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Use of growing degree days to model the dynamics of aboveground biomass and nitrogen accumulation of winter cover crops

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Abstract

Cover cropping is an important management practice that can benefit the cash crop and the environment. Plant species, weather, and cover crop termination influence biomass production and N fixation potential. This study was conducted to determine optimal termination dates for production systems in Arkansas based on growing degree days (GDD) for eight different cover crop species: Austrian winter pea (AWP) (*Pisum sativum*), balansa clover (*Trifolium michelianum*), barley (*Hordeum vulgare*), black-seeded oats (*Avena sativa*), common vetch (*Vicia sativa* var. Cahaba), cereal rye (*Secale cereale*), crimson clover (*Trifolium incarnatum*), and hairy vetch (*Vicia villosa*). Field studies were conducted at three research stations in Arkansas to provide differences in climate and rate of GDD accumulation. An area of 0.17 m^2 was harvested for aboveground biomass and total N uptake randomly within each experimental unit every 2 weeks, starting on February 15. Aboveground biomass accumulation and N content were regressed as a function of GDD for each cover crop treatment. At the Rohwer site, AWP, for example, accumulated an average of 3643 kg ha^{-1} of biomass and 107 kg N ha^{-1} at termination, whereas 30 days before termination, the average was 1868 kg ha^{-1} of biomass and 69 kg N ha^{-1}. The growth rate increased dramatically closer to termination due to warmer temperatures, which allowed for rapid GDD and aboveground biomass accumulation. These results suggest that termination dates can be identified using previous and forecasted weather data.

Plain Language Summary

Predicting aboveground biomass and total nitrogen accumulation associated with winter cover crops can aid producers in effective planning and successful implementation of regenerative agricultural practices. Our work models aboveground

Abbreviations: AWP, Austrian winter pea; GDD, growing degree days; PTRS, Pine Tree Research Station; RRS, Rohwer Research Station; VRS, Vegetable Research Station.

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biomass and total nitrogen accumulation in eight winter cover crop species commonly used across the United States. We matched aboveground biomass and total nitrogen accumulation with growing degree days to develop a model relating these factors. The results show that trends in biomass and nitrogen accumulation were similar across species, but the degree days and actual accumulation rates were different. Future research should look at process based modeling to improve predictions and provide producers with easy to use tools to aid in effective whole farm management.

1 | INTRODUCTION

Cover crops are becoming more integrated into winter fallow, conventionally tilled production systems each year. In 2012, the USDA reported approximately 4.2 million ha of cover crops, and in 2022, it had increased to 7.3 million ha. The USDA defines cover crops as plant species that are grown during the periods of the year when the area was traditionally fallow, and these plants cannot be harvested for grain (USDA, 2018). There is some flexibility to use cover crops for hay or silage, but it is recommended to leave as much of the residue on the soil surface to maximize the benefits of cover crop use. Specific cover crop species can bring several benefits to the environment, the following cash crop, and the overall crop production system. According to the USDA, cover crops are legume, grass, and other broadleaf species that are planted for the benefits they can bring to the soil, such as building soil health, providing soil surface residue, reducing or preventing erosion, suppressing weeds, increasing soil moisture and nutrient content, and providing wildlife habitat (USDA, 2018). Cover crop plant species can be greatly beneficial to the production system; they can often improve crop yield and reduce the potential negative impact of management on the environment (Burger et al., 2017; Ruis et al., 2019; Schipanski et al., 2014; Snapp et al., 2005), although their primary purpose is not economic.

The aboveground biomass produced by the cover crops, also known as residue, is a major contributor to the potential benefits that can be achieved by adding cover crops to the crop rotation. The aboveground biomass improves weed suppression/control, helps maintain soil moisture, reduces nutrient leaching (Brandi-Dohrn et al., 1997), and can be a source of nutrients after decomposition. The belowground biomass increases water infiltration and reduces soil erosion (Blanco-Canqui & Jasa, 2019; Blanco-Canqui & Lal, 2004; Kaspar & Singer, 2011; Langdale et al., 1991), helps maintain soil structure, and reduces soil compaction (Kaspar & Singer, 2011; Langdale et al., 1991; Williams & Weil, 2004). In addition, grasses or cereal crops can increase soil infiltration and decrease water loss from the landscape (Ebelhar et al., 1984; Basche & DeLonge, 2019). Some species have the potential to accumulate large amounts of biomass, for example, barley (*Hordeum vulgare*) can produce up to 9 Mg ha^{-1} of aboveground biomass in a single season (Patterson et al., 2004).

