

## ABSTRACT

OAKES, JOSEPH CARROLL. Adaptive Wheat Management: A System for Managing Wheat Based on Plant Physiology and Growth Responses to Environmental Conditions. (Under the direction of Ronnie W. Heiniger.)

Due to its ability to adapt to changing environmental conditions, wheat is one of the more difficult crops to manage. Since wheat has the ability to adapt to changing environmental conditions, it is essential for wheat growers to focus on an adaptive management approach that changes from season to season based on current and predicted environmental conditions rather than a prescription management approach that is the same each season. Two keys that are necessary to the successful implementation of an adaptive management system are 1) the ability to understand the plant growth response to different environmental conditions, and 2) the ability to predict weather conditions during critical growth periods that influence the development of each yield component.

To determine plant growth responses to the environment, this research focused on the environmental conditions and management practices that influence leaf development. In particular, the influence of planting date and environmental conditions following planting were of interest. The selection of planting date of wheat is an essential component in successful wheat production as it directly influences early leaf and fall tiller production which correspond to high yields. However, the proper planting date often varies with year. When a cold fall is forecasted, it is essential to plant early in order to develop adequate fall tillers before dormancy. When warm temperatures last into December, the planting date may be delayed. A two-year study examining leaf development at two planting dates was performed. In 2012-13, the later planting date resulted in greater fall tillers and higher yields

due to a shorter phyllochron interval in November than in December. However, in 2013-14, more fall tillers and higher yields were produced in the early planting date as a cold December, January, and February severely limited GDD accumulation which reduced the wheat planted late had to develop tillers.

In the second study, the grain fill period was examined in order to quantify kernel set in response to growing conditions in April and May and how it can be impacted by environmental and management factors such as light interception, fungicide, and nitrogen. The shaded treatment resulted in the lowest rate of grain fill and yields, which indicate the importance of proper light interception during the grain fill period. While neither a fungicide nor nitrogen application at GS70 had an effect on the rate of grain fill or yield, a fungicide application may be necessary when there is intense disease pressure which will limit light interception during the grain fill period.

Since there is a need to be able to predict weather conditions during critical growth periods, it is necessary to use some type of weather pattern as a guide for determining planting date. Therefore, we have attempted to use the El Niño Southern Oscillation and the North Atlantic Oscillation weather events to properly select a planting date based on which pattern minimizes the time necessary for the plant to develop its first tiller. Results show that the El Niño and Cool October North Atlantic Oscillation phases often provide the most favorable conditions for fall tiller production.

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Adaptive Wheat Management: A System for Managing Wheat Based on Plant Physiology  
and Growth Responses to Environmental Conditions

by  
Joseph Carroll Oakes

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APPROVED BY:

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Carl R. Crozier

---

J. Paul Murphy

---

Gail G. Wilkerson

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Ronnie W. Heiniger  
Chair of Advisory Committee

## **DEDICATION**

This dissertation is dedicated to my mom and dad, as well as my fiancée Krista Casper for their countless words of support and encouragement throughout this journey.

Thanks!

## **BIOGRAPHY**

Joseph Carroll Oakes was born on February 4, 1987, in Kinston, NC and was raised in the nearby town of Grifton, NC. Joseph accepted Jesus Christ as his personal savior in 2002 and graduated from high school in 2005. Throughout his high school years, Joseph enjoyed working many hours with his father at a research farm, where he developed a passion and a love for agriculture. In 2010, Joseph graduated from Bob Jones University with a B.S. in Biology, and began graduate school at NC State that same year. Joseph completed a M.S. in Crop Science in 2012 and began working on a Ph.D. in Crop Science.

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## CHAPTER ONE

### **Phyllochron Interval and Yield Response to Starter Fertilizer and Planting Date in Wheat**

JOSEPH C. OAKES and RONNIE W. HEINIGER

#### **ABSTRACT**

An understanding of early leaf and tiller growth in wheat (*Triticum aestivum* L.) and how it impacts yield is an important concept for properly managing wheat in North Carolina. Field trials were conducted at four locations in North Carolina in 2012-13 and 2013-14 to investigate the effects of planting date and starter fertilizer on phyllochron interval (PI) and yield. Planting date caused a response in PI and yield in each site-year. In each site year, the later planting usually resulted in a shorter average PI. However, the earlier planting date resulted in the highest yields in 2013-14, while the later planting date resulted in the highest yields in 2012-13. Higher yield at the second planting date in 2012-13 was due to the fact that environmental conditions in November increased PI for the early planting while ideal growing conditions in December resulted in a shorter PI for the early growth period at the later planting date. Coupled with warm winter weather, the late planting was able to develop more growth in the form of tillers resulting in greater yield. Despite the shorter PI at the later plantings at the Tidewater Research Station (TRS) and the Piedmont Research Station (PRS) in 2013-14, GDD were not accumulated as rapidly in December, January and February as in the previous year and the plant could not compensate for the later planting. A response to starter fertilizer (11-37-0 & 9-18-9) applied at planting was observed at TRS in 2014 and it resulted in a shorter PI and higher tiller counts than observed in the untreated control. This

resulted in an increased yield, and was largely due to abundant rainfall and potential nutrient leaching at the location where the yield response was observed. Therefore, the results of this study indicate that choosing the proper planting date based on fall and winter weather conditions is one of the most influential decisions on yield. A starter fertilizer may be necessary if there is a potential for nutrient leaching.

