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Using Thermal Units to Predict Biomass Accumulation and Total Nitrogen Uptake for Cover Crops in Arkansas

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Abstract

Including cover crops in agricultural production systems is an important management practice. Cover cropping can improve soil health, increase plant-available nitrogen (N), provide surface residue to prevent erosional soil loss, increase water infiltration, and increase weed suppression. Cover crops growth can be predicted using thermal days or growing degree days [GDD] similar to commodity crops such as corn (*Zea mays* L.) or rice (*Oryza sativa*). Growing degree day calculations are a well-known tool to predict crop growth stage or development stage and can be adapted for use in any plant species, including cover crops. Identifying and developing the relationship between cover crop growth and GDD parameters could improve the estimation of biomass production of cover crops. Generally, GDD is the summation of daily thermal units [DTU], and DTU can be calculated using several different methods, but all use species-specific cardinal temperatures. There are very basic equations to determine DTU accumulation that only account for the average daily temperature and the species base temperature. There are also very complex and more realistic equations that account for the other cardinal temperatures (optimum and maximum) to help improve the precision of the DTU and ultimately the GDD estimation. The cardinal temperatures are not well defined in the literature for most cover crop species, leading to a less accurate calculation of GDD for many of these species. To have a more accurate and realistic estimation of plant growth, these cardinal temperatures for each cover crop species are necessary and represent the first objective of this research. The second objective of this study is to estimate cover crop biomass accumulation and total N uptake based on GDD for Arkansas production systems. The first step to achieve this goal was a growth chamber experiment used to determine the cardinal temperatures for eight cover crops species, including Austrian winter pea [AWP] (*Pisum sativum*), balansa clover (*Trifolium michelianum),* crimson clover (*Trifolium*

incarnatum), common vetch (*Vicia sativa*), hairy vetch (*Vicia villosa*), barley (*Hordeum vulgare*), black-seeded oats (*Avena sativa*), and cereal rye (*Secale cereale*). Identifying the cardinal temperatures will allow the use of more complex, plant-growth prediction models. The data collected from the growth chamber experiment was regressed to estimate the cardinal temperatures for each species. The estimated base, optimum, and maximum temperatures for each species were, respectively, -0.1, 25.4, and 40.2 °C for AWP, 3.4, 26.6, and 31.5 °C for balansa clover, 0.4, 18.4, and 47.4 °C for barley, 3.4, 17.8, and 44.6 °C for black-seeded oat, -4.5, 24.8, and 36.4 °C for cereal rye, 1.3, 23.7, and 33.2 °C for common vetch, 3.9, 26.6, and 39.1 °C for crimson clover, and 2.8, 26.3, and 34.7 °C for hairy vetch. Many of these temperatures were not defined previously in the literature and add valuable information regarding the growth of these cover crop species. The successful identification of these cardinal temperatures supported the work in the second objective, which is a field experiment designed to identify a possible relationship between biomass accumulation and total N uptake based on GDD accumulation. The experiment was conducted at the Rohwer Research Station, near Watson, Pine Tree Research Station, near Colt, and Vegetable Research Station, near Kibler, in Arkansas to provide differences in climate and rate of GDD accumulation using the same eight cover crop species. Aboveground biomass production and total N uptake were regressed as a function of GDD for each cover crop treatment. The result was a three-way interaction among cover crop species, GDD, and location for total N and aboveground biomass accumulation. A similar increase in aboveground biomass accumulation and N uptake was observed across all locations. The growth rate was higher closer to termination since warmer temperatures allow each species to accumulate more GDD. This research will assist in developing decision aid tools that producers can use to determine ideal cover crop termination dates and the potential N accumulation in cover crop biomass.

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Introduction

Cover Crop

The inclusion of cover crops in agricultural production systems is an important management practice. Cover crops can increase plant-available nitrogen [N], provide surface residue, and help with pest and weed suppression (Snapp et al., 2005). In addition to that, cover crops can help increase water 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 the 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).

There are three main families that encompass most cover crops: Fabaceae (legumes), Brassicaceae (brassicas), and Poaceae (grasses). Legumes are important for N fixation (Ebelhar et al., 1984), grasses help prevent soil erosion (Blanco-Canqui & Jasa, 2019), and brassicas have been shown to reduce soil compaction (Williams & Weil, 2004) and in some cases can be used as biofumigants (Sarwar et al., 1998). These plant species or cover crops are planted to build soil health and promote increased soil and plant productivity. Cover crops, as other plant species, have their growth limited by the air temperature (Thapa et al.,2018), depending if the average daily temperature is above or below their cardinal temperatures the plant will respond with a different growth rate. The cardinal temperatures are base temperature [T_b], which is the lowest temperature that a plant will grow, optimum temperature [T_{opt}], is the temperature(s) which plant growth rate will be at its peak (Went, 1953), and maximum temperature [T_{max}], is the upper temperature limit where the plant stops growing due to excessive heat. Each plant species has its own unique cardinal temperatures.

The benefits of implementing these cultural practices may not always be economical, but they can almost always improve crop performance and reduce the impact on the environment (Snapp et al., 2005). Cover crops can be grown as a monoculture or a mixture of brassicas, legumes, and grass species. In some cases, mixtures produced a larger volume of biomass than monocultures (Thapa et al., 2018). Cover crop blends tend to complement the canopy and root system and have a lower establishment budget compared to monocultures (Snapp et al., 2005). Either way, the use of cover crops as mixtures or monocultures can bring environmental and production benefits to a wide area of the Arkansas Delta region.

The cover crop season needs to be adjusted to the growing period of the cash crops when grown in a rotational system, as these plants grow when the cash crop is absent, which would typically be during a fallow period. Cover crops can be grouped into species from different families of winter (cool season) and summer (warm season). Winter cover crops need to be established in the late fall to avoid losses due to cold temperatures, due to poor establishment, and the plants can be in dormancy through the coldest temperatures (Ebelhar et al., 1984). Cool-season cover crops are terminated at early to mid-spring, before or near the cash crop planting date. Commonly used cool-season cover crops in Arkansas are barley (*Hordeum vulgare*), cereal rye (*Secale cereale*), oats (*Avena sativa*), wheat (*Triticum aestivum),* turnip (*Brassica rapa*), radishes (*Raphanus sativus*), clovers (*Trifolium*), hairy vetch (*Vicia villosa*), and Austrian winter pea [AWP] (*Pisum arvense)* (Roberts et al., 2018). Summer cover crops are usually planted in mid-summer since these crops need warm soil to germinate (Penn State Extension, 2016). Frequently used warm-season cover crops are buckwheat *(Fagopyrum esculentum),* soybean *(Glycine max),* Japanese millet *(Enchinochloa frumentacea),* cowpea *(Vigna unguiculata),* and sunnhemp *(Crotalaria juncea)* (Creamer & Baldwin, 2019). Following the recommended planting and termination dates for cover crops based on the rotational cash crop is essential to ensure maximum benefits from the cover crop are achieved (Clark et al., 1997).

Legumes

The Fabaceae family, also known as legumes, is characterized by ability to perform biological N fixation [BNF] via the symbiotic relationship between the legumes and rhizobia bacteria. The bacteria from the Rhizobium family "infect" the plant roots and form nodules and transform the N_2 into ammonium which the plant can use (Brill, 1977). In exchange for N, the plant provides energy in the form of carbohydrates and oxygen [O] for the bacteria (Mylona et al., 1995). This symbiotic relationship will typically provide a significant portion of the necessary N for the legume plant to grow and reproduce. The N provided via BNF is accumulated in the plant biomass. After termination, the legume cover crop residue remains on the soil surface, and the N becomes available for the next crop as the residue decomposes (Brill, 1977).