When planted as a cover crop, the legume species are also used as a nitrogen (N) source (Ebelhar et al., 1984). The N is accumulated in the plant biomass via biological N fixation during the growing season. Nitrogen accumulated in the cover crop biomass becomes available for the next crop after the residue decomposes (Brill, 1977) and increases plant-available N in the soil. Species vary in the amount of biomass N they can accumulate, for example, Austrian winter pea (AWP) (*Pisum arvense*) can accumulate up to 208 kg N ha^{-1}, and hairy vetch (*Vicia villosa*) up to 213 kg N ha^{-1} (Parr et al., 2011). Therefore, these plant species can reduce the need to apply synthetic N fertilizers or other organic-N amendments, reducing the total N application rate and the associated costs (USDA-Natural Resources Conservation Service, 2021).

Cover crops can be grown during summer or winter, depending on the production system. A cover crop is grown in a rotation with the cash crops. To choose the best cover crop, the farmer needs to consider which species would best fit their rotation management system. Following the recommended planting and termination dates for cover crops based on the cash crop and the management plan is essential to ensure that maximum benefits from the cover crop are achieved (Clark et al., 1997; Wilson et al., 2013). Cool season cover crops are established in the late fall to give them enough time to establish and enter dormancy before the coldest temperatures occur (Ebelhar et al., 1984; Gailans, 2017). These cool season cover crops are terminated in early spring to mid-spring, either before or in conjunction with the row crop planting date.

Like any other plant, cover crop development and growth are regulated by temperature. The benefit of this plant response characteristic is that growing degree days (GDD) can be used as a parameter to estimate plant development (Baraibar et al., 2018; Chatterjee et al., 2020; Gailans, 2017). The mathematical model for GDD that is used to estimate plant growth and development is based on the air

temperature and the species' cardinal temperatures (Pessotto et al., 2023). GDD prediction tools are well known and used in row crops such as corn (*Zea mays*) (Gilmore & Rogers, 1958) and rice (*Oryza sativa*) (Hardke & Norman, 2017) to predict growth stages and crop development. The accumulation of GDD influences plant growth and biomass accumulation (Thapa et al., 2018; Baraibar et al., 2018; Chatterjee et al., 2020). Therefore, the potential biomass production of a cover crop can be modeled as a function of accumulated GDD from emergence to the termination date.

The use of cover crops continues to increase every year, and as more farmers adopt these practices into their crop rotations, more decision-making tools need to be developed or adapted to help them manage their cover crops effectively. A tool that uses GDD to model plant biomass production would greatly benefit producers in selecting cover crop species, the length of the growing season, and the ideal cover crop termination date according to the producer's short- and long-term interests. This project aims to (i) investigate the relationship between plant growth and GDD to understand the relative growth pattern of commonly grown cover crops in the mid-south United States and (ii) compare the biomass and N accumulation for different termination timings. The successful identification of a relationship between cover crop aboveground biomass or N accumulation would allow producer decision aids to be developed that predict ideal cover crop termination dates.

Core Ideas

- Winter cover crop aboveground biomass and total N accumulation are related to growing degree days (GDD) accumulation.
- Modeling GDD accumulation by winter cover crops can predict aboveground biomass production and total N uptake.
- Using GDD models can help determine termination dates for winter cover crops.