## **INTRODUCTION**

The importance of early leaf and tiller growth in wheat and its effect on grain yield has long been understood (Friend et al., 1962). Tilley & Heiniger (unpublished data) examined the role of fall tiller production in North Carolina and observed that fall tiller production is crucial to producing high yields. Tillers that were produced in the fall contributed to nearly 90% of the total number of heads that were present at harvest. Likewise, fall tillers produced nearly 95% of the final grain yield. This emphasizes the importance of early leaf and tiller production in wheat. Therefore, there is a need to understand the impact of various management practices at planting time on early leaf growth.

To fully understand leaf growth and development, it is necessary to describe conditions that cause new leaves to appear and expanding leaves to mature (Cao and Moss, 1989). Both mainstem leaf development and tiller formation are plant measurements used to examine the quality of the growth environment of wheat (Klepper et al., 1982). The mainstem leaf stage is a numerical value, which defines the number of leaves present on the mainstem of the plant and is numbered according to order of appearance. The leaf appearance rate is more strongly correlated with thermal units than it is with chronological time (Gallagher, 1970) . Many of the scales used to describe wheat growth emphasize the

stages of kernel development (Wilhelm and McMaster, 1995). One exception is the Haun scale (Haun, 1973) which defines wheat growth based on vegetative rather than reproductive development. Since the Haun scale is strongly correlated with accumulated thermal units, it provides a more precise measure of leaf appearance than does just counting leaves. The Haun scale is also more definitive and sensitive to changes in plant morphology than is any other scale (Bauer et al., 1984). A plant's Haun age is determined from the number of fully expanded leaves plus the ratio of lamina length of the last visible growing leaf to that of the preceding leaf. The time interval between the appearance of successive leaves measured in thermal units is known as a phyllochron interval (PI) (Baker et al., 1986). A PI is defined as the developmental time it takes for elongation of successive mainstem leaves. It is measured as the number of GDD required to complete a mainstem leaf stage (Krenzer, Jr. and Nipp, 1991). Therefore, the smaller the PI, the faster leaves are appearing on the mainstem.

Several different environmental and management factors have been shown to influence PI in wheat. These factors include temperature, daylength, available moisture, and cultivar (Bauer et al., 1984; Cao and Moss, 1989). Baker et al. (1986) examined the effect of temperature on PI in both spring and winter wheat. In winter wheat, drought stress decreased the PI and caused an acceleration in plant development. This reduction in PI is thought to be caused by the non-irrigated plants being warmer relative to the irrigated plants, which increased accumulated GDD's. Krenzer et al. (1991) observed results which were opposite to that of Baker et al. (1986). Among the first three phyllochron intervals, Krenzer et al. (1991) found that low moisture treatments exhibited a longer PI than did high moisture treatments. This suggests that moisture stress can have a direct effect on slowing leaf development.

However, by the development of the fifth leaf, there was no significant difference in GDD required per leaf between low and high moisture treatments.

Daylength is important in early growth of wheat and has been shown to have an impact on PI. Cao and Moss (1989) examined the effect of daylength on leaf emergence in wheat and barley. They observed that the leaf emergence rates of all genotypes increased with increasing daylength. As daylength increased, fewer GDD were needed to produce a leaf, and therefore leaves were produced quicker. Cao and Moss (1989) also showed that PI changed quickly and significantly in response to a daylength change during growth. In a study examining the effects of temperature on leaf appearance, Baker et al. (1986) found that not only did temperature influence PI but that differences in PI were also found among winter wheat cultivars.

Planting date has the potential to influence several of the factors that impact PI (moisture, temperature, and photoperiod), and is one of the most important production factors that can be controlled by the grower (Campbell et al., 1991; McLeod et al., 1992). While little research has examined the relationship between PI and planting date, research has examined the relationship between planting date and plant height. Knapp and Knapp (1978) found that delayed planting date reduced plant height. According to McLeod et al. (1992), late planting reduced plant height 5-10 cm depending on soil type. Plant population is also influenced by planting date, with fall tillers often declining significantly as planting is delayed (McLeod et al., 1992). Planting date influences GDD accumulation and precipitation throughout the growing season (Tapley et al., 2013). Later planted wheat is more likely to experience lower temperatures during early leaf and tiller development than is



