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ORIGINAL ARTICLE

Determining cardinal temperatures for eight cover crop species

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Abstract

Growing degree days (GDD) is a tool to predict plant growth and can be adapted for use in any plant species, including cover crops. A limitation of the GDD calculation is accurate temperature parameters used to predict plant development. For most cover crop species, the cardinal temperatures are not well defined in the literature, leading to a less accurate calculation of GDD. The objective of this study was to determine the cardinal temperatures of eight cover crop species, including Austrian winter pea (*Pisum sativum*), balansa clover (*Trifolium michelianum)*, barley (*Hordeum vulgare*), black-seeded oats (*Avena sativa*), common vetch (*Vicia sativa*), cereal rye (*Secale cereale*), crimson clover (*Trifolium incarnatum*), and hairy vetch (*Vicia villosa*), using a growth chamber experiment. Seven different temperature regimes from 4 to 34˚C were implemented, and the number of leaves was counted from day 0 to 21. As a result, the data were regressed to estimate the cardinal temperatures for each species. The results of this research identified base (2), optimum (3), and maximum (8) temperatures for cover crops that were not previously reported. Five cardinal temperatures determined in this study were different from what was previously recorded; base and optimum temperatures were −4.5 and 24.8˚C for cereal rye, 3.9 and 26.6˚C for crimson clover, and the base temperature was 3.4˚C for balansa clover. The successful identification of these cardinal temperatures for cover crops will allow the development of plant growth and biomass prediction models to aid in cover crop termination decision support tools.

1 | INTRODUCTION

The inclusion of cover crops in agricultural production systems is an important management practice. The United States Department of Agriculture (USDA) defines cover crops as grasses, legumes, and forbs that are planted for erosion control, improving soil structure, moisture, and nutrient content, increasing beneficial soil biota, suppressing weeds, providing habitat for beneficial predatory insects, facilitating crop pollinators, providing wildlife habitat, and as forage for farm animals. Furthermore, cover crops can provide energy savings both by adding nitrogen (N) to the soil and by facilitating soil nutrient availability, thereby reducing the need to apply fertilizer (USDA-Natural Resources Conservation Service, 2021). Cover crops can increase plant-available N, provide surface residue, and help with pest and weed suppression (Snapp et al., 2005). In addition, cover crops can help increase water

Abbreviations: AWP, Austrian winter pea; DTU, daily thermal unit; GDD, growing degree days; RH, relative humidity; T_b, base temperature; T_{max}, maximum temperature; T_{opt}, optimum temperature.

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infiltration and reduce soil sediment loss via erosion. The USDA defines a cover crop as a plant that can be harvested as hay or silage, but not as grain, and is grown in periods of the year when the cash crop is absent, although most of the cover crop benefits come from leaving the residue on the soil. In 2017, the USDA reported approximately 6.2 million ha of cover crops planted on US soil (Wallander et al., 2021).

Plant growth is influenced by many different environmental and weather conditions, such as sunlight quantity and quality, rainfall, soil moisture, and other biotic and abiotic stresses. However, one of the most important factors that impacts plant growth and development is temperature. Temperature plays a major role in plant growth, and exposure to both heat and cold can be very important depending on the plant species or growth stage. For example, cold/freezing temperatures are essential for many winter cereals to vernalize and switch from vegetative to reproductive growth (Chouard, 1960). Conversely, warm-season annuals such as corn (*Zea mays* L.) require a certain number of heat units to be accumulated before putting out another leaf (Kumudini et al., 2014). The ability to predict plant developmental stages can be very important for a variety of cultural management practices in crop production. For many plant species, the relationship between temperature and growth rate or developmental stage can be correlated and predicted using mathematical models.