Austrian winter pea

Austrian winter pea [AWP] is a cool-season plant often used as a cover crop due to the potential to accumulate up to 6.2 Mg ha^{-1} of biomass and 208 kg N ha^{-1} (Parr et al., 2011) and its rapid growth rate (Clark et al., 2007). Another benefit of AWP is that it has a low C:N ratio, allowing rapid decomposition and release of nutrients to the soil sooner than other species. In addition to that, it helps with erosion control and weed suppression due to a large amount of biomass produced; to maximize these two benefits, it can be planted in a mixture with a winter cereal (Roberts et al., 2018).

The planting window for AWP in Arkansas is September to November, and the seeding rate can vary from 34 to 67 kg ha^{-1} depending on the planting method, and the use of inoculants is strongly recommended (Roberts, 2021). The optimum germination temperature for this species is from 10 to 25 °C (Brar et al., 1991), and the ideal termination time for this plant is from mid-March to early April (Roberts et al., 2021). The literature does not describe the base and optimum growing temperatures for AWP, but the base temperature is often assumed to be 0 °C. While letting the AWP grow for an extended period would increase N and biomass accumulation, it significantly increases the difficulty of termination.

Clover

Crimson clover (*Trifolium incarnatum*) can be grown as a winter or summer cover crop, and it has been grown in the US as green manure or forage since the 1940s. It has become more important for agriculture over the years due to its inclusion and suitability as a cover crop (Smith, 2010). This clover is an excellent N source fixing up to 163 kg N ha^{-1} (Parr et al., 2011) even with relatively low biomass accumulation. The optimum germination temperature for this clover is from 15 to 20 °C (Brar et al., 1991). Furthermore, the base and optimum temperatures are frequently assumed in the literature since they have not been described by any paper. The assumed base and optimum temperatures for crimson clover are 0 °C and 30 °C, respectively (Butler et al., 2002). The ideal planting time is from September to mid-October, with a seeding rate of 34 kg ha^{-1}. Crimson clover is not tolerant of poorly drained soils but does perform well in acid soils (Philipp et al., 2021).

Even though balansa clover (*Trifolium michelianum)* is less common in the US, it is well known for its forage use in New Zealand, and it can be used as a cover crop. This species can fix up to 124 kg N ha^{-1} and typically have slightly higher aboveground biomass than crimson clover at flowering (Parr et al., 2011). Moreover, the ideal temperature described in the literature for germination is 14 °C (Monks et al., 2009), for vegetative growth is 15 °C, while the base temperature is 2.5 °C (Monks et al., 2010). Since this plant species is not commonly grown in the US, it is assumed that it has the same planting requirements as the crimson clover or any other annual clover.

Vetch

Hairy vetch is well used across the US in monocultures or cover crop mixture with cereal rye. The monoculture of hairy vetch can produce up to 213 kg N ha^{-1} with a significant amount of aboveground biomass (Parr et al., 2011). At the same time, the mixture with cereal rye could be a better combination because it produces more biomass than the monoculture of both species alone (Clark et al., 1997; Parr et al., 2011), and that can represent a higher potential N credit for the next crop.

Common vetch (*Vicia sativa* var. Cahaba) has a rapid growth habit, and it accumulates a large amount of biomass; therefore, it is a good cover crop for weed suppression. In addition to high biomass accumulation, it can fix up to 188 kg N ha^{-1} (Parr et al., 2011).

Both common and hairy vetch are cool-season cover crops and have similar planting requirements; the ideal planting date is from late August to mid-October with a seeding rate of 45 to 78 kg ha^{-1} as a monoculture or 17 to 28 kg ha^{-1} in a mixture. The germination temperatures are 15 to 20 °C for hairy vetch and 10 to 20 °C for common vetch (Brar et al., 1991). Furthermore, the base and optimum temperature are not described in the literature, but the base temperature is often assumed to be 4 °C for hairy vetch (Teasdale et al., 2004) or 0°C for common vetch.

Cereals

Grass cover crops help prevent erosion (Langdale et al., 1991) and reduce nutrient leaching (Brandi-Dohrn et al., 1997). Grass root development reduces soil compaction and helps maintain soil structure (Langdale et al., 1991). In addition, grasses can increase soil infiltration and decrease water loss from the landscape (Ebelhar et al., 1984). One unique aspect of the cereal family of cover crops is that they can produce a large amount of biomass with minimal input cost, which is important for weed suppression and erosion control (Mirsky et al., 2011). Another aspect of cereal crops that differentiates them is that they typically have a large C:N ratio that slows decomposition. Slower decomposition can be beneficial as it helps maintain surface residues for extended periods, but it can reduce or prevent nutrients in the cereal biomass from becoming plant available.

Barley

Barley is an annual winter cereal, and it is mainly consumed as a grain or used to produce alcoholic beverages such as beer. Nevertheless, it is a successful weed suppressor since it can produce up to 9 Mg ha^{-1} of biomass without fertilizer (Patterson et al., 2004) and releases allelopathic chemicals to help aid in weed control/suppression (Jacobs, 2016). As a cover crop, barley provides erosion protection and nutrient recycling and is tolerant to drought stress (Ullrich, 2011).

The planting window for barley is from mid-September to mid-November (Roberts et al., 2018), with a seeding rate ranging from 40 to 67 kg ha^{-1}. The base and optimum temperatures for barley's vegetative growth are 0.02 °C and 20 °C, respectively (Cao & Moss, 1989), and the germination temperature is often assumed to be 20 °C.

Black-seeded oat

Black-seeded oat is a cool-season cereal primarily used as an animal forage. In addition to that, when used as a cover crop, it can accumulate up to 3.5 Mg ha^{-1} of dry matter depending on planting and termination dates (Bauer & Reeves, 1999). In addition to a large amount of biomass, oats release allelopathic chemicals (Weston,1996), making them an excellent cover crop for weed control.

Black-seeded oats are tolerant to poorly drained soils and have a planting window from early September to November (Roberts et al., 2018) with a seeding rate of 50 to 67 kg ha^{-1}. The optimum germination temperature is 20 °C (Tang et al., 2020), and for the vegetative growth, the base and optimum temperatures were determined by Mantai et al. (2017) as 4 °C and 22 °C, respectively.

Cereal rye

Cereal rye is one of the most widely grown cool-season cover crops in the US, and it can perform well in various soil textures and climatic environments (Roberts et al., 2018). In addition to being a cover crop, cereal rye is grown as forage and for human consumption. Like the other cereals, cereal rye has a rapid growth habit that produces a large amount of biomass, accumulating up to 7.1 Mg ha^{-1} of aboveground residue (Clark et al., 1994). Like other cereals, this species also produces allelopathic chemicals (Barnes & Putnam, 1983), and the combination of these chemicals and the biomass makes cereal rye well known for its weed suppression abilities.

Cereal rye is an annual winter crop with a deep root system that helps prevent soil erosion and decrease soil compaction. Cereal rye can be planted as a monoculture cover crop or in a mixture with legumes such as AWP or hairy vetch to maximize benefits, especially nutrient availability for the subsequent cash crop. The ideal planting date for this crop is late summer to mid-November, with a seeding rate of 40 to 67 kg ha^{-1} (Roberts et al., 2018). There is no recent literature determining cereal rye cardinal temperatures, and it is often assumed that the base temperature is 4.4 °C and optimum temperature is 10 °C to 24 °C (Nuttonson, 1958). The optimal germination temperature for cereal rye is often assumed to be 20 to 25 °C.

Growing Degree Days

Growing degree days [GDD] is a parameter used to estimate plant growth based on air temperature and plant cardinal temperatures. GDD usually influence plant growth and biomass production (Thapa et al., 2018). Therefore, any temperature outside the base-maximum temperature range will result in no net growth and can potentially lead to lower biomass or lower yield (Bollero et al., 1996). Thus, a given plant's growth rate and potential biomass production can be determined or modeled as a function of GDD accumulated from planting or emergence.