wheat planted on-time (Thiry et al., 2002). Therefore, an earlier planting date should favor the accumulation of more GDD than a later planting date. Planting date also influences grain yield by affecting the timing and development of tillers (Thiry et al., 2002). Early planting promotes higher tillering in the fall, while late planting results in more spring tillers. Spring tillers have a lower weight and harvest index. The importance of tillers is paramount in determining grain yield. As much as 70% of grain yield can potentially come from tillers and the mainstem (Thiry et al., 2002). However, few tillers can develop when moisture, nutrition, and other growing conditions are poor; therefore, planting date is an important aspect in tiller development. By planting too early, too many fall tillers will develop which will result in increased disease, competition, and will deplete soil moisture. In contrast, when wheat is planted late there is not enough time to develop adequate fall tillers, and there is an inadequate number of spikes. An optimum planting date will encourage the development of both fall and spring tillers, while reducing competition and promoting optimum yield (Thiry et al., 2002).

Late planting has also been shown to delay maturity and affect grain quality. McLeod et al. (1992) examined seeding date in Southwestern Saskatchewan and observed that the time required to reach maturity was delayed 10-11 days when planting was delayed from September to November. Delayed maturity can also expose the crop to rust, disease, and moisture – all of which can negatively affect grain quality. McLeod et al. (1992) also observed that both test weights and kernel weights declined as planting date was delayed. This was due to the fact that later planted wheat ran out of water and matured in a drier period than did earlier planted wheat.

Nitrogen management is one of the most important aspects to successful winter wheat production in North Carolina. Generally, when wheat is planted on time, 15-30 lbs. of pre-plant nitrogen are necessary to promote adequate growth and tillering (Weisz, and Heiniger, 2013). As previously mentioned, adequate tillering is crucial to high yields. Nitrogen stress can prevent adequate tillering; therefore, pre-plant nitrogen is often necessary for improving tillering and yield. When temperatures are too cold, late planted wheat may not respond to pre-plant nitrogen due to the fact that temperatures are too low to allow the plant to develop leaves and tillers. Thus, the nitrogen cannot be taken up, and can be leached out of the soil before the plant can use it (Weisz, and Heiniger, 2013). Knapp and Knapp (1978) observed that when planting is delayed, treatments only receiving nitrogen yielded less than did wheat which received no fertilizer, and that nitrogen alone delayed maturity. In contrast, Ottman (2008) found that pre-plant nitrogen resulted in quicker flowering and heading; however, grain yield was not affected.

Phosphorus and potassium are also extremely important in achieving high wheat yields, and the possibility of applying them pre-plant must also be examined. Phosphorus plays an integral role in germination and early plant growth, as well as promoting winter hardiness (Crozier et al., 2013). Both slow growth and stunting are signs of a phosphorus deficiency. In both early and late planted wheat, there was a reduction in spike number and yields when pre-plant phosphorus was not applied (Knapp and Knapp, 1978). It was noted that phosphorus produced wheat with more rigorous growth, improved tillering, and increased winter survival. In delayed planted wheat, phosphorus is important for seedling maturation and can offset the negative effects of late planting (Knapp and Knapp, 1978).

Potassium is important in maintaining grain quality and test weight (Crozier et al., 2013). It also prevents lodging, and helps with drought and disease tolerance.

The contrasting findings in many of these studies on the effects of planting date and fertility on tillering and yield suggests a need for a better understanding of how these factors influence leaf growth in wheat. Since leaf growth is related to tiller formation (Klepper et al., 1982), an understanding of how these management practices influence leaf growth would help determine why studies conducted under different environments could result in different conclusions. The objective of this study was to examine the effects of two planting dates and three fertilizer solutions applied at planting on phyllochron interval and yield.

## **MATERIALS AND METHODS**

### **Field Experiment**

Four sites were selected in North Carolina to correspond with three major wheat-producing regions of the state: tidewater, coastal plain, and the piedmont. In the 2012-13 growing season research was conducted at a private farm location near Hertford (Roanoke silt loam- fine, mixed, semiactive, thermic Typic Endoaquults). During the 2013-14 growing season research was conducted at three locations: the Tidewater Research Station (TRS) in Plymouth (Portsmouth fine sandy loam- fine loamy over sandy or sandy-skeletal, mixed, semiactive, thermic Typic Umbraquults), the Piedmont Research Station (PRS) in Salisbury (Lloyd clay loam- fine, kaolinitic, thermic Rhodic Kanhapludults), and at a private farm location in Chowan County (Altavista fine sandy loam- fine loamy, mixed semiactive, thermic Aquic Hapludults).