The temperatures governing plant growth and development are known as cardinal temperatures (Yin et al., 1995). The cardinal temperatures are the base temperature (T_b), which is the lowest temperature at which a plant will still have a measurable growth rate. The optimum temperature (T_{opt}) is where plant growth is at its peak or maximal rate (Went, 1953). Lastly, the maximum temperature (T_{max}) is the temperature at which plant growth ceases due to excessive heat. These temperatures are determined empirically and are specific to each plant species. For example, the cardinal temperatures for corn are $T_b = 10^{\circ}C$, $T_{max} = 47^{\circ}C$, and $T_{opt} = 18–33^{\circ}C$ (Hollinger & Angel, 2021).

Once cardinal temperatures have been successfully defined for a plant species, growth models can be established to track plant development and even predict upcoming developmental stages based on forecasted or mean annual temperatures. A parameter called growing degree days (GDD) was designed using cardinal temperatures to estimate plant growth and normalize plant responses to varying temperatures (Thapa et al., 2018). The GDD calculation combines the cardinal temperatures and the daily temperature during the growing season. Typically, GDD is the sum of the daily thermal units (DTU). Over the years, several different methods have been developed to calculate DTU, depending on the goal and available information. Each method to calculate the DTU would account for a different number of parameters and have different accuracies based on the information available to include in the calculation.

Core Ideas

- Cardinal temperatures are required to model plant growth and development.
- Cardinal temperatures are not readily available, and reported values were often not empirically determined.
- Fourteen newly identified cardinal temperatures were determined for eight cover crop species.
- Five cardinal temperatures empirically determined here were different from those previously reported.

A simple DTU equation (Equation 1) that is often used is the average daily temperature (T_{avg}) minus T_b (McMaster & Wilhelm, 1997). However, this equation fails to consider the change in daily temperature over the growing season and how that might negatively affect plant growth when temperatures are above the optimum. Another way of calculating DTU is a model described by Yin et al. (1995) that accounts for all cardinal temperatures and, therefore, would be more accurate to estimate plant growth (Equation 2).

$$\mathrm{DTU} = \begin{cases} 0 & T_{avg} < T_b \\ T_{avg} - T_b & T_b < T_{avg} < T_{opt} \\ T_{opt} - T_b & T_{avg} \geq T_{opt} \end{cases}, \quad (1)$$

$$\mathrm{DTU} = \mathrm{DTU}_{max}\left[\left(\frac{T_{max} - T_{avg}}{T_{max} - T_{opt}}\right)\left(\frac{T_{avg} - T_b}{T_{opt} - T_b}\right)^{\frac{T_{max} - T_{opt}}{T_{opt} - T_b}}\right]. \quad (2)$$

These plant growth estimation models that use GDD are well known for predicting growth stages and management practice implementation (Miller et al., 2018) in cash crops such as corn (Gilmore & Rogers, 1958) and rice (*Oryza sativa* L.; Hardke & Norman, 2017). To our knowledge, there are limited cover crop biomass accumulation or growth and development models that exist due to the lack of information on cover crop cardinal temperatures in the literature. A single study conducted by Feyereisen et al. (2006) attempted to model cereal rye biomass accumulation and N-scavenging potential. However, it is unclear whether they used T_b or T_{opt} temperatures for cereal rye, wheat, or oats, but they point out the lack of cardinal temperature data that are readily available for modeling cover crop growth and development.

Interest in cover crops continues to increase, and with each passing year, there is a greater demand from producers for decision management tools to aid their ability to maximize the benefits of cover crop implementation. Many of the benefits associated with cover crop implementation are associated

with biomass production, specifically with greater biomass production leading to greater benefits. Conversely, greater amounts of aboveground biomass can result in greater difficulty in establishing the following cash crop. Therefore, a decision management tool that predicts the development or biomass production of cover crop species could greatly benefit producers and increase their ability to time cover crop termination to maximize cover crop benefits but reduce the potential negative aspects of cover crops on the following cash crops. Prior to the successful development of these decision aids, an accurate and robust set of cardinal temperatures must be available for each cover crop species. In an effort to fill some of the knowledge gaps and develop cover crop management decision aids, our project's objective is to determine the cardinal temperatures for some commonly used cover crop species that are currently not available in the published literature.