2 | MATERIALS AND METHODS

Experiments were conducted in three different locations in Arkansas from 2019 to 2021, in areas that represent a typical mid-southern production system. The locations used in the trial were three University of Arkansas System Division of Agriculture Experiment stations. The locations included the Vegetable Research Station (VRS), near Kibler, AR, on a Roxanna silt loam soil (coarse-silty, mixed, superactive, nonacid, thermic Typic Udifluvents); the Rohwer Research Station (RRS), near Watson, AR, on a McGehee silt loam (fine-silty, mixed, active, thermic Aeric Epiaqualf); and the Pine Tree Research Station (PTRS), near Colt, AR, on a Calloway silt loam soil (fine-silty, mixed, active, thermic Aquic Fraglossudalfs). Soil samples were taken at 0- to 10-cm depth at each location, these samples were collected across the field prior to planting. Soil samples were submitted to the University of Arkansas System Division of Agriculture's Diagnostic Lab (Fayetteville, AR) for nutrient analysis. Samples were analyzed for phosphorus (P) and potassium (K) using the Mehlich 3 (1:10 soil/extractant ratio by weight) method (Helmke & Sparks, 1996). Since there is no fertilization guideline for cover crops by the University of Arkansas, soil nutrient levels were interpreted based on the recommendation for winter wheat (*Triticum aestivum* L.). The nutrient levels were considered above optimum for K, and optimum for P at VRS, above optimum for P and medium for K at RRS, and low for P and K at PTRS.

All trials were planted on October 24, 2019, and November 5, 2020, and terminated on May 1, 2020, and May 31, 2021. The first trial had three commonly grown cover crop species treatments: barley, black-seeded oats (*Avena sativa*), and cereal rye (*Secale cereale*). The second trial had winter or cool-season legumes and included AWP, balansa clover (*Trifolium michelianum*), common vetch (*Vicia sativa* var. Cahaba), crimson clover (*Trifolium incarnatum*), and hairy vetch.

2.1 | Winter cereal cover crop trial

Winter cereal cover crop treatments (barley, black-seeded oats, and cereal rye) were in a rotation system with soybean (*Glycine max* L.) as the cash crop. Prior to planting the cover crop treatments, soybean was harvested, and the area was tilled to a 10-cm depth at each location. After cover crops were planted for the first year of the experiment, both the cover and cash crops for the subsequent years were managed in a no-till system. The experimental design was a randomized complete block design with four replications and three treatments, with experimental units measuring 43 m in length and 2.3 m in width. The cover crops were seeded using a drill planter with 19 cm row spacing, and the seeding rate for all winter cereals was 45 kg ha^{-1} (Roberts, 2021). All cover crop treatments were chemically terminated, on May 1, 2020, and May 31, 2021, using an herbicide mixture of paraquat at 1 kg ai ha^{-1} and propanil at 4.48 kg ai ha^{-1}.

2.2 | Winter legume cover crop trial

Legume cover crop trials were established in a fallow field with similar site and soil characteristics for both years to avoid nutrient (primarily N) build-up across consecutive years. Prior

to experiment establishment, the area was tilled to a 0- to 10-cm depth at each location. The experimental design followed a randomized complete block with five cover crop species treatments and four replications, and the experimental units measured 2.3 m in width and 43 m in length. The cover crop treatments were drilled with a row spacing of 19 cm, and the seeding rate was 67 and 34 kg ha^{-1} for large (e.g., AWP) and small (e.g., clovers and vetches) seeded species (Roberts, 2021). Winter legume cover crop seeds were inoculated with the proper species of rhizobium prior to planting to ensure that nodulation would occur. All cover crop treatments were chemically terminated on May 1, 2020, and May 31, 2021, using an herbicide mixture of paraquat at 1 kg ai ha^{-1} and propanil at 4.48 kg ai ha^{-1}.

2.3 | Data collection

2.3.1 | Aboveground biomass accumulation and total nitrogen uptake

Aboveground biomass samples were randomly collected from an area of 0.17 m^2 within each experimental unit biweekly from February (prior to each cover crop species breaking dormancy) until chemical termination. These samples were dried in an air-forced oven at 60°C for 7 days and weighed. The dry weights were used to calculate aboveground biomass accumulation and extrapolated to kg ha^{-1} at each sampling time.