At each location, the cultivar ‘Dyna-Gro Shirley’ was planted at 82 seeds per row meter on 16.9 cm rows, with individual plots being 13.72 m by 1.83 m. Plots were planted in a conventionally-tilled field at all locations except PRS, which was planted no-till into corn stubble. Plots were arranged into a split-plot design with the main plots consisting of the two planting dates and the subplots consisting of the fertilizer treatments and an untreated control. The two planting dates represented an on-time and a late planting date for each location. At Hertford, plots were planted on 12 Nov and 4 Dec 2012. In 2013, plots at TRS and Chowan were planted on 11 Nov and 6 Dec, while plots at PRS were planted on 21 Oct and 15 Nov. The three fertilizer subplot treatments applied broadcast at planting with a backpack sprayer consisted of 87.93 L ha<sup>-1</sup> of 30% UAN, 233.85 L ha<sup>-1</sup> of 11-37-0, and 280.62 L ha<sup>-1</sup> of 9-18-9. The main and subplot treatments were replicated four times. At PRS, both paraquat dichloride and chlorsulfuron/flucarbazone-sodium were applied pre-emergence for weed control. Nitrogen was applied at jointing on 22 Mar 2013 at Hertford. In 2014, nitrogen was applied on 10 Mar at TRS and Chowan, and on 13 Mar at PRS. Rates were adjusted based on the previous fertilizer application so that all plots received a total of 134.52 kg N ha<sup>-1</sup>. Plots were harvested in mid-June both seasons. In 2013, plots were harvested using a Wintersteiger Delta combine, and in 2014 plots were harvested using a Gleaner K2 combine. Both machines were equipped with a Harvestmaster GrainGage to record moisture, grain weight, and test weight.

In order to measure phyllochron interval, mainstem leaves were counted during the vegetative period and regressed against growing degree days (GDD) accumulated since planting. Five plants were randomly chosen from each plot and were marked with a flag at

each location. Mainstem leaves were counted and recorded at bi-weekly to monthly intervals beginning at emergence and continuing to flag leaf. At Hertford, leaves were counted on 12 Dec 2012, 10 Jan 2013, 21 Jan, 6 Feb, 5 Mar, 20 Mar, 3 Apr, 10 Apr, and 17 Apr. Leaf counts at TRS were taken on 6 Dec 2013, 9 Jan 2014, 20 Jan, 17 Feb, 10 Mar, 17 Mar, 4 Apr, 10 Apr, and 24 Apr. Meanwhile, at Chowan counts were taken on 6 Dec 2013, 9 Jan 2014, 20 Jan, 7 Feb, 24 Feb, 10 Mar, 27 Mar, 10 Apr, 21 Apr. Finally, at PRS counts were taken on 14 Nov 2013, 12 Dec, 19 Dec, 6 Jan 2014, 15 Jan, 27 Jan, 10 Feb, 18 Feb, 13 Mar, 3 Apr, and 22 Apr. These mainstem leaves were counted according to the Haun scale (Haun, 1973). The Haun scale makes use of the regular appearance of leaves at the growing point, and each new leaf represents a unit of development. A plant's Haun stage is determined by the total number of fully developed leaves, plus a fractional portion of the next leaf. Therefore, a plant with three fully expanded leaves and a fourth leaf that is halfway expanded would have a Haun stage of 3.5. At each counting date, the last fully expanded leaf was marked with a black mark so as to record the last fully expanded leaf for future countings.

Tiller counts were taken just prior to harvest in order to determine how many tillers were still viable and contributing to yield. This was done by counting the number of tillers that had headed in a 1-m row section of each plot.

### **Statistical Procedure**

Phyllochron interval (PI) for leaf appearance on the main stem was calculated in a manner similar to that described by Baker et al., 1986. The reciprocal of the slope of the relationship between Haun growth scale units and GDD is the thermal time interval between appearances of successive leaves known as the PI. PI is the amount of time in GDD it takes

for the plant to grow a new leaf. GDD was calculated from the daily maximum and minimum temperatures as indicated in the following formula:

$$Tu=[(T_{max}+T_{min})/2]-T_b,$$

where Tu is daily thermal units (GDD), T<sub>max</sub> is the daily maximum temperature, and T<sub>min</sub> is the daily minimum temperature (Baker et al., 1986). Leaf development is almost linear when temperature is above a minimum and below an optimum temperature. Hence, the base temperature (T<sub>b</sub>) is estimated by extrapolation to a temperature axis where the leaf appearance rate is zero (Baker et al., 1986). In this study, a base temperature of 0°C was used.

