germination and emergence. The model fit statistics for the analyses of covariance are shown in Table 4. Both the BIC and the AIC are smaller for GDD15 compared to GDD5 in 2013 and 2014. Odds ratios are 1:2 and 1:2.58 which also favors a GDD15 over GDD5. These results indicate

TABLE 3 *P* values for results of the analysis of covariance to evaluate the effects of cultivars and time of seeding and their interactions on bermudagrass germination rate. The covariate is the emergence calculated as growing degree days (GDD) using a base temperature of either 5 ˚C (GDD5) or 15 ˚C (GDD15)

	2013		2014	
Treatment	GDD5	GDD15	GDD5	GDD15
Cultivar (CV)	.1728	.2019	<.0001	<.0001
Time of seeding (TS)	<.0001	<.0001	.0740	.0059
CV × TS	.0043	.0142	.9448	.9579
GDD	.0017	.0037	.0166	.0231

TABLE 4 Model fit statistics for the analysis of covariance, with growing degree days as covariate calculated with either 5 ˚C (GDD5) or 15 ˚C (GDD15) as base temperature for 2013 and 2014

	2013		2014	
Fit statistics	GDD5	GDD15	GDD5	GDD15
–2 Res log-likelihood	100.45	99.16	83.07	81.17
AIC (smaller is better)	164.45	163.16	147.07	145.17
AICC (smaller is better)	245.68	244.39	228.30	226.40
BIC (smaller is better)	230.93	229.64	213.55	211.65
CAIC (smaller is better)	262.93	261.64	245.55	243.65
HQIC (smaller is better)	190.40	189.11	173.02	171.12
Pearson chi-square	8.89	9.10	6.63	6.70
Pearson chi-square /df	0.15	0.15	0.11	0.11

Note. –2 Res log-likelihood, residual log likelihood; AIC, Akaike's Information Criterion; AICC, corrected Akaike's Information Criterion; BIC, Bayesian Information Criterion; CAIC, comparison of Akaike's Information Criterion; HQIC, Hannan–Quinn Information Criterion.

that despite both GDD15 and GDD5 affecting germination and emergence outcome significantly (Tables 3 and 4), GDD15 explains germination and emergence more accurately than GDD5.

Our results corroborate previous studies by Deaton and Williams (2013) and Giolo et al. (2014, 2019). The authors also reported significant differences in germination and emergence between bermudagrass genotypes as affected by different temperature conditions. Similar to our findings, the authors demonstrated that the accuracy of the algorithm used to calculate GDD is strongly influenced by the T_{BASE} used. The GDD calculated for the same cultivars sown at different dates should result in near equal values.

These findings are particularly important for field experiments. For example, Richardson et al. (2004) recommended that bermudagrass be established as early as possible in spring to reduce injuries during the first winter following seeding. However, in transition zones, spring temperatures can vary strongly between years and within years (Giolo et al, 2019; Pornaro et al., 2019). Therefore, it is challenging to define a priori the optimum time of year for seeding bermudagrass. Several studies highlight the importance of temperatures for germination (Forcella et al., 2000). Similarly, GDD calculated for the same cultivars seeded at different dates should result in near equal values. However, the assumption that soil temperatures lower than T_{BASE} should be treated as equivalent to T_{BASE} can result in different calculated GDD if the bermudagrass is seeded at different times of the year. The model fit statistics for the analyses of covariance performed on GDD5 and GDD15 suggests that for bermudagrasses, a T_{BASE} of 15 ˚C provides a better estimation of cumulative GDD than a T_{BASE} of 5 ˚C.

4 | CONCLUSIONS

The study confirms that temperatures strongly influence seed germination and seedling emergence and highlight significant differences in GDD among bermudagrass cultivars. Our findings support the hypothesis that the sum of GDD for germination and emergence is influenced by the T_{BASE}. Moreover, the impact of T_{BASE} will depend on the temperatures occurring during the period following seeding. Based on our findings, a T_{BASE} of 15 ˚C provides a more accurate estimation of germination and emergence GDD than a T_{BASE} of 5 ˚C.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

ORCID

C. Pornaro https://orcid.org/0000-0002-7513-747X
S. Macolino https://orcid.org/0000-0002-5521-9929
B. Leinauer https://orcid.org/0000-0002-3700-2005

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