2 | MATERIALS AND METHODS

The cover crop species growth rate and GDD experiment were conducted at the University of Arkansas Altheimer Lab and Crop Science Building (Fayetteville, AR) in a 183 × 81 × 142 cm PGR15 CONVIRON growth chamber (CONVIRON). The eight cover crop species for the study included Austrian winter pea (AWP; *Pisum arvense*), balansa clover (*Trifolium michelianum*), barley (*Hordeum vulgare*), black-seeded oats (*Avena sativa*), cereal rye (*Secale cereale* var. Wrens Abruzzi), common vetch (*Vicia sativa* var. Cahaba), crimson clover (*Trifolium incarnatum*), and hairy vetch (*Vicia villosa*) and were chosen to represent the most commonly grown cover crop species in the mid-southern United States. Each cover crop species was grown in seven different temperature regimes, starting at 4˚C and increasing by 5˚C, with the highest overall temperature being 34˚C, which was the upper limit of the growth chamber's temperature capabilities.

2.1 | Germination and establishment

Prior to plants being placed in the growth chamber at the predetermined temperatures, cover crops were germinated in a greenhouse in plastic seeding trays (each tray had six cells, and each cell was 4 cm square by 6 cm deep) with PRO-MIX M mycorrhizae potting mix (Premier Tech Horticulture) and remained in the greenhouse until the cover crop seedling grew at least one true leaf but no more than three true leaves. First, the winter cereal species were germinated, and when they had at least one leaf, they were vernalized in a cold storage room at 4.5˚C for 10 days before going into the growth chamber. As the winter cereal vernalization process was occurring, the legume species were germinated to allow all the plants to have at least 1–3 true leaves and be ready to enter the growth chamber simultaneously. Germination and establishment procedures for each cover crop species were repeated prior to each temperature cycle.

When all plants were ready to be moved to the growth chamber, they were transplanted one plant per pot (20 × 20 cm, 1.21 L pot with potting mix). Each plant species was treated as an individual trial, and the pots were arranged inside the growth chamber in a completely randomized design with three replications. The experiment was conducted twice, between July 22 and December 19, 2020, and between March 16 and September 17, 2021.

2.2 | Leaf appearance rate

Once placed in the growth chamber, the plants were exposed to each predetermined temperature and 500 µmol light intensity in a 12-h daylight/nighttime regime for 21 days. The pots were watered as needed (at least every 2 days) through each temperature cycle to simulate optimum growing conditions. In addition, temperature and relative humidity (RH) were monitored using a HOBO U23 Pro v2 data logger (ONSET). The average RH was 78% for the duration of this experiment. For the data analysis, the mean temperature recorded on the data logger during each 21-day cycle was used.

During the 21-day period, the number of leaves of each plant was counted every other day (Gramig & Stoltenberg, 2007). A new leaf was considered when a leaf on the cereal species resulted in a new collar, or for the broad leaf species, when the tips of the leaf were unfurled or no longer touching. For this experiment, leaves were only considered on the main stem (excluding cotyledons) (Alm et al., 1988; Gramig & Stoltenberg, 2007), even when the plant developed secondary branches or tillers. After 21 days of growth within a predetermined temperature setting, the trials were terminated.

2.3 | Data analyses

The data were analyzed in R 4.1.1 (R Core Team, 2021). Leaf appearance rates were calculated for each experimental unit as the slope of the relationship between leaf number and chronological time in units of leaves per day. Relative growth (leaf appearance) rate was calculated (data not shown) as the ratio between the leaf appearance rate of a given experimental unit and the average maximum leaf appearance rate of the three replications.