Subsamples were then ground using a Thomas-Wiley (Thomas Scientific) laboratory mill to pass through a 1-mm sieve. Total N was analyzed by high-temperature combustion using an Elementar vario Macro (Elementar Analysesysteme GmbH). Total N uptake was calculated using Equation 1.

$$N_{accumulation} = Biomass \times N_{tissue} \quad (1)$$

where $N_{accumulation}$ is the total N in plant tissue from (kg N ha^{-1}), Biomass is the dried aboveground cover crop biomass (kg ha^{-1}), and N_{tissue} is the concentration of N (%) in a subsample of dried cover crop tissue. Biomass and total N uptake values for the trials are listed in Table S1.

2.3.2 | GDD calculation

The average daily temperature was recorded for all locations from the date of cover crop emergence until the last biomass samples were collected and the cover crops were chemically terminated. These temperatures were obtained from the southern regional climate center website (SRCC, 2021), and for any missing data, NASA-POWER (Sparks, 2018) was used. Then, the daily thermal units were calculated using Equation 2 described by Zhou and Wang (2018), where each cover crop species' empirically determined cardinal temperatures were used (Pessotto et al., 2023). The base, optimum, and maximum temperatures for these species were −0.14°C, 25.4°C, and 40.18°C for AWP; 3.37°C, 26.55°C, and 31.5°C for balansa clover; 0.38°C, 18.38°C, and 47.44°C for barley; 3.37°C, 17.84°C, and 44.64°C for black-seeded oat; −4.52°C, 24.84°C, and 36.38°C for cereal rye; 1.25°C, 23.7°C, and 33.16°C for common vetch; 3.92°C, 26.59°C, and 39.1°C for crimson clover; and 2.83°C, 26.27°C, and 34.68°C for hairy vetch, respectively (Pessotto et al., 2023). The accumulated GDD was calculated using Equation (3) for each species at all locations.

$$DTU = \begin{cases} 0 & T_{avg} < T_b \\ T_{avg} - T_b & T_b \le T_{avg} \le T_{opt} \\ \frac{T_{opt} - T_b}{T_{max} - T_{opt}} \left(T_{max} - T_{avg}\right) & T_{opt} < T_{avg} \le T_{max} \\ 0 & T_{avg} > T_{max} \end{cases} \quad (2)$$

$$GDD = \sum DTU \quad (3)$$

2.3.3 | Data analysis

Data were analyzed in R 4.3.3 (R Core Team, 2024) and the relationships between the dependent variables, above ground biomass and total N accumulation, and the independent variable, GDD, were modeled using a nonlinear logistic equation (Equation 4). The motivation for using the logistic model is that this equation provides flexibility to the sigmoidal data model, such as the accumulated biomass and N, and provides interpretable parameters (Archontoulis & Miguez, 2015). To aid model convergence, the aboveground biomass and total N uptake values were normalized to relative values (values range between 0 and 1) by dividing each observation within a location and cover crop species by the highest recorded individual replicate value for that location and cover crop species combination. The mixed effects nonlinear models were built using the "nlraa" and "nlme" packages (Miguez, 2021; Pinheiro et al., 2020) in increasing order of complexity. The final model was selected using the Akaike information criterion (AIC) and for both dependent variables contained cover crop species as a fixed effect on the model parameters *xmid* and *scal*. Since the data had been standardized, the parameter *Asym* did not vary with cover crop species. Furthermore, the model also included random effects of *location* and *year* nested within *location* (Figures 1 and 2). To evaluate the difference in relative biomass and N accumulation between the time of termination and 4 weeks prior to termination, we