Prior to calculating PI, within each planting date at each site-year the Haun scale growth units for each individual plant across all fertility treatments were plotted against accumulated GDD since planting to determine if the relationship was linear. In several cases, these plots indicated that the rate of leaf development differed at different stages of plant growth (Figure 1.1). To determine if the relationship between Haun scale growth units and GDD could be represented by a single linear relationship or if the relationship differed significantly at different growth stages, a statistical test was performed which compared a model representing multiple linear relationships which were fit using the NLIN non-linear regression procedure (SAS Institute, 2010) with a single linear relationship. This was done by comparing the error sum of squares (SSE) of the multiple linear regression models calculated by the NLIN procedure with the SSE of the single linear model using an F-test (Ott, 1988). When this test indicated that there was a significant difference between the multiple and single linear regression models, multiple regression segments were used to

represent leaf development in response to GDD for that planting date at that location. The length (range in GDD) of each segment was determined using the NLIN procedure to identify inflection points between linear segments. For either the multiple or single linear regression segments identified by the NLIN procedure at each location, the slope of the linear relationship between Haun scale growth units and GDD within the segment range was calculated using measurements taken from the five plants within each plot. PI was then calculated for either the multiple or single linear segment for each planting date and treatment by taking the inverse of these slopes.

The Proc GLM procedure in SAS (SAS Institute, 2010) was used to determine if there were differences in PI among different segments within and across planting dates or, when a single linear model was appropriate, across the entire growth period across planting dates and among starter fertilizer treatments within planting dates. Likewise, Proc GLM was used to determine if there were differences in tiller density and yield among the planting dates and starter fertilizer treatments. Since there were differences in planting dates among site years, it was necessary to analyze each location separately. When differences were detected, Fisher's protected LSD was used to separate the means.

## **RESULTS AND DISCUSSION**

### **Phyllochron Interval**

The tests of multiple linear regressions versus a single linear regression indicated that multiple regression segments were a better fit to the data at three of the four site-years (Table 1.1). At Hertford, the NLIN procedure identified two segments at each planting date (Figure 1.1). The early segment at the November planting date encompassed the period from planting

to 853.6 GDD with the later segment covering the period from 853.6 GDD to 1374.9 GDD (Table 1.2). The early segment at the December planting date encompassed the period from planting to 792.6 GDD with the later segment covering the period from 792.6 GDD to 1037.1 GDD. Analysis of variance (ANOVA) for PI among these four segments and four starter fertilizer treatments did not identify any significant interactions between segments and fertilizer treatments but did identify a significant segment main effect (Table 1.3). The PI for the early growth segment for the 12 November planting date (182 GDD per leaf) was significantly longer than the PI for the early segment at the 4 December planting date (112 GDD per leaf) (Figure 1.2). The PIs for the later segments within each planting date were significantly shorter than the two earlier segments, but there was no significant difference between the later segments at either planting date.

The comparison between multiple linear versus a single linear segment indicated that there no significant advantage to using multiple linear segments at TRS (Table 1.1). ANOVA indicated that there were both a significant date and treatment main effect for PI at TRS (Table 1.3). Wheat planted on 12 November required an average of 105 GDD per leaf, while wheat planted on 6 December required an average of 92 GDD per leaf (Figure 1.3). For the treatment main effect, both 30% UAN and 9-18-9 had a shorter PI than did the untreated control (Figure 1.4). The average PI for the untreated control at TRS was 102 GDD, while the average PI for 30% UAN and 9-18-9 was 97 GDD.

At Chowan, the NLIN procedure identified two segments within each planting date (Figure 1.5). The early segment at the November planting date encompassed the period from planting to 861.7 GDD with the later segment covering the period from 861.7 GDD to 1321



GDD (Table 1.2). The early segment at the December planting date encompassed the period from planting to 783.6 GDD with the later segment covering the period from 783.6 GDD to 1151 GDD. Analysis of variance (ANOVA) for PI among these segments and starter fertilizer treatments did not identify any significant interactions between segments and fertilizer treatments but did identify a significant segment main effect (Table 1.3). The PIs for the early growth segments for the 12 November and 4 December planting dates (116 and 119 GDD per leaf, respectively) were significantly longer than the PIs for the later growth segments (86 and 82 GDD per leaf, respectively) (Figure 1.6). No significant differences in PIs for corresponding growth segments were found between planting dates.

At PRS, the NLIN procedure identified two segments at the first planting date and only one segment at the second planting date (Figure 1.7). The early segment at the November planting date encompassed the period from planting to 892.7 GDD with the later segment covering the period from 892.7 GDD to 1121 GDD (Table 1.2). Analysis of variance (ANOVA) for PI among these segments and starter fertilizer treatments did not identify any significant interactions between segments and fertilizer treatments but did identify a significant segment main effect (Table 1.3). The PI for the early growth segment for the 21 October planting date (104 GDD per leaf) was significantly shorter than the PI for the later growth segment (121 GDD per leaf) (Figure 1.8). The 15 November planting required an average of 102 GDD per leaf for the entire growth period which was not significantly different from the PI of the early growth segment at the 21 October planting date, but was significantly shorter than the PI of the late growth period at the 21 October planting date.