The relationship between relative leaf appearance rate and mean air temperature was investigated by fitting a bilinear model (Equation 3) in which "T_b" is the base temperature,

"T_{opt}" is the optimum temperature for crop development, and "T_{max}" is the ceiling (or maximum) temperature. This model assumes that crop development ceases when the air temperature is below the base temperature, increases linearly when the air temperature is between the base and optimum temperatures, decreases linearly when the air temperature is between the optimum and ceiling temperatures, and ceases when the air temperature is above the ceiling temperature. The model was fit using the maximum log-likelihood method in a nonlinear mixed model using the "nlme" (Pinheiro et al., 2020) and "nlraa" (Miguez et al., 2021) packages. The model was constructed in increasing order of complexity as described in Pinheiro and Bates (2006), and relative growth was expressed as a function of mean air temperature. The effect of cover crop species was investigated by including the species as a fixed effect in the model. Subsequently, random effects for run and replication within run were tested in the model. The effect of replication within run was found to be non-significant and dropped from consideration. The final model included the fixed effect of cover crop species and the random effect of run.

$$f(x) = \begin{cases} 0, & T_{avg} \le T_b \\ \frac{T_{avg} - T_b}{T_{opt} - T_b}, & T_b \le T_{avg} \le T_{opt} \\ 1 - \frac{T_{avg} - T_{opt}}{T_{max} - T_{opt}}, & T_{opt} \le T_{avg} \le T_{max} \\ 0, & T_{avg} \ge T_{max} \end{cases}. \quad (3)$$

3 | Results and Discussion

For the 21-day duration of the study, relative growth was highly correlated to temperature as temperature increased from 4 to 34°C, where it was not possible to collect more data due to the upper stable temperature limit of the growth chamber. Therefore, the maximum temperature was estimated for most plant species, as shown in Figure 1. The lower temperature range of the growth chamber was set at 4°C to provide an above-freezing temperature that was near or above previously reported T_b temperatures. Although several of the T_b values determined here are below the lowest temperature treatment, the T_b values we report have relatively low standard deviations, and the data fit to the predicted line provides confidence that the values are reliable. Each cover crop species exhibited the same pattern of relative growth, even though the various cover crop species had different responses to temperature. The general trend for each cover crop species was a linear increase in the relative growth rate when increasing the average temperature from the base temperature until the optimum temperature. The species then achieved a 100% relative growth rate at the optimum temperature. Above the optimum temperature, or the breaking point (T_{opt}), the relative growth rate has a linear decrease when increasing the daily temperature until the relative growth is zero, which is considered the maximum temperature (T_{max}).

There were no T_{max} values reported in the literature for the cover crop species that were investigated in this study (Table 1). When producing crops for grain, forages, or even as cover crops, having a well-defined T_{max} can be essential to implementing cultural management practices. Having well-defined T_{max} values for these cover crop plant species in the mid-southern United States is even more relevant due to the speed with which temperatures increase in the late winter and early spring and the relatively high levels they can reach prior to cover crop flowering or termination. Due to the lack of data previously reported for these cover crop species, it was pertinent to empirically determine the T_{max} values for the cover crops investigated here. Of the eight cover crop species investigated in this study, five resulted in T_{max} estimates that were beyond the upper temperature limits of the growth chamber used in the study. Only the T_{max} values for balansa clover, common vetch, and hairy vetch were below the 34°C upper limit of our growth chambers (Table 1). Of the five species where the predicted T_{max} was beyond the upper limit of our growth chamber, there are varying levels of reliability associated with the values, as evidenced by the confidence intervals presented in Figure 1. As expected, when the predicted T_{max} value was well above (>5°C) our highest temperature of 34°C, the confidence intervals were relatively large, ranging from ~3 to 7°C. Based on the information presented in Figure 1, it is apparent that the resultant decrease in plant growth rate for temperatures above the optimum occurs more quickly than the increase in plant growth rate when temperatures are below the T_{opt}. These results suggest that an accurate prediction of the T_b and T_{opt} is of more importance than correctly identifying the T_{max} when modeling cover crop species growth and development.

During this study, all cardinal temperatures were determined for each cover crop species and their associated confidence intervals (Table 1). The confidence interval for the maximum temperatures was greater than 3°C for all the cover crop species except hairy vetch and balansa clover. The confidence intervals were below 3°C for the optimum and base temperatures of all the cover crop species, except for the T_{opt} for cereal rye. The cardinal temperatures determined in this study were compared to the cardinal temperatures that could be found in the literature and are presented in Table 1. The T_b values were not found for AWP and common vetch. The T_{opt} was not found for AWP, common vetch, and hairy vetch, and the T_{max} was not found in the literature for any of the cover crop species.