Typically, GDD is calculated as the summation of daily thermal units [DTU] (Equation 1.1.). The daily thermal unit for a day can be calculated using different methods depending on the goal. The simplest equation (Equation 1.2.) is the average daily temperature [T_{avg}] minus T_b (McMaster & Wilhelm, 1997). In Equation 1.2., when the T_{avg} is below T_b, the DTU is considered zero because it is impossible to have negative growth. In addition to that, when the T_{avg} reaches T_{opt}, it is common to replace the daily average temperature with the optimum temperature in the calculation.

Equation 1.1.

$$GDD = \sum DTU$$

Equation 1.2.

$$DTU = \begin{cases} 0 & T_{avg} < T_b \\ T_{avg} - T_b & T_b < T_{avg} < T_{opt} \\ T_{opt} - T_b & T_{avg} \geq T_{opt} \end{cases}$$

Equation 1.2. uses just two parameters (T_b and T_{opt}), and for this reason, it fails to account for the decrease in growth rate for temperatures above optimum. Thus, a model that considers all cardinal temperatures as parameters as Equation 1.3. described by Yin et al. in 1995 would be more accurate for estimating plant growth. On Equation 1.3., DTUmax is the T_{opt} minus T_b.

Equation 1.3.

$$DTU = DTUmax\left[\left(\frac{T_{max} - T_{avg}}{T_{max} - T_{opt}}\right)\left(\frac{T_{avg} - T_b}{T_{opt} - T_b}\right)^{\frac{Tmax-Topt}{Topt-Tb}}\right]$$

Modeling crop growth using growing degree days is a well-known tool for predicting growth stages in crops, such as corn (*Zea mays*) (Gilmore & Rogers, 1958) and rice (*Oryza sativa*) (Hardke & Norman, 2017) production. It can be used for growth stage prediction and management practice implementation from emergence until maturity of the crop (Miller et al., 2018). Thus, several important cash crops grown already have their cardinal temperatures and heat unit requirements identified. Corn for example the cardinal temperatures are T_b = 10 °C, T_{max} = 47 °C, and T_{opt} = 18 °C to 33 °C (Hollinger & Angel, 2021).

Study Objectives

As a general rule of thumb, it is safe to say that as more GDD accumulate more plant biomass should accumulate. Therefore, a relationship between GDD, biomass and the amount of N accumulated in the aboveground biomass exists, but it seems to differ among species. In addition to that, the GDD is directly related to the species cardinal temperature, and these temperatures are not described in the literature for all plant species that are typically used for cover crops in Arkansas.

The main goal of this study was to determine cover crop biomass and aboveground N accumulation for commonly grown cool-season cover crops in Arkansas as a function of GDD. To achieve this goal, the study was divided into two objectives. The first objective was to determine the cardinal temperatures of AWP, balansa clover, barley, black-seeded oats, cereal rye, common vetch, crimson clover, and hairy vetch. The second objective was to measure biomass accumulation and N uptake of the same eight cover crop species grown in a field environment and determine if a relationship with GDDs exists and if a predictive model could be developed.

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CHAPTER 2

Determining Cardinal Temperatures for Common Cover Crop Species

Abstract

Growing degree days [GDD] is a well-known tool to predict plant growth and can be adapted for use in any plant species, including cover crops. The primary 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 [AWP] (*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 every other day 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 in the literature. Five cardinal temperatures reported here were different than what was previously recorded, base and optimum temperatures as -4.5 and 24.8 °C for cereal rye, and 3.9 and 26.6°C for crimson clover, and the base as 3.4 °C for balansa clover, which were determined within this trial. The successful identification of these cardinal temperatures for common cover crop species will allow the development of plant growth and biomass prediction models to aid in cover crop termination decision support tools.

Keywords: Cardinal temperatures, growing-degree days, cover crop, growth chamber, thermal units.

Introduction

The inclusion of cover crops in agricultural production systems is an important management practice. The USDA's definition of cover crop states cover crops are grasses, legumes, and other 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 N to the soil and making more soil nutrients available, thereby reducing the need to apply fertilizer (USDA-Natural Resources Conservation Service, 2021). Cover crops can increase plant-available nitrogen (N), provide surface residue, and help with pest and weed suppression (Snapp et al., 2005). In addition, cover crops can help increase water 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 are grown in the 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 impact 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)* 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 base temperature [T_b], which is the lowest temperature that 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 where plant growth ceases due to excessive heat. These temperatures are determined empirically and are specific for each plant species. The cardinal temperatures for corn are T_b = 10 °C, T_{max} = 47 °C, and T_{opt} = 18 °C to 33 °C (Hollinger & Angel, 2021).

Once cardinal temperatures have been defined successfully 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 response 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 summation of the daily thermal units [DTU]. Over the years, several different methods were 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.

A simple DTU equation (Equation 2.1.) 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 the plant growth when temperatures are above the optimum. Another way of calculating DTU is a model described by Yin et al. in 1995 that accounts for all cardinal temperatures and, therefore, would be more accurate to estimate plant growth (Equation 2.2.).

Equation 2.4.

$$DTU = \begin{cases} 0 & T_{avg} < T_b \\ T_{avg} - T_b & T_b < T_{avg} < T_{opt} \\ T_{opt} - T_b & T_{avg} \geq T_{opt} \end{cases}$$

Equation 2.2.

$$DTU = DTUmax \left[\left(\frac{T_{max} - T_{avg}}{T_{max} - T_{opt}} \right) \left(\frac{T_{avg} - T_b}{T_{opt} - T_b} \right)^{\frac{Tmax-Topt}{Topt-Tb}} \right]$$

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*) (Hardke & Norman, 2017). To our knowledge there are no 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.

Interest in cover crops continues to increase and with each 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 leads to greater benefits. Conversely, greater amounts of aboveground biomass can result in a greater difficulty in establishing the following cash crop. Therefore, a decision management tool that predicts development or biomass production of cover crops 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 prior to model development. In an effort to fill some of the knowledge gaps and develop cover crop management decision aids, this project aims to determine the cardinal temperatures for some commonly used cover crops species that are currently not available in the published literature.

Materials and Methods

The cover crop species growth rate and GDD experiment was conducted at the University of Arkansas Altheimer Lab and Crop Science Building (Fayetteville, AR) in a 183 x 81 x 142 cm PGR15 CONVIRON growth chamber (CONVIRON, Manitoba, Canada). 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*), 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 USA. Each cover crop species was grown in seven different temperature regimes, starting at 4 °C and increased by 5 °C with the highest overall temperature being 34 °C, which was the upper limit of the growth chamber’s temperature capabilities.

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 6 cells, and each cell was 4 cm square by 6 cm deep) with PRO-MIX M mycorrhizae potting mix (Premier Tech Horticulture, Pennsylvania, USA), 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 ten 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 x 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 two times, between the 22nd of July and the 9th of December 2020 and between the 16th of March and the 17th of September 2021.

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-hr daylight/nighttime regime for 21 days. The pots were watered as needed (at least every two 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, Massachusetts, United States). 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) (Gramig & Stoltenberg, 2007; Alm et al., 1988), even when the plant developed secondary branches or tillers. After 21 days of growth within a predetermined temperature setting, the trials were terminated.

Data analyses

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 day^{-1}. Relative 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 2.3.) in which 'T_b' is the base temperature, 'T_{opt}' is the optimum temperature for crop development, 'T_{max}' is 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 optimum and ceiling temperatures; and ceases when the air temperature is above ceiling temperature. The model was fit using the maximum log-likelihood method in a nonlinear mixed model (NLMM) in which the response variable was the relative leaf appearance rate or relative growth; the random variable was the mean air temperature, cover crop species was considered a fixed effect in the model, and run was considered a random effect.