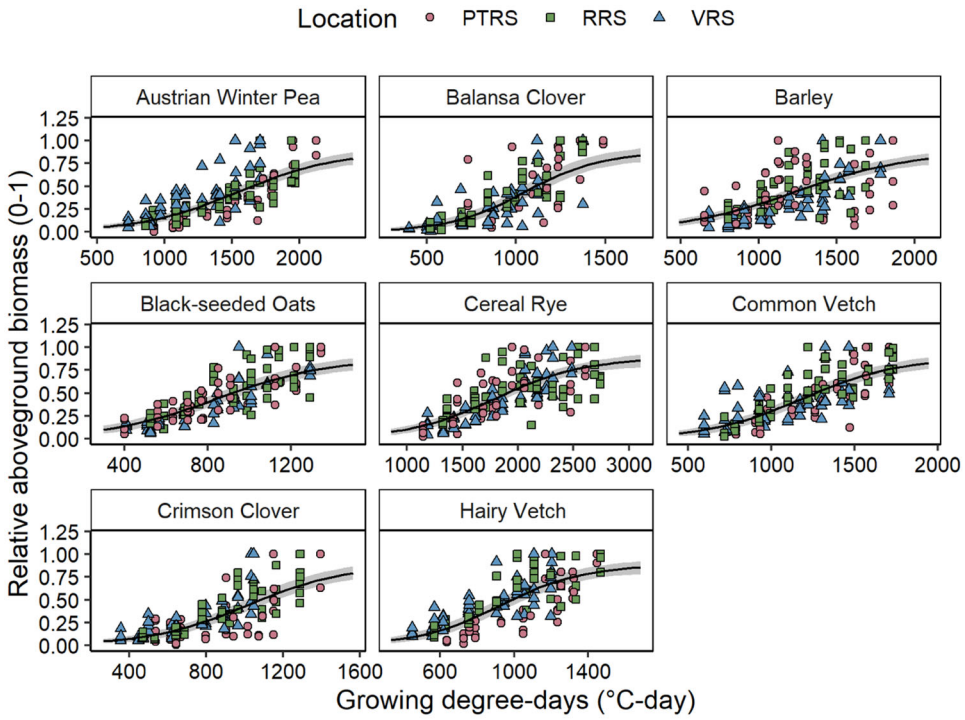


FIGURE 1 Relationship between relative cover crop biomass accumulation and growing degree days for each cover crop species. The black line shows the mean relationship across different locations. The shaded area shows the 95% confidence interval for the mean relationship.

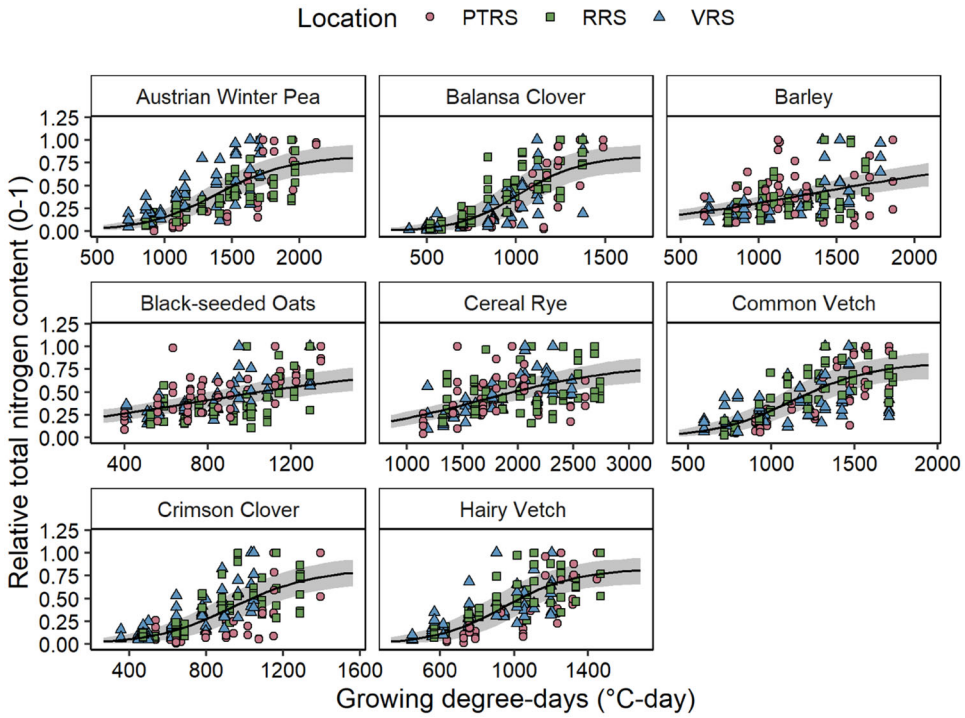


FIGURE 2 Relationship between relative cover crop total N and growing degree days for each cover crop species. The black line shows the mean relationship across different locations. The shaded area shows the 95% confidence interval for the mean relationship.