None of the cardinal temperatures for AWP were identified in the literature search prepared for this study. However, there are some data available for field pea (*Pisum sativum* L.), which is noted to be the same species and is most likely a close relative. The reported cardinal temperatures for field pea are

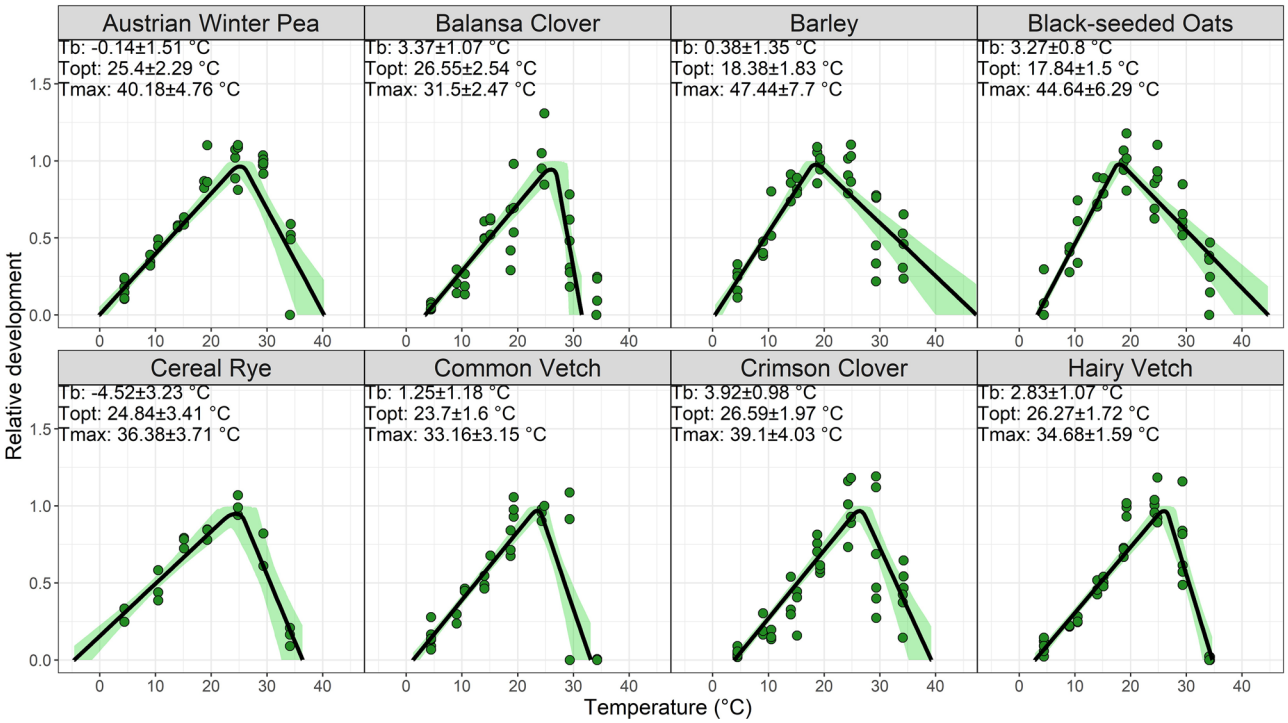


FIGURE 1 Relative growth by temperature in degree Celsius for Austrian winter pea (*Pisum sativum*), balansa clover (*Trifolium michelianum*), barley (*Hordeum vulgare*), black-seeded oats (*Avena sativa*), common vetch (*Vicia sativa*), cereal rye (*Secale cereale*), crimson clover (*Trifolium incarnatum*), and hairy vetch (*Vicia villosa*). Each graph has three cardinal temperatures with the confidence interval for each cover crop species. T_b, base temperature; T_{opt}, optimum temperature; T_{max}, maximum temperature.