Equation 2.3.

$$f(x) = \begin{cases} 0, & T_{avg} \leq T_b \\ \dfrac{T_{avg} - T_b}{T_{opt} - T_b}, & T_b \leq T_{avg} \leq T_{opt} \\ 1 - \dfrac{T_{avg} - T_{opt}}{T_{max} - T_{opt}}, & T_{opt} \leq T_{avg} \leq T_{max} \\ 0, & T_{avg} \geq T_{max} \end{cases}$$

Results and Discussion

For the 21-day duration of the trial, 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 2.1. 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 trial (Table 2.1.). When producing crops for grain, forages or even using them as cover crops the benefit of 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 USA 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 within this trial, five resulted in T_{max} estimates that were beyond the upper temperature limits of the growth chamber used in the trial. 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 2.1). 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 2.1. 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 ~3-7 °C. Based on the information presented in Figure 2.1., it is apparent that the resultant decrease in plant growth rate for temperatures above the optimum occur 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} are of more importance than correctly identifying the T_{max} when modeling cover crop species growth and development.

During this trial, all cardinal temperatures were determined for each cover crop species and their associated confidence intervals (Table 2.1.). 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 trial were compared to the cardinal temperatures that could be found in the literature and are presented in Table 2.1. 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 preparing for this trial. However, there is 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 0, 28 and 38 ºC for the T_b, T_{opt} and T_{max}, respectively (Olivier & Annandale, 1998). The temperatures determined in this trial were T_b -0.14 ºC ± 1.51, T_{opt} 25.4 ºC ± 2.29, and T_{max} 40.18 ºC ± 4.76. 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 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 indicate 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 ºC (Monks et al., 2010), respectively. The lack of data for this clover species suggests that there is little data available to support the reported cardinal temperatures. During this trial it was determined that balansa clover exhibits a T_b of 3.37 ºC ± 1.07, a T_{opt} of 26.55 ºC ± 2.54, and a T_{max} of 31.5 ºC ± 2.47 as its cardinal temperatures. Although the T_b reported in the literature is within the confidence interval reported for balansa clover determined in this trial, the T_{opt} is more than 10 ºC different and there is no T_{max} reported. The results of our trial indicated that the T_{opt} for balansa clover was 26.55 ºC, 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 ºC (Caos & Moss, 1989), respectively. The cardinal temperatures determined for barley in this trial were 0.38 ºC ± 1.35 as T_b, 18.38 ºC ± 1.83 as T_{opt}, and 47.44 ºC ± 7.7 as T_{max}. Even though the reported values from the literature and the cardinal temperatures determined here are not that 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 help determine cover crop termination dates, but are even more important for cultural management practices in a barley grain crop. In this case, the T_b values reported in the literature would be overestimating the plant growth, and the T_{opt} values reported in the literature would be underestimating plant growth when compared to the numbers reported here.

Black-seeded oat's T_b and T_{opt} listed in the literature was 4 and 22º C (Mantai et al., 2017), respectively. Our results suggested that the cardinal temperatures for this species were

3.27 ºC ± 0.8 for base, 17.84 ºC ± 1.5 for optimum, and 44.64 ºC ± 6.29 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 to 24 ºC (Nuttoson, 1958), respectively. Unlike the other crops investigated in this trial, 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. Following the trial and data analysis steps, it was determined that the cardinal temperatures for cereal rye were -4.52 ºC ± 3.23 as base, 24.84 ºC ± 3.41 as optimum, and 36.38 ºC ± 3.71 as the maximum. There is quite a large difference in the T_b and T_{opt} range presented in the literature and what was determined within the scope of this trial. The reported T_b in the literature was ~9 ºC higher than what was determined here. The T_{opt} values reported in the literature ranged from 10 to 24 ºC and were lower than the T_{opt} reported here of 24.84 ºC. 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 ½ of what we determined. Conversely, the T_b determined in this trial is significantly lower from the one presented in the literature, which indicates that the 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 trial, the use of values reported in the literature would grossly 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 ºC (Teasdale et al., 2004). The data provided from this project indicate that hairy vetch has cardinal temperatures of 2.83 º C ± 1.07 as the base, 26.27 º C ± 1.72 as the optimum, and 34.68 º C ± 1.59 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 trial, 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 ºC ±1.18 as the base, 23.7 ºC ±1.6 as the optimum, and 33.16 º C ±3.15 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 trial is even less than that reported for hairy vetch. Also, the common vetch T_b value determined in this study is less than ½ 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 ºC (Butler et al., 2002), respectively. 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 trial were 3.92 ºC ±0.98 as the base, 26.59 ºC ±1.97 as the optimum, and 39.1 ºC ±4.03 as the maximum. The T_b reported for crimson clover in the literature is one of the few that were actually lower than what was determined in the current study. Using a T_b of 0 vs 3.9 ºC would lead to two errors in the DTU and GDD calculation. Firstly, using a T_b of 0 ºC 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. Secondly, this would result in a gross 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 trial would underestimate crimson clover growth and development.

Conclusion

The results presented here identify and provide revised cardinal temperatures for eight commonly grown cover crop species in the Mid-southern USA. The T_b's 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 trial were for cereal rye where our value was almost 9 ºC 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 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 vs when no growth is occurring at all. Following T_b, the T_{opt} is probably the second most influential cardinal temperature. The present study identified T_{opt} for three of the eight cover crops 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 trial as no previous reports for any of the cover crop species could be found in the literature. Although the T_{max} may not be as critical for modeling growth of cover crop species as T_b or T_{opt} it may be more important in the Mid-south or Southern USA 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 trial for all the cover crop species.

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 growing degree days yields better and more accurate results on the estimation of growth and biomass production (Yin et al., 1995). The refinement or identification of 18 of the 24 possible cardinal temperatures investigated in this trial generates a significant step forward in the ability to model cover crop species growth and development. Prior to this work, 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. 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.

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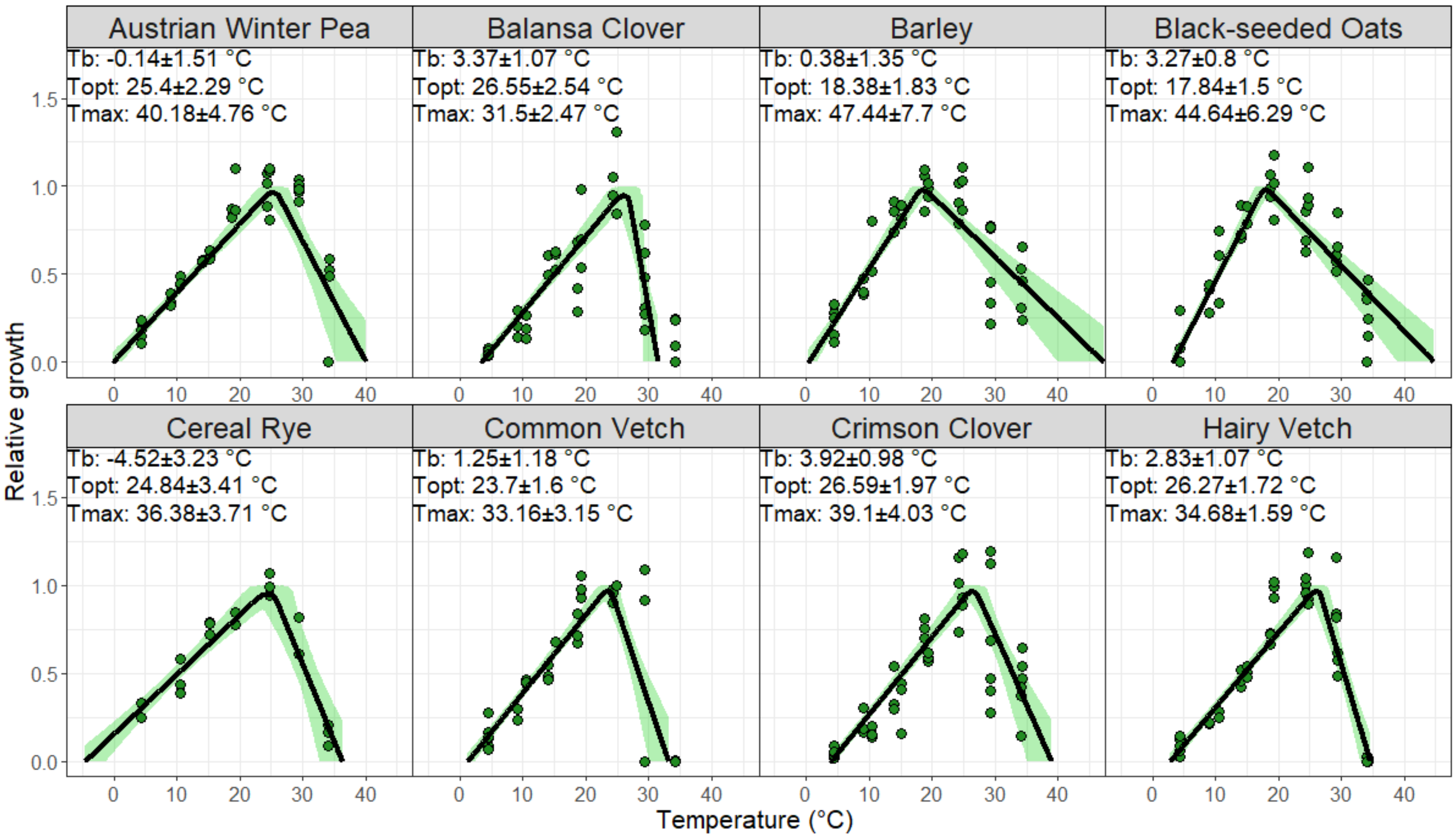
Tables and Figures