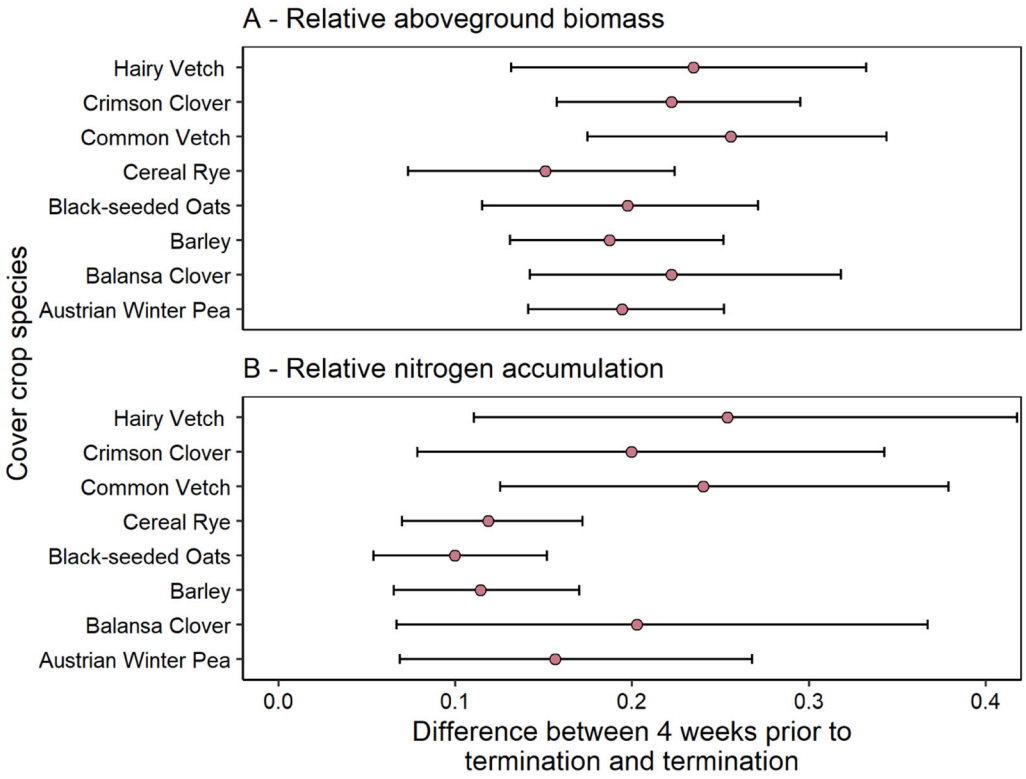


FIGURE 3 Differences in relative aboveground biomass (A) and relative nitrogen accumulation (B) between the date of termination and 4 weeks prior to the date of termination for different cover crop species. The filled circles represent the mean difference and the whiskers represent the 95% confidence interval.

conducted a nonparametric bootstrap with 10,000 iterations. For each iteration, this process consisted of resampling the original data set, with replacement, to generate a simulated data set of the same size. Subsequently, the same model was fit to the resampled data set, and the relative biomass and N accumulation were predicted for the number of GDD accumulated at the two times of interest (Figure 3). We chose to specifically compare the biomass accumulation and total N uptake within the last 4 weeks of each trial to explore the consequences of management decisions related to termination date.

$$f\ (x) = \frac{Asym}{\left(1 + \exp\left[\frac{xmid - x}{scal}\right]\right)} \quad (4)$$

where *Asym* represents the maximum value attained by the function; *xmid* represents the inflection point of the curve, which is the point at which the growth of the curve is at its maximum; and *scal* controls the steepness of the curve.