TABLE 1 The cardinal temperatures determined by this project compared to the data reported in the literature for Austrian winter pea (*Pisum sativum*), balansa clover (*Trifolium michelianum*), barley (*Hordeum vulgare*), black-seeded oats (*Avena sativa*), common vetch (*Vicia sativa*), cereal rye (*Secale cereale*), crimson clover (*Trifolium incarnatum*), and hairy vetch (*Vicia villosa*).

Plant species	Cardinal temperature (˚C)					
	Base temperature (T_b)		Optimum temperature (T_{opt})		Maximum temperature (T_{max})	
	Previously reported	Current Study	Previously reported	Current study	Previously reported	Current study
Austrian winter pea	No data	−0.14	No data	25.40	No data	40.18
Balansa clover	2.5[a]	3.37	15[b]	26.55	No data	31.50
Barley	0.02[c]	0.38	20[c]	18.38	No data	47.44
Black-seeded oat	4[d]	3.27	22[d]	17.84	No data	44.64
Cereal rye	4.4[e]	−4.52	10–24[e]	24.84	No data	36.38
Common vetch	No data	1.25	No data	23.70	No data	33.16
Crimson clover	0[f]	3.92	30[f]	26.59	No data	39.10
Hairy vetch	4[g]	2.83	No data	26.27	No data	34.68

[a]Monks et al. (2009).
[b]Monks et al. (2010).
[c]Cao and Moss (1989).
[d]Mantai et al. (2017).
[e]Nuttonson (1958).
[f]Butler et al. (2002).
[g]Teasdale et al. (2004).

0°C, 28°C, and 38°C for the T_b, T_{opt}, and T_{max}, respectively (Olivier & Annandale, 1998). The temperatures determined in this study were T_b of −0.14 ± 1.51°C, T_{opt} of 25.4 ± 2.29°C, and T_{max} of 40.18 ± 4.76°C. The cardinal temperatures found in the literature for field pea are within the confidence intervals of the cardinal temperatures determined here for AWP and suggest that these two are very similar in their response to temperature as it pertains to growth and development. These results are not surprising since they are the same species, but the lack of research containing cardinal temperature data specific to AWP was concerning. The similarity in the data reported for field pea and what is reported here for AWP indicates that models using either set of cardinal temperatures would provide similar estimates of growth and development.

The T_b and T_{opt} reported for balansa clover in the literature were 2.5 (Monks et al., 2009) and 15°C,), respectively (Monks et al., 2010). The lack of data for this clover species suggests that there are little data available to support the reported cardinal temperatures. During this study, it was determined that balansa clover exhibits a T_b of 3.37 ± 1.07°C, a T_{opt} of 26.55 ± 2.54°C, and a T_{max} of 31.5 ± 2.47°C as its cardinal temperatures. Although the T_b reported in the literature is within the confidence interval reported for balansa clover determined in this study, the T_{opt} is more than 10°C different, and there is no T_{max} reported. The results of our study indicated that the T_{opt} for balansa clover was 26.55°C, which suggests that the growth rate continues to increase beyond what was reported previously. Using the T_{opt} reported in the literature would result in a gross overestimation of balansa clover growth rate based on the results determined here. Such a large difference in T_{opt} for balansa clover suggests that the effective prediction of cover crop growth rate can only be achieved when accurate cardinal temperatures are used and may need to be cultivar specific rather than a generic number for a given species.

Barley is more often grown as a cash crop than a cover crop and therefore has an abundance of data as it relates to cardinal temperatures. The T_b and T_{opt} most reported in the literature for barley were 0.02 and 20°C, respectively (Caos & Moss, 1989). The cardinal temperatures determined for barley in this study were 0.38 ± 1.35°C as T_b, 18.38 ± 1.83°C as T_{opt}, and 47.44 ± 7.7°C as T_{max}. Even though the reported values from the literature and the cardinal temperatures determined here are not substantially different, as the season progresses, the small differences in T_{opt} could amass to significant differences in the estimation of barley growth and development. The accuracy of a model for predicting growth and development is critical to determine cover crop termination dates, but it is even more important for cultural management practices in a barley grain crop. In this case, the T_b values reported in the literature would overestimate plant growth, and the T_{opt} values reported in the literature would underestimate plant growth when compared to the numbers reported here.