Table 2.1. The cardinal temperatures determined by this project compared to 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	*	-0.14	*	25.40	*	40.18
Balansa Clover	2.5 [1]	3.37	15 [2]	26.55	*	31.50
Barley	0.02 [3]	0.38	20 [3]	18.38	*	47.44
Black-seeded Oat	4 [4]	3.27	22 [4]	17.84	*	44.64
Cereal Rye	4.4 [5]	-4.52	10 - 24 [5]	24.84	*	36.38
Common Vetch	*	1.25	*	23.70	*	33.16
Crimson Clover	0 [6]	3.92	30 [6]	26.59	*	39.10
Hairy Vetch	4 [7]	2.83	*	26.27	*	34.68

[1] Monks et al., 2009; [2] Monks et al., 2010; [3] Cao & Moss, 1989; [4] Mantai et al., 2017; [5] Nuttonson, 1958; [6] Butler et al., 2002; [7] Teasdale et al., 2004; * no data reported.

Figure 2.1. Relative growth by temperature in degrees 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 the three cardinal temperatures with the confidence interval for each cover crop species. T_b = base temperature, T_{opt} = optimum temperature and T_{max} = maximum temperature.



CHAPTER 3

Use of Growing Degree Days to Predict Aboveground Biomass and Total Nitrogen Accumulation of Winter Cover Crops

Abstract

The inclusion of cover crops in agricultural production systems is an important management practice that can bring several benefits to the cash crop as well as the environment. Plant species, weather conditions, and cover crop termination date influence total biomass production and N fixation potential. The present 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 two weeks. Aboveground biomass accumulation and N content were regressed as a function of GDD for each cover crop treatment. At the Rohwer site, AWP accumulated an average of 3643 kg ha^{-1} of biomass and 107 kg N ha^{-1} at termination, whereas thirty days before termination, the average was 1868 kg ha^{-1} of biomass and 69 kg N ha^{-1}. A similar increase in aboveground biomass accumulation and N uptake over the last ~4 weeks of the season was measured for all plant species. The growth rate and biomass accumulation increased dramatically closer to termination due to warmer temperatures, which allowed for rapid GDD accumulation.

Keywords: Cover crop, biomass, N uptake, GDD

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 2017 it had increased to 6.2 million ha (Wallander et al., 2021). 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. 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 legumes, grasses, and other broadleaves 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, providing wildlife habitat. Cover crop plant species can be incredibly beneficial to the production system; they can almost always improve crop performance and reduce the potential negative impact of management on the environment (Snapp et al., 2005), although their primary purpose is not economical.

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; Langdale et al., 1991), helps maintain soil structure, and reduces soil compaction (Williams & Weil, 2004; Langdale, et al., 1991). In addition, grasses or cereal crops can increase soil infiltration and decrease water loss from the landscape (Ebelhar et al., 1984). 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 cover crop 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. Some species have the potential to accumulate high amounts of N in their biomass, 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 season 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, and the plant species used as a cover crop needs to be chosen following the rotation management. Following the recommended planting and termination dates for cover crops based on the rotational cash crop is essential to ensure maximum benefits from the cover crop are achieved (Clark et al., 1997). 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). These cool season cover crops are terminated in early 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 day [GDD] can be used as a parameter to estimate plant development. 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. Growing degree day 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 successful prediction of crop growth stage can also allow producers to implement other cultural management practices such as fertilizer or pesticide applications and scouting for pests (Miller et al., 2018). The accumulation of GDD influences plant growth and biomass accumulation (Thapa et al., 2018). 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 investigate the relationship between plant growth and GDD to understand the relative growth pattern of commonly grown cover crops in the Mid-south USA. 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.

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). Soils samples were taken at 0-10 cm depth at each location, these samples were collected across the field prior 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). Fertilization is not currently recommended for cover crops by the University of Arkansas. Alternatively, based on the University of Arkansas recommendation for winter wheat (*Triticum aesteivum* L.), the nutrient levels were considered above optimum for K, and optimum for P at the VRS, above optimum for P and medium for K at the RRS, and low for P and K at the PTRS.

The experiments were divided into two trials to improve the management according to the cover crop species for all three locations. The first trial was composed of three treatments that included commonly grown winter cereals where each treatment is a different cover crop species and included barley, black-seeded oats (*Avena sativa*), and cereal rye (*Secale cereale*). The second trial was composed of winter or cool-season legumes and included Austrian winter pea, balansa clover (*Trifolium michelianum),* common vetch (*Vicia sativa* var. Cahaba), crimson clover (*Trifolium incarnatum*), and hairy vetch. All trials were planted on the 24th of October 2019 and 5th of November 2020 and terminated on the 1st of May 2020 and the 31st of May 2021.

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 plot establishment, soybean was harvested, and the area was tilled to a 10-cm depth at each location. Winter cereal cover crop treatments and the following soybean from that initiation tillage were managed using no-tillage production practices for the duration of the experiment.

Plots were flat-planted with a plot size of 2.3-m wide by 43-m long with 19-cm row spacing, and the seeding rate for all winter cereals regardless of species was 45 kg ha^{-1} (Roberts, 2021). Cover crop treatments were arranged in a randomized complete block design, with four replications, with each cover crop species representing a treatment. Each cover crop treatment was chemically terminated on the same day using an herbicide mixture of paraquat at 1 kg ai ha^{-1} and propanil at 4.48 kg ai ha^{-1}.

Winter Legume Cover Crop Trial

Each year, the legume cover crop trial was established in a fallow field with similar site and soil characteristics to avoid nutrient (primarily N) build-up across consecutive years. Prior to plot establishment, the area was tilled to a 0-10 cm depth at each location. Plots were flat-planted with a plot size of 2.3-m wide by 43-m long with 19-cm row spacing, and the seeding rate was 67 kg ha^{-1} for large seed species such as AWP and 34 kg ha^{-1} for the small seed species such as crimson clover, balansa clover, common vetch, and hairy vetch (Roberts, 2021). Each winter legume cover crop species seed was inoculated with the proper species of rhizobium prior to planting to ensure that nodulation would occur. The treatments were monocultures of the five legume cover crop species (AWP, balansa clover, common vetch, crimson clover, and hairy vetch) arranged in a randomized complete block design with four replications. Each cover crop treatment was chemically terminated on the same day using an herbicide mixture of paraquat at 1 kg ai ha^{-1} and propanil at 4.48 kg ai ha^{-1}.