3 | RESULTS AND DISCUSSION

The dynamics of biomass and N accumulation of eight cover crop species as a function of GDD accumulation were investigated in the present study using a logistic model (Figures 1 and 2; Tables 1 and 2). Across all cover crop species, the point of inflection for the curve (*xmid*), which is also the time at which the function presents a value of 50% of the asymptote, varied greatly (Figures 1 and 2). For biomass production, cereal rye presented the greatest *xmid* value of 1783˚C-day, followed by AWP (1551˚C-day). The lowest *xmid* values were shown by black-seeded oats (843˚C-day) and hairy vetch (924˚C-day) (Table 1). In contrast, the *scal* parameter, although variable, presented a less clear separation between the cover crop species. The greatest values for this parameter were presented by cereal rye (383˚C-day), barley (382˚C-day), and AWP (370˚C-day), indicating that these species required more GDD for biomass and N accumulation than hairy vetch, for instance, which presented a *scal* parameter value of 219˚C-day.

The N accumulation dynamics presented similar patterns to those seen in biomass accumulation (Figures 1 and 2). For instance, cereal rye presented the greatest value to reach 50% of the asymptote value (*xmid*), with a value of 1746˚C-day, followed by barley (1458˚C-day) and AWP (1435˚C-day) (Table 2). In contrast, the cover crop species that required the least number of GDD for growth and development were black-seeded oats (895˚C-day), crimson clover (960˚C-day), and hairy vetch (976˚C-day). The *scal* parameter for N accumulation showed that all cereal crops required more thermal time

TABLE 1 Logistic model parameter estimates and standard error for the relationship between relative aboveground biomass growing degree days for the different cover crop species.

	Model parameter		
Cover crop species	***Asym* (0–1)**	***Xmid* (˚C-day)**	***Scal* (˚C-day)**
Austrian winter pea	0.88 (±0.05)	1551 (±64.3)b	370 (±42.9)bc
Balansa clover		1049 (±45.4)d	213 (±31.1)d
Barley		1242 (±65.8)c	382 (±49.6)ab
Black-seeded oats		843 (±50.1)f	252 (±37.1)cd
Cereal rye		1783 (±70.8)a	383 (±52.2)ab
Common vetch		1185 (±55.9)c	285 (±38.7)bcd
Crimson clover		1020 (±49.0)d	254 (±33.6)cd
Hairy vetch		924 (±48.2)e	219 (±34.5)d

Note: Numbers followed by the same letter presented little evidence ($p > 0.05$) of differing from each other.

TABLE 2 Logistic model parameter estimates and standard error for the relationship between relative nitrogen accumulated and growing degree days for the different cover crop species.

	Model parameter		
Cover crop species	***Asym* (0–1)**	***Xmid* (˚C-day)**	***Scal* (˚C-day)**
Austrian winter pea	0.88 (±0.09)	1435 (±91.8)b	291 (±118.5)b
Balansa clover		1039 (±83.7)d	165 (±99.0)d
Barley		1458 (±136.0)b	769 (±107.0)a
Black-seeded oats		895 (±121.1)d	664 (±37.8)a
Cereal rye		1746 (±127.8)a	674 (±36.6)a
Common vetch		1174 (±89.4)c	256 (±32.4)bc
Crimson clover		960 (±84.4)d	181 (±30.6)cd
Hairy vetch		976 (±85.4)d	196 (±30.0)cd

Note: Numbers followed by the same letter presented little evidence ($p > 0.05$) of differing from each other.

to accumulate N than legume crops. While cereal crops presented *scal* values ranging from 664˚C to 769˚C-day, legume crops presented values as low as 165˚C-day (Table 2).

The accumulated biomass at the termination date differs considerably from the biomass 4 weeks prior to termination (Figure 3). The greatest differences in biomass accumulation between termination dates were seen in common and hairy vetch, with values of 25% and 23%, respectively. In contrast, cereal rye presented the smallest difference when comparing the termination dates in biomass accumulation, with an average of 15%. Similarly, the N uptake presented differences between the two periods of interest, termination and 4 weeks prior to termination (Figure 3). While the cereal crops presented a difference ranging from 9% to 12% in N accumulation, the legume crops presented a difference of upward of 25%. This indicates that the termination date can greatly impact the benefits provided by the cover crop, such as residue and biological N fixation.

Understanding the differences in rate of biomass accumulation and N uptake can aid producers in selecting a cover crop species that aligns with their objectives and production system (Chatterjee et al., 2020). Benefits provided by cover crops include erosion prevention, weed control, N fixation, and ecosystem services (Finney et al., 2016), and different species can align with different goals (Acharya et al., 2016). For example, if the goal for planting a cover crop is to provide residue biomass in a production system in which the cash crop is planted earlier in the spring, our results show that cereal rye would be the least affected cover crop if terminated earlier (Figure 3). Conversely, if the goal is to add biologically fixated N to the production system, our results show that terminating legume cover crops about 4 weeks earlier can decrease the N fixated 15%–25% (Figure 3). Out of the legume species, the one that showed the lowest reduction in N fixation was AWP, with a reduction of 15%. The results of this trial can also be used to educate producers on how delaying cover crop termination by 2–4 weeks can have a profound effect on the aboveground biomass accumulation, which is directly related to many of the positive benefits associated with cover crop implementation (Clark et al., 1997; Finney et al., 2016).

A limitation of our approach is that the GDD method accounts solely for the effect of temperature on crop growth and development, ignoring the effects of precipitation, solar radiation, and biotic stresses (Chatterjee et al., 2020; Wilson et al., 2013). Although our experimental setting represents typical mid-southern production fields, these results are applicable to the Arkansas production system. For instance, northern production systems have reported a 74% reduction in cereal rye biomass accumulation when the cover crop was terminated 4 weeks earlier than the recommended (April 1 versus April 30) (Chatterjee et al., 2020). This reduction in biomass production is greater than our results indicate and can be caused by the difference in temperature, solar radiation, and precipitation between Arkansas and Nebraska. To fill this gap, an improvement upon our methodology would be to use process-based crop models, such as the agricultural production systems simulator (Holzworth et al., 2014), which can model crop growth as a response to environmental conditions and soil processes.

4 | CONCLUSION

The study demonstrated a clear and consistent relationship between GDD and both aboveground biomass production and total N accumulation across eight winter cover crop species in Arkansas. The logistic modeling approach effectively captured the sigmoidal growth patterns, revealing significant variation among species in their thermal time requirements for biomass and N accumulation. Cereal rye required the most GDD to reach 50% of its maximum biomass and N accumulation, while species like black-seeded oats and hairy vetch required fewer GDDs, indicating faster early growth. Importantly, biomass and N accumulation increased substantially during the last 4 weeks before termination, especially for legume species, highlighting the critical impact of termination timing on the benefits provided by cover crops, such as residue contribution and biological N fixation.

These findings underscore the value of using GDD as a predictive tool for managing cover crop growth and optimizing termination dates tailored to specific species and local environmental conditions. By tracking GDD accumulation, producers can make more informed decisions that balance the trade-offs between maximizing biomass and N benefits and fitting within cash crop planting schedules. This approach offers a practical decision support framework that could improve cover crop integration into mid-southern cropping systems, enhancing soil health and nutrient management while potentially reducing synthetic fertilizer inputs. Future research should expand this modeling to cover crop mixtures and evaluate economic outcomes to further refine recommendations for diverse production contexts.

AUTHOR CONTRIBUTIONS

M. V. Pessotto: Data curation; formal analysis; investigation; writing—original draft; writing—review and editing. **T. L. Roberts**: Conceptualization; data curation; funding acquisition; investigation; methodology; project administration; resources; supervision; writing—review and editing. **C. dos Santos**: Formal analysis; methodology; writing—review and editing. **K. A. Hoegenauer**: Investigation; methodology; writing—review and editing. **M. Bertucci**: Investigation; methodology; writing—review and editing. **W. J Ross**: Investigation; methodology; writing—review and editing. **M. Savin**: Investigation; methodology; writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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