Black-seeded oat's T_b and T_{opt} listed in the literature were 4 and 22°C, respectively (Mantai et al., 2017). Our results suggested that the cardinal temperatures for this species were 3.27 ± 0.8°C for base, 17.84 ± 1.5°C for optimum, and 44.64 ± 6.29°C for maximum. Similar to what was observed for barley, the values determined in this study were comparable to previously reported cardinal temperatures. However, due to the nature of the DTU calculations, slight differences in T_b or T_{opt} can have profound impacts on the total GDD accumulated as small differences are compounded over weeks or even months of the growing season. The values in the literature are different enough that when compared with the temperatures reported in this project for black-seeded oat, the temperatures reported in the literature would most likely underestimate the plant growth.

The base and optimum temperatures of cereal rye have been reported as 4.4 and 10–24°C, respectively (Nuttoson, 1958). Unlike the other crops investigated in this study, the literature search revealed a wide range of values for the T_{opt} suggesting that there is a wide variety of responses to temperature within this species or that these values may have been estimated from other sources and not determined empirically. We determined that the cardinal temperatures for cereal rye were −4.52 ± 3.23°C as the base, 24.84 ± 3.41°C as the optimum, and 36.38 ± 3.71°C as the maximum. There is quite a large difference between the T_b and T_{opt} ranges presented in the literature and what was determined within the scope of this study. The reported T_b in the literature was ∼9°C higher than what was determined here. The T_{opt} values reported in the literature ranged from 10 to 24°C and were lower than the T_{opt} reported here of 24.84°C. Although the upper bound of T_{opt} data reported in the literature is within the confidence interval determined from this dataset, the lowest reported T_{opt} is less than the half of what we determined. Conversely, the T_b determined in this study is significantly lower than the one presented in the literature, which indicates that plant growth starts earlier (at a lower temperature) than what was reported. Similar to what was suggested for many of the other species included in this study, the use of values reported in the literature would underestimate the growth of the cereal rye at the base temperature and overestimate the growth at the optimum temperature compared to the temperatures determined in this project.

The only cardinal temperature reported for hairy vetch in the literature was the T_b, and it was found to be 4°C (Teasdale et al., 2004). The data provided from this project indicate that hairy vetch has cardinal temperatures of 2.83 ± 1.07°C as the base, 26.27 ± 1.72°C as the optimum, and 34.68 ± 1.59°C as the maximum temperature. The T_b value for hairy vetch was the only data point available from previous work, and it was slightly higher than what was found in this study but within the upper bounds of the confidence interval. Since there were no values reported previously for the T_{opt} or the T_{max} of

hairy vetch, it is hard to compare the data presented here to previous work. However, it does appear that the legume species investigated here have similar T_{opt} values, which suggests that the growth rates of hairy vetch, balansa clover, and AWP would all peak at a similar ambient temperature. When comparing DTU and GDD estimations for hairy vetch, the T_b value presented in the literature would underestimate plant growth, and the lack of either a T_{opt} or T_{max} prevents even a remotely precise estimate of hairy vetch growth and development.

After a thorough review of the literature, the cardinal temperatures for common vetch were not found, which was not surprising as only the T_b for hairy vetch was previously reported. The cardinal temperatures determined for common vetch in this experiment are 1.25 ± 1.18°C as the base, 23.7 ± 1.6°C as the optimum, and 33.16 ± 3.15°C as the maximum. Considering that common vetch and hairy vetch are at least similar plant species, researchers might use the data for hairy vetch's T_b as a surrogate for common vetch in DTU or GDD calculations in which case the values would be significantly underestimated. The T_b for common vetch determined in this research study is even less than that reported for hairy vetch. Also, the common vetch T_b value determined in this study is less than the half of that previously reported in the literature for hairy vetch and not within the confidence intervals of this dataset.