Data collection

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 at each sample time using the following Equation 3.1.

Equation 3.5.

$$\text{Biomass } (\text{kg ha}^{-1}) = \frac{\text{Oven Dry Weight}}{\text{Sample Area}}$$

Sub-samples were then ground using a Thomas-Wiley (Thomas Scientific, Swedesboro, NJ) laboratory mill to pass through a 1-mm sieve. Total N was analyzed by hist-temperature combustion using an Elementar vario Macro (Elementar Analysesysteme GmbH, Hanau, Germany). Total N uptake was calculated using Equation 3.2. below.

Equation 3.2.

$$\text{Total Nitrogen Uptake (kg N ha}^{-1}\text{)} = \text{Aboveground biomass (kg ha}^{-1}\text{)} \times \text{N concentration in sample (\%)}$$

Growing Degree Day Calculation

The average daily temperature was recorded for all locations from 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 (Texas A&M, 2021), and for any missing data, NASA-POWER (Sparks, 2018) was used. Then, the daily thermal units [DTU] were calculated using Equation 3.3., described by Zhou & Wang in 2018, where each cover crop species' empirically determined cardinal temperatures were used (Chapter 2). The base, optimum and maximum temperatures for these species were -0.14, 25.4, and 40.18 °C for AWP, 3.37, 26.55, and 31.5 °C for balansa clover, 0.38, 18.38, and 47.44 °C for barley, 3.37, 17.84, and 44.64 °C for black-seeded oat, -4.52, 24.84, and 36.38 °C for cereal rye, 1.25, 23.7, and 33.16 °C for common vetch, 3.92, 26.59, and 39.1 °C for crimson clover, and 2.83, 26.27, and 34.68 °C for hairy vetch, respectively. The accumulated GDD were calculated using Equation 3.4. for each species at all locations.

Equation 3.6.

$$DTU = \begin{cases} 0 & T_{avg} < T_b \\ T_{avg} - T_b & T_b \leq T_{avg} \leq T_{opt} \\ \dfrac{T_{opt} - T_b}{T_{max} - T_{opt}} (T_{max} - T_{avg}) & T_{opt} < T_{avg} \leq T_{max} \\ 0 & T_{avg} > T_{max} \end{cases}$$

Equation 3.4.

$$GDD = \sum DTU$$

Data analysis

All the statistical analysis was conducted in R 4.1.1. (R Core Team, 2021). The increase in aboveground biomass accumulation and total N accumulation data collected from the termination date and four weeks prior to termination were compared for each cover crop species in all locations, using a one-way analysis of variance (ANOVA) in which location, plant species, and time were fixed effects, and year and replication were random effects at a significance level of 0.05.

Prior to further statistical analysis the aboveground biomass and total N uptake values were normalized to relative values 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. Therefore, the relative aboveground biomass and total N uptake values range between 0-1.0. The relationship between relative biomass production and GDD was investigated by fitting a 2nd order polynomial model in which relative biomass was the response variable, GDD was the random variable, and cover crop species and location were fixed effects. In addition to that, the significance of the fixed effects was evaluated using a two-way ANOVA in which location and plant species were fixed, and GDD and replications were random effect at a significance level of 0.05.

The relationship between relative total N uptake and GDD was also investigated by fitting a 2nd order polynomial model in which total N uptake was the response variable, GDD was the random variable, and cover crop species and location were fixed effects. Then, the significance of the fixed effects was analyzed using a two-way ANOVA in which GDD and replications were random, and cover crop species and location were fixed effects, at a significance level of 0.05.

Results and Discussion

Data were analyzed by location and cover crop species, since the interaction between species and location was significant. The species-specific data from each of the three locations are presented on the same graph to allow for visual comparison. The ANOVA test indicated a significant treatment or cover crop species effect for all variables. Cover crop biomass accumulation increased with more accumulated GDD, and this response was consistent across all cover crop species at each location. All the relationships exhibited an exponential growth model as each cover crop species was terminated prior to the peak of either the aboveground biomass accumulation or the total N uptake. The authors chose to specifically compare the biomass accumulation and total N uptake within the last four weeks of each trial when the plant growth rates were the highest. When comparing the biomass at the termination date and four weeks prior to termination, it has a considerable increase in most cases, as shown in Table 3.1. This same trend can also be seen for total N uptake (Table 3.1) in most species except for crimson clover and barley at PTRS and barley at the RRS suggesting that termination date has a profound impact on the biomass production, total N accumulation and the potential benefits of a cover crop to a production system.

Aboveground Biomass Accumulation

The amount of accumulated biomass varies among plant species and location. Overall, PTRS resulted in a lower final biomass amount for all cover crops due to the lower fertility of the area and a higher weed pressure compared to the other locations. The differences in biomass accumulation between VRS and RRS are due mainly to the RRS being the farthest south and warmer location, and because of that, the plants were able to accumulate more GDD and therefore accumulate a higher amount of biomass overall (Thapa et al., 2018) in a similar number of calendar days.

From four weeks prior to termination to the termination date, most cover crops had a substantial increase in their biomass amount at all three locations (Table 3.1). In some cases, such as VRS, all plant species, except cereal rye and hairy vetch, increased 100% of their biomass in the last four weeks; and these two species had at least an increase of at least 50% in the same period. On the other hand, at the RRS cereal rye and hairy vetch exhibited an increase of 10-20% of their biomass during this same four-week time period. In the case of hairy vetch, the cover crop had already generated a substantial amount of biomass prior to the last two sampling periods. Additionally, barley, common vetch, and AWP increased by at least 50%, and black-seeded oat, crimson clover, and balansa clover increased 100% in their biomass in the same four-week period. Even though PTRS had a lower amount of biomass accumulation when compared to the other locations, there was a substantial increase in the residue accumulation in the last four weeks prior to termination. Crimson clover and AWP resulted in an increase of aboveground biomass greater than 100%. While, cereal rye, balansa clover, common vetch, hairy vetch, and black-seeded oat had an increase of at least 50% in their biomass within the last four weeks. Barley exhibited the lowest overall biomass accumulation increase of 40% during the same period.

Figure 3.1. shows the relative biomass by the GDD for all locations by each cover crop species. The graphical representation of the data allows the reader to visualize the trends in relative biomass accumulation exhibited by each species across the three locations included in

this trial. Most plant species exhibit the same growth trend (exponential growth) although to varying magnitudes. However, the general trend for all cover crop species at all locations was for the highest aboveground biomass to occur when the most GDD were accumulated. The exception to this trend was barley at PTRS and cereal rye at RRS. While these two species have a different growth pattern than the other locations, they still follow a trend of increasing biomass as more GDD's accumulate. These data indicate that cover crop biomass accumulation can vary greatly across species within a location. Understanding the differences in rate of biomass accumulation under similar growing conditions can aid producers in selecting a cover crop species that can produce substantial amounts of biomass prior to termination. Producers who wish to plant their cash crops earlier in the spring may choose to plant species such as common vetch, hairy vetch or barley as these species tend to increase biomass more rapidly in the spring. If the producer has more flexibility in their planting date, then they have more cover crop species options from which to choose. The results of this trial can also be used to educate producers on how delaying cover crop termination by two to four 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).

Total Nitrogen Uptake

Similar to biomass accumulation, the amount of N accumulated in the aboveground biomass was affected by the number of GDD accumulated, the cover crop plant species and location. Since the amount of N has a proportional relationship with the amount of biomass, the results from PTRS are affected by the low fertility and weed pressure. Implementing common producer practices for cover crop management was important and therefore the locations were not fertilized and winter annual weeds were not managed to best replicate the conditions experienced in most production fields. In addition, a general trend for an overall higher rate of N uptake at the RRS is mainly due to it being the southernmost location and the weather (warmer seasonal temperatures). Another essential factor in the amount of N accumulated in the residue is the botanical family of the cover crops species, as the legumes species can form a symbiotic relationship with rhizobium and facilitate biological N fixation [BFN] as well as accumulate plant-available N from the soil. The winter cereal cover crop species only accumulate the plant-available N from the soil and their aboveground N accumulation will be impacted by residual soil inorganic-N.

From four weeks prior to the termination date to chemical termination, the cereal species had a reasonable increase in the aboveground total N content of their biomass, as shown in Table 3.1. At the termination date, the highest N content was for black-seeded oat at the RRS with 52.3 kg N ha^{-1}, and the lowest was barley at PTRS with 12.9 kg N ha^{-1}. In the same four-week period, the amount of total N uptake for the cereal rye increased by 20% at all locations. The total N accumulation of the winter cereal cover crop species is merely a function of overall plant growth and residual N in the soil. The black-seeded oat is the cereal species that resulted in the greatest increase in total N uptake over the four weeks prior to termination, increasing 300% at the RRS, 95% at VRS, and 65% at PTRS. The results for black-seeded oat are interesting because in the same period that total N uptake increased 3x the biomass merely doubled, indicating that the total N accumulation occurred at a faster rate than biomass accumulation during the same period. On the other hand, barley had an increase of 100% in the total N uptake at VRS. However, the amount of N accumulated by barley at PTRS and the RRS was the same at the beginning and end of the four-week period, even though it had an increase in biomass during this same period.

For the legumes, the amount of total N accumulated in the aboveground biomass was substantially higher, with a few exceptions. In Table 3.1, it is possible to compare the increase of N from four weeks prior to termination date to the amount accumulated at termination. The only case of decrease of N content was crimson clover at PTRS, which had a reduction of 3.7 kg N ha^{-1}, whereas crimson clover at the other two locations had an increase in total N uptake of at least 40%. The species that accumulated the highest amount of N was the hairy vetch across all locations and both periods of comparison, which had amounts ranging from 105.5 to 150 kg N ha^{-1} on the termination date. Common vetch also performed well with an almost 100% increase at the VRS and PTRS and exhibited a final total N uptake amount of ~69 kg N ha^{-1} at the RRS. Vetches are known for their high N accumulation potential, which was also observed in this trial (Bouquet & Dabney, 1991).

Balansa clover resulted in a lower amount of total N accumulated due to the species' lower potential for biomass accumulation. The lower biomass accumulation and total N uptake for balansa clover may indicate that the species is not well suited for the soils or growing conditions found in the Mid-southern USA. At RRS and PTRS, the total N uptake of balansa clover increased at least 70%, and at VRS this increase was over 200%. Although the relative increases in total N uptake were significant, the final total N uptake values for balansa clover were the lowest of all the legume species included in this trial. Previous research has suggested that balansa clover is not that competitive and typically only performs well when grown in a monoculture (Ross et al., 2001). The weed competition at some of the locations may have been substantial enough to limit the ability of balansa clover to grow effectively.

Austrian winter pea is another species with a high potential for aboveground biomass production and N fixation and average values range from 100-165 kg N ha^{-1} (Clark, 2007). The results for our trial were slightly lower with a range of 76.1 kg N ha^{-1} at VRS to a high of 106.7 kg N ha^{-1} at the RRS. In this experiment during the final four weeks of the trial, AWP exhibited an increase in total N uptake of 50% at the RRS, 100% at the VRS, and 200% at the PTRS. The lower total N accumulation values reported here compared to previous literature may be due to the selected termination date and may have continued to increase if allowed to grow longer in the spring.

As shown in Figure 3.2., the increase in the amount of total N uptake in the aboveground biomass over time is shown as the relative total N accumulation by GDD. These results indicate that all the legumes follow a similar pattern of total N uptake as GDD are accumulated, even though each location has a different magnitude of accumulation due to weather and environmental conditions. A similar trend is seen with the cereal species that have the same growth trend, except for barley at PTRS and cereal rye at VRS, in which they accumulated more N on their biomass when more GDDs are accumulated by the plant. The results of this trial can indicate that when the plant growth is between dormancy and flowering/heading, delaying cover crop termination by two to four weeks can lead to a significant increase in the total N accumulated in the aboveground biomass, especially for legume cover crop species. This information may be of particular interest to producers that intend to plant a cereal or non-legume cash crop as the termination date of a leguminous cover crop species has a profound impact on the potential N credits accumulated. With current fertilizer prices at near record levels waiting a mere two to four weeks and doubling the BNF and N credits could greatly increase the profitability of a production system by reducing the rate or reliance on commercial fertilizer.

Conclusion

The present study investigated and confirmed the relationship between biomass production and GDDs and the relationship between total N accumulation and GDDs. The establishment of this relationship allows the development of decision support tools to aid producers in managing cover crops effectively. Our results indicate that the number of growing days or number of calendar days may be important, but tracking the GDD accumulation can be a better and more accurate predictor of cover crop plant growth, aboveground biomass accumulation and total N uptake. Cool season cover crops, which are the species studied here, are dormant below their base temperature and their growth tends to increase linearly until the optimum temperature occurs. Therefore, cover crops tend to grow at a higher rate coming out of winter and into the spring season, but their growth rate may actually slow if temperatures continue to increase in southern latitudes. This increase in growth rate is due to the daily temperatures getting close to the optimum temperatures of each species, meaning that the plants are growing closer to 100% of their potential. Therefore, a larger aboveground biomass accumulation will occur when the daily temperatures are closer to the cover crops optimal temperature.

Growing degree days are already a well-known parameter to predict plant growth and development (growth stages) in row crops. Using this parameter to predict growth or biomass accumulation of cover crops would greatly improve production system management. Predicting the amount of potential biomass residue or amount of N in this residue would be a useful prediction tool to help producers decide when to terminate the cover crops according to their needs, the environment, and the following cash crop. A tool that would predict biomass accumulation using GDD as the primary variable for different cover crop species would bring a huge advancement to the production systems that we have now by allowing producers to hone their cover crop management such as termination date to the day.

The information provided by this study will aid farmers and researchers on deciding the best cover crop species based on their productions system and the length of cover crop growing season that they have available prior to cash crop planting. Implementing cover crops into crop rotations is a good management practice when it is well organized and gives the cover crops enough time to accumulate biomass or N and bring potential benefits to the production area and environment. Knowing if one-week vs ten days of added growing time could significantly increase the biomass or the N accumulated in the residue is information that can affect the management greatly. Our results provide the proof of concept that GDD can be used to predict biomass accumulation and total N uptake of cover crop species. Therefore, a decision management tool that incorporates cover crop species and site-specific weather data can be developed to show current biomass based on previous weather data and forecast biomass accumulation based on future weather forecasts similar to crop management models widely implemented for crops such as corn and rice.

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Tables and figures

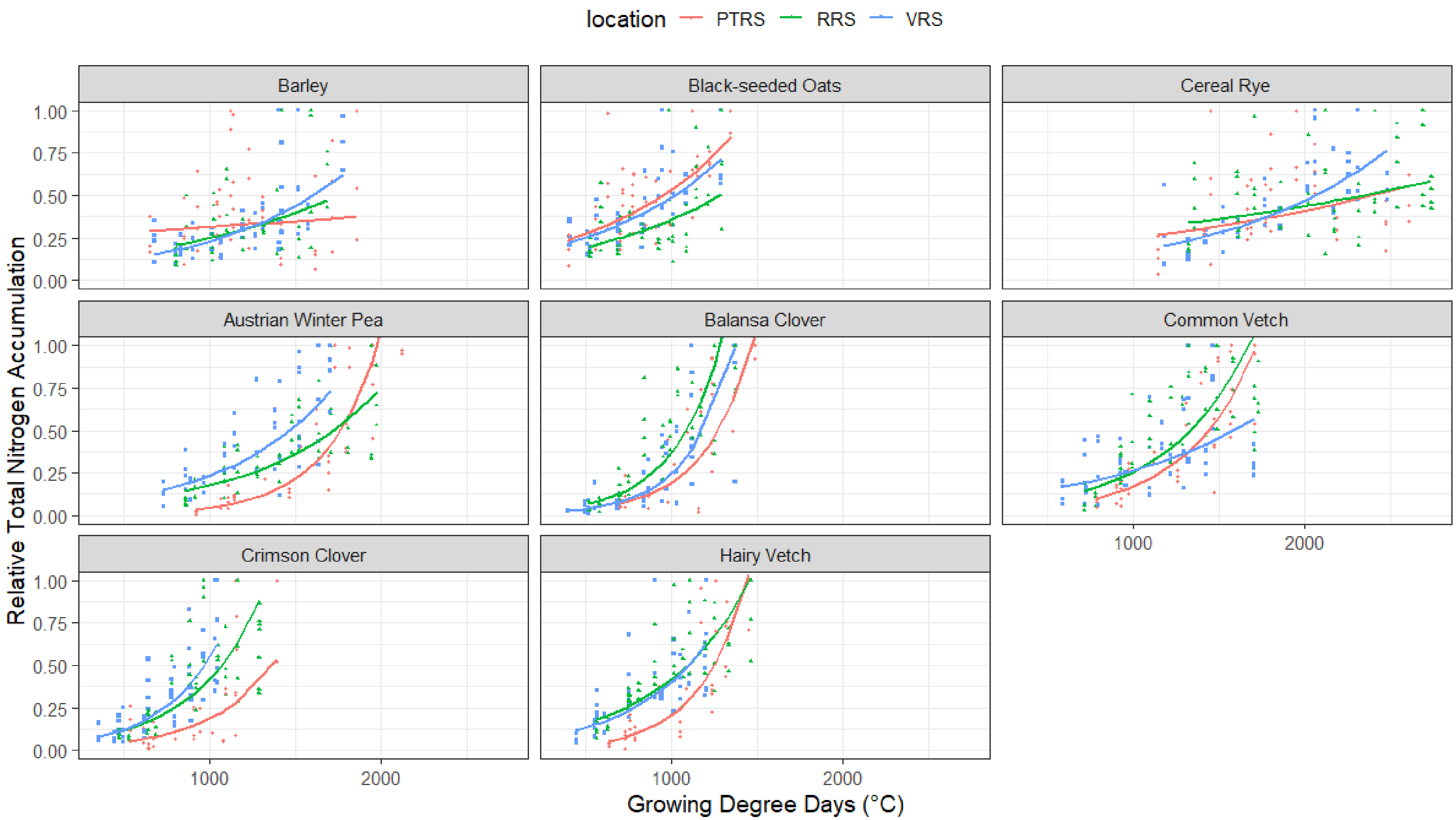
Table 3.2. Mean aboveground biomass and total N accumulation on the day of cover crop termination and four weeks prior to termination for Austrian winter pea, balansa clover, common vetch, crimson clover, hairy vetch barley, black-seeded oats, and cereal rye at the Vegetable Research Station (VRS), the Pine Tree Research Station (PTRS) and the Rohwer Research Station (RRS).

Cover Crop	Location	4 weeks before Termination		Termination	
		Biomass	Total N	Biomass	Total N
		kg ha^{-1}	kg N ha^{-1}	kg ha^{-1}	kg N ha^{-1}
Austrian Winter Pea	VRS	1411.4*	33.9*	3326.6*	76.1*
	PTRS	785.0*	27.0*	2674.1*	88.8*
	RRS	1868.3*	68.9*	3642.7*	106.7*
Balansa Clover	VRS	637.2*	14.7*	1894.8*	48.7*
	PTRS	383.3	13.2	704.7	27.8
	RRS	1041.1*	35.4*	2459.1*	60.9*
Common Vetch	VRS	1278.1*	33.0*	2726.9*	67.4*
	PTRS	977.8*	33.4*	1938.6*	63.6*
	RRS	1811.5	61.3	2474.5	68.8
Crimson Clover	VRS	1639.7	39.7	3418.9	61
	PTRS	270.4	21.2	642.1	17.5
	RRS	1699.6	50.0	3724.4	71.6
Hairy Vetch	VRS	2023.4*	64.7*	3304.7*	105.5*
	PTRS	2160.3*	66.6*	3479.8*	140.9*
	RRS	3425.7*	119.5*	3931.7*	150.2*
Barley	VRS	1268.2	16.7	2934.3	35.2
	PTRS	790.9	12.8	1118.1	12.9
	RRS	1718.9	21.6	2594.5	21.5
Black-seeded Oat	VRS	1521	19.6	3699.2	38.9
	PTRS	963.0	13.6	1782.8	22.8
	RRS	1668.7*	17.2*	3372.6*	52.3*
Cereal Rye	VRS	1766.1	26.3	3164.4	32.5
	PTRS	837.4	13.4	1361.7	16.2
	RRS	1938.9	29.6	2343.7	37.1

*significant difference at 0.05 between termination and 4 weeks prior to termination.

Figure 3.1. Relative cover crop biomass accumulation by growing degree days for each cover crop species and location.

Figure 3.2. Relative cover crop total N accumulation by growing degree days for each cover crop species and location.



CHAPTER 4

Summary and Conclusions

Incorporating cover crops into the production system is a best management practice that can bring several benefits to the environment and the future cash crops. Some of these benefits are maintenance of soil moisture, weed suppression, and increased plant available N. These benefits are directly related to the amount of biomass produced and being able to model and predict the amount of residue left on the soil is a great advancement to aid in cover crop management and can help maximize their benefits. A review of the literature indicated that there were few cardinal temperatures available for the commonly grown cover crop species in the Mid-southern, USA and even less effort to model cover crop growth or biomass accumulation. Having access to this information can be a useful decision-making tool that will influence the choice of the plant species and the length of cover crop growing season based on the rotational system, and the amount of N and biomass desired. The purposes of this study were to 1) identify the cardinal temperatures for eight commonly grown cover crop species in the Mid-southern USA, and 2) evaluate the relationship between the aboveground biomass accumulation and growing degree days [GDD], and total nitrogen [N] accumulation and GDD.

For a parameter such as GDD, it is important to have an accurate calculation of thermal units, since a more precise calculation will lead to a more realistic estimation of plant growth. To achieve this, it is necessary to have species specific information on the cardinal temperatures rather than relying on data collected on similar species or families of plants. In the case of many cover crop species, the data on well-defined cardinal temperatures was either outdated or non-existent. Therefore, the empirical determination of the cardinal temperatures for these eight common cover crops species in AR was essential for a better estimation of plant growth.

The results of the growth chamber experiment successfully identified the base temperatures for two cover crop species, the optimum temperature for three cover crop species and the maximum temperature for all eight of the cover crop species included in the trial that were not previously identified in the literature. Additionally, data suggested that five other cardinal temperatures, which were previously reported in the literature may need to be revised as the results previously presented were well outside the confidence intervals of the current dataset. The successful identification or revision of these cardinal temperatures for commonly grown cover crop species in the Mid-southern USA will allow more accurate determination of DTU values and GDD.

Results from the field trials identified a strong relationship between GDD and cover crop aboveground biomass accumulation and total N uptake. It appears that GDD can be an adequate predictor of cover crop growth, biomass accumulation as well as total N uptake. Although growth models have been widely implemented for many cash crop species such as corn (*Zea mays)* and rice (*Oryza sativa* L.), models were not found that have been developed to estimate or predict cover crop biomass or total N uptake. The results presented here confirm the positive relationship between thermal units a cover crop accumulates and crop aboveground biomass will be generated. Similarly, and especially for the legume species investigated, the accumulation of GDD can be related to total N uptake and potential N credits generated by the various cover crop species. The establishment of these relationship will allow the development of decision support tools to aid producers in both their cover crop and subsequent cash crop management.