## **Tiller Number**

Tiller counts were taken just prior to harvest in order to determine the number of viable tillers that were contributing to yield. As with PI the key difference in tiller number at each location was planting date (Table 1.4). However, unlike PI, tiller number differed between years with the late planting date having the most tillers in 2013 and the early planting date having the most tillers in 2014. At Hertford in 2013, there was both a date and treatment significant main effect, but there was no interaction. Wheat planted at the later date of 4 December produced an average of 109 tillers per square meter while wheat planted earlier on 12 November produced an average of 89 tillers per square meter (Figure 1.9). Plots to which the 9-18-9 starter solution was applied produced an average of 115 tillers per square meter, while the remaining treatments produced an average of 88 tillers per square meter (Figure 1.10). There was also a significant date main and treatment main effect at Plymouth in 2014 (Table 1.4), however in this case the earlier planting resulted in more tillers than did the later planting. Plots planted on 12 November produced an average of 147 tillers per square meter, while plots planted on 6 December produced an average of 126 tillers per square meter (Figure 1.11). Among treatments, 9-18-9 had higher tillers per square meter (149) than 30% UAN (128) and the untreated control (123), while 11-37-0 (147) also had higher tillers per meter than the untreated control (Figure 1.12). At both Chowan (Figure 1.13) and Salisbury (Figure 1.14), there were only significant date main effects (Table 1.4) with the early planting again resulting in higher tillers per meter than the later planting.

The differences in ranking in tiller counts from the early and late planting date between the 2012-13 and 2013-14 seasons can be explained by the differing growing

conditions between the two years. During the 2012-13 growing season, it was warmer in the fall and winter and more GDD were accumulated over a shorter period of time (Figure 1.20). In the 2013-14 growing season, it was much colder in the fall and winter and GDD did not accumulate as quickly. Therefore, a combination of a shorter PI and faster GDD accumulation caused the later planting to produce more tillers in 2012-13. Even though the later planting had a shorter PI in 2013-14, the shorter PI was not able to compensate for fewer GDD accumulated. Since it was planted later and fewer GDD were accumulated, the plant was not able to produce as many tillers when planted later in the season in 2013-14.

### **Grain Yield**

As with PI and tiller counts, differences in grain yield were observed between the two planting dates with a significant date main effect at each of the four locations (Table 1.5). Grain yield at Hertford had the same pattern as that found in PI and tiller counts with the later planting having higher yield than the earlier planting. Plots planted on 4 December had a grain yield of 6.46 mt ha<sup>-1</sup>, while plots planted on 12 November had a grain yield of 5.58 mt ha<sup>-1</sup> (Figure 1.15). At Plymouth, there was both a significant date and treatment main effect for yield (Table 1.5). However in this case, grain yields were higher at the earlier planting date than at the later planting date, with the 12 November planting yielding 5.78 mt ha<sup>-1</sup> and the 6 December planting yielding 5.18 mt ha<sup>-1</sup> (Figure 1.16). Among treatments, both 11-37-0 and 9-18-9 yielded higher than the remaining two treatments (Figure 1.17). There was only a significant date main effect at both Chowan and Salisbury (Table 1.5). At both locations, the earlier planting date resulted in a higher yield than the late planting date (Figures 1.18 & 1.19). No treatment differences were observed at either location.

## Summary

Analysis of leaf development across different planting dates and locations found that the rate of leaf development can differ across the growing season. Differences in the rate of leaf development within the growing season in conjunction with milder temperatures can result in differences in total leaf and tiller number between planting dates and can lead to significant yield differences between planting dates. At Hertford in 2012-13, the early planting date had a longer PI during the early growth period (0-853.6 GDD), fewer tillers, and a lower yield compared to the later planting date which had a shorter PI during the early growth period (0-792.6), higher tiller numbers, and therefore a higher yield. The length of the PI during the early growing period coupled with warm temperatures in January and February which resulted in a rapid accumulation of GDD during that period (Figure 1.20) was an integral part in determining tiller number and grain yield. At TRS in 2013-14, the PI over the entire period from emergence to GS 30 for the later planting date was shorter than the PI for the early planting date over the same period. However, cooler winter temperatures resulted in less accumulated GDD (Figure 1.20) which limited the number of leaves and tillers developed at the later planting date. As a result, the early planting date produced more tillers and a greater yield. At Chowan there were no differences in PI within either the early or late growth periods between the 12 November and 4 December planting dates. As a result, the 12 November planting date resulted in significantly higher tiller counts and yield than the 4 December planting date. In contrast to the other site-years, the PI for later growth period at the 21 October planting date at PRS (892.7-1121 GDD) was longer than the PI for the early growth period (0-892.7), while the PI for the later planting date did not differ from

emergence to GS 30. Despite this disadvantage, the earlier planting date still resulted in more tillers and a greater yield due to the lack of GDD accumulated during the months of January and February.

The total number of leaves a wheat plant develops is a function of the rate of leaf development (PI) and the number of GDD available for leaf development. While the average rate of leaf development across segments at Hertford 2012-13, TRS 2013-14, and PRS 2013-14 was significantly shorter during the period from emergence to GS 30, only at Hertford 2012-13 did this advantage result in more tillers and higher yield at the later planting date. This was the result of a winter where the late planting date benefited from a shorter average PI and an adequate number of heat units. In fact, December 2012 was actually warmer than November 2012 as more GDD were accumulated in the three weeks after the second planting than in the three weeks after the first planting (Figure 1.21). This warmer period in 2012-13 combined with a shorter PI allowed the later planting to develop leaves quicker over a period that was long enough to allow the later planted wheat to catch and surpass the earlier planted wheat, therefore producing more viable tillers and ultimately producing higher yields. This observation emphasizes the importance of PI and heat unit accumulation during the early growth period in producing adequate tillers and high yields.

While planting date was the key element in this study, there was a positive yield response to a starter fertilizer in only one of the four site-years. Conditions at TRS during the 2013-14 growing season contributed to the yield response to 11-37-0 and 9-18-9. Heavy rainfall throughout most of the fall and winter likely resulted in some nutrient leaching. The average rainfall for November and December combined in 2013 was 19.5 cm, while the

average rainfall for November and December from 2005 through 2012 was 16.3 cm (Figure 1.22). Thus, a yield response was observed when a fertilizer solution was added at planting. However, in locations where there was no nutrient deficiency due to leaching (Chowan and PRS), there was no yield benefit from adding fertilizer at planting.

This study shows that PI can change across the course of the growing season from emergence to GS 30. Differences in PI accompanied by adequate accumulation of GDD can influence tiller number and grain yield and result in differences in grain yield between planting dates. In general, the average PI during the period from emergence to GS 30 was more likely to be longer when wheat was planted early. This may be due to dramatic temperature changes which are more likely to occur during the month of November. While the average PI for the earlier planting date may often be longer, the lack of GDD accumulated during the winter months usually makes it difficult for the late planting date to produce enough leaves and tillers to overtake the earlier planting. Therefore, only on rare occasions such as at Hertford 2012-13 does the later planting date produce a greater yield compared to an earlier planting date.

## REFERENCES

- Baker, C.K., Gallagher, J.N., and Monteith, J.L. (1980). Daylength Change and Leaf Appearance in Winter Wheat. *Plant Cell Environ.* 3, 285–287.
- Baker, J.T., Pinter, Jr., P.J., Reginato, R.J., and Kanemasu, E.T. (1986). Effects of Temperature on Leaf Appearance in Spring and Winter Wheat. *Agron. J.* 78, 605–613.
- Bauer, A., Frank, A.B., and Black, A.L. (1984). Estimation of Spring Wheat Leaf Growth Rates and Anthesis from Air Temperature. *Agron. J.* 76, 829–835.
- Campbell, C.A., Selles, F., Zetner, R.P., McLeod, J.G., and Dyck, F.B. (1991). Effect of Seeding Date, Rate, and Depth on Winter Wheat Grown on Conventional Fallow in S.W. Saskatchewan. *Can. J. Plant Sci.* 71, 51–61.
- Cao, W., and Moss, D.N. (1989). Temperature and Daylength Interaction on Phyllochron in Wheat and Barley. *Crop Sci.* 1046–1048.
- Crozier, C., Heiniger, R.W., and Weisz, R. (2013). Nutrient Management for Small Grains. In *North Carolina Small Grain Production Guide*, (NCSU), pp. 32–38.
- Friend, D.J.C., Helson, V.A., and Fisher, J.E. (1962). Leaf Growth in Marquis Wheat as Regulated by Temperature, Light Intensity, and Daylength. *Can. J. Bot.* 40, 1299–1311.
- Gallagher, J.N. (1970). Field Studies in Cereal Leaf Growth. I. Initiation and Expansion in Relation to Temperature and Ontogeny. *J. Exp. Bot.* 30, 625–636.
- Haun, J.R. (1973). Visual Quantification of Wheat Development. *Agron. J.* 65, 116–119.
- Klepper, B., Rickman, R.W., and Peterson, C.M. (1982). Quantitative Characterization of Vegetative Development in Small Cereal Grains. *Agron. J.* 74, 789–792.
- Knapp, W.R., and Knapp, J.S. (1978). Response of Winter Wheat to Date of Planting and Fall Fertilization. *Agron. J.* 70, 1048–1053.
- Krenzer, Jr., E.G., and Nipp, T.L. (1991). Mainstem Leaf Development and Tiller Formation in Wheat Cultivars. *Agron. J.* 83, 667–670.
- Leong, S.K., and Ong, C.K. (1983). The Influence of Temperature and Soil Water Deficit on Development and Morphology of Ground-nut. *J. Exp. Bot.* 34, 1551–1561.
- McLeod, J.G., Campbell, C.A., Dyck, F.B., and Vera, C.L. (1992). Optimum Seeding Date for Winter Wheat in Southwestern Saskatchewan. *Agron. J.* 84, 86–90.

- Ott, L. (1998) *An Introduction to Statistical Methods and Data Analysis*. 3<sup>rd</sup> ed. PWS-Kent, Boston. p. 835
- Ottman, M.J. (2008). Can Preplant Fertilization of Small Grains be Eliminated? *Forage Grain Rep.* 7–11.
- Tapley, M., Ortiz, B.V., van Santen, E., Balkcom, K.S., Mask, P., and Weaver, D.B. (2013). Location, Seeding Date, and Variety Interactions on Winter Wheat Yield in the Southeastern United States. *Agronomy* 105, 509–518.
- Tilley, M.S. and Heiniger, R.W. (2012) Productive Tiller Development in Wheat. Unpublished data.
- Thiry, D.E., Sears, R.G., Shroyer, J.P., and Paulsen, G.M. (2002). Planting Date Effects on Tiller Development and Productivity of Wheat. Kansas State University Agricultural Experiment Station and Cooperative Extension Service, 133.
- Weisz, R., and Heiniger, R.W. (2013). Nitrogen Management for Small Grains. In *North Carolina Small Grain Production Guide*, (NCSU), pp. 25–31.
- Wilheml, W.W., and McMaster, G.S. (1995). Importance of the Phyllochron in Studying Development and Growth and Grasses. *Crop Sci.* 35, 1–3.



**Table 1.1: F-test for multiple versus single linear regression at each site-year.**

Single vs. Multiple	Sum of Squares <sub>1</sub>	Sum of Squares <sub>2</sub>	Mean Square Error <sub>1</sub>	F Value	Significant
Hertford 2012- 13	211.6	212.7	0.2315	4.75	*
TRS 2013-14†	206.8	207.2	0.2385	1.68	NS
Chowan 2013- 14	252.1	249.5	0.2147	7.92	*
PRS 2013-14†	359.8	355.0	0.3268	14.69	*

† TRS: Tidewater Research Station; PRS: Piedmont Research Station

- Indicates significant difference between a multiple linear model and a single linear model at  $p < 0.05$ .

**Table 1.2: Slopes and R<sup>2</sup> values for each growth period within planting date at each site-year.**

Site-Year	Plant Date	Period (GDD)	Slope	R <sup>2</sup>
Hertford 2012-13	Nov	<853.6	0.0058	0.994
		>853.6	0.0110	0.996
	Dec	<792.6	0.0091	0.998
		>792.6	0.0119	1.000
TRS 2013-14	Nov	N/A	0.0095	0.995
	Dec	N/A	0.0901	0.993
Chowan 2013-14	Nov	<861.7	0.0087	0.991
		>861.7	0.0117	0.997
	Dec	<783.6	0.0089	1.000
		>783.6	0.0122	0.998
PRS 2013-14	Nov	<892.7	0.0096	0.997
	Dec	>892.7	0.0083	0.960
	Dec	N/A	0.0098	0.998

**Table 1.3: Analysis of variance table for phyllochron interval at each site-year. †**

Source of Variation	Hertford		TRS 2013-14††		TRS 2013-14		PRS 2013-14††	
	DF		DF		DF		DF	
segment	3	***	1	***	3	***	2	**
treatment	3	NS	3	*	3	NS	3	NS
segment*treatment	9	NS	3	NS	9	NS	6	NS

† \*, \*\*, \*\*\* indicate significance at the 0.05, 0.01, and 0.001 significance level respectively. NS indicates not significant.

†† TRS: Tidewater Research Station; PRS: Piedmont Research Station

**Table 1.4: Analysis of variance table for tiller counts at each site-year. †**

Source of Variation	DF	Hertford 2012-13	TRS†† 2013- 14	Chowan 2013- 14	PRS†† 2013- 14
date	1	***	*	**	***
treatment	3	**	*	NS	NS
date*treatment	3	NS	NS	NS	NS

† \*, \*\*, \*\*\* indicate significance at the 0.05, 0.01, and 0.001 significance level respectively. NS indicates not significant.

†† TRS: Tidewater Research Station; PRS: Piedmont Research Station

**Table 1.5: Analysis of variance table for grain yield at each site-year. †**

Source of Variation	DF	Hertford 2012-13	TRS†† 2013- 14	Chowan 2013- 14	PRS†† 2013- 14
date	1	***	***	***	***
treatment	3	NS	***	NS	NS
date*treatment	3	NS	NS	NS	NS

† \*, \*\*, \*\*\* indicate significance at the 0.05, 0.01, and 0.001 significance level respectively. NS indicates not significant.

†† TRS: Tidewater Research Station; PRS: Piedmont Research Station