Crimson clover has base and optimum temperatures reported in the literature as 0 and 30°C, respectively (Butler et al., 2002). Crimson clover has been widely used as a cool-season forage crop, and it was surprising that a T_{max} value was not reported previously. The cardinal temperatures determined in this study were 3.92 ± 0.98°C as the base, 26.59 ± 1.97°C as the optimum, and 39.1 ± 4.03°C as the maximum. The T_b reported for crimson clover in the literature is one of the few that was actually lower than what was determined in the current study. Using a T_b of 0 versus 3.9°C would lead to two errors in the DTU and GDD calculations. First, using a T_b of 0°C would suggest that the plant starts accumulating heat units and growing at lower ambient air temperatures when in fact there would be no growth at all. Second, this would result in an overestimation of DTU and GDD calculations, resulting in poor predictions of crimson clover growth and development. Conversely, the T_{opt} reported in the literature when compared to the value reported in this study would underestimate crimson clover growth and development. Temperature is one of the most limiting factors for plant growth (Went, 1953), and having accurate information on the limiting temperatures is important when estimating and simulating plant growth. Using all three cardinal temperatures to calculate thermal units and GDD yields better and more accurate results on the estimation of growth and biomass production (Yin et al., 1995).

4 | CONCLUSION

Our project aims to determine the cardinal temperatures for some commonly used cover crop species that are currently not available in the published literature. The results presented here identify and provide revised cardinal temperatures for eight commonly grown cover crop species in the mid-southern United States. The T_b values for two cover crops (AWP and common vetch) were identified as they had not been previously reported in the literature, and at least three of the T_b values determined here were different than what was previously reported. The most surprising difference in T_b values between previous reports and this study was for cereal rye, where our value was almost 9°C lower than what was found in the literature. Such a large difference in T_b values would lead to gross underestimations of plant growth and development for cereal rye when using the data reported in the literature. Proper identification of the T_b is pertinent to plant development modeling, as this value indicates the temperature at which the plant will begin to grow versus when no growth is occurring at all. Following T_b, the T_{opt} is the second most influential cardinal temperature. The present study identified T_{opt} for three of the eight cover crop species (AWP, common vetch, and hairy vetch) for which there were no values found in the literature. Of the remaining five cover crop species, the T_{opt} was similar for two of them (barley and crimson clover) and very different for the remaining three. The T_{max} was determined for all eight of the species included in this study, as no previous reports for any of the cover crop species could be found in the literature. Although T_{max} may not be as critical for modeling the growth of cover crop species as T_b or T_{opt}, it may be more important in the mid-south or southern United States where temperatures rise quickly in the late winter and early spring and will often exceed 30°C well before cover crop heading or blooming. It should be noted that 30°C is above the T_{opt} reported in the literature and empirically determined within the scope of this study for all the cover crop species.

The refinement or identification of 18 of the 24 possible cardinal temperatures investigated in this study generates a significant step forward in the ability to model cover crop species growth and development. Prior to this study, the use of previously reported values or estimations based on similar plant species would have led to vastly unreliable estimates of cover crop growth.

The information on cardinal temperatures presented in this study is valuable for farmers and researchers to improve their production systems based on the implementation of cover crops into their crop rotation. Future studies should focus on the development of cover crop growth and development prediction models and then validate these data at the field scale. The development of decision support tools using this information could aid producers in the successful implementation

of cover crops in their production systems by helping predict proper cover crop termination timing.

AUTHOR CONTRIBUTIONS

Mila V. Pessotto: Formal analysis; investigation; methodology; writing – original draft; writing – review and editing. **Trenton L. Roberts**: Conceptualization; funding acquisition; investigation; methodology; project administration; resources; supervision; writing – review & editing. **Matthew Bertucci**: Investigation; methodology; writing – review & editing. **Caio dos Santos**: Methodology; resources; software; writing – review & editing. **Jeremy Ross**: Conceptualization; methodology; resources; writing – review & editing. **Mary Savin**: Investigation; resources; writing – review & editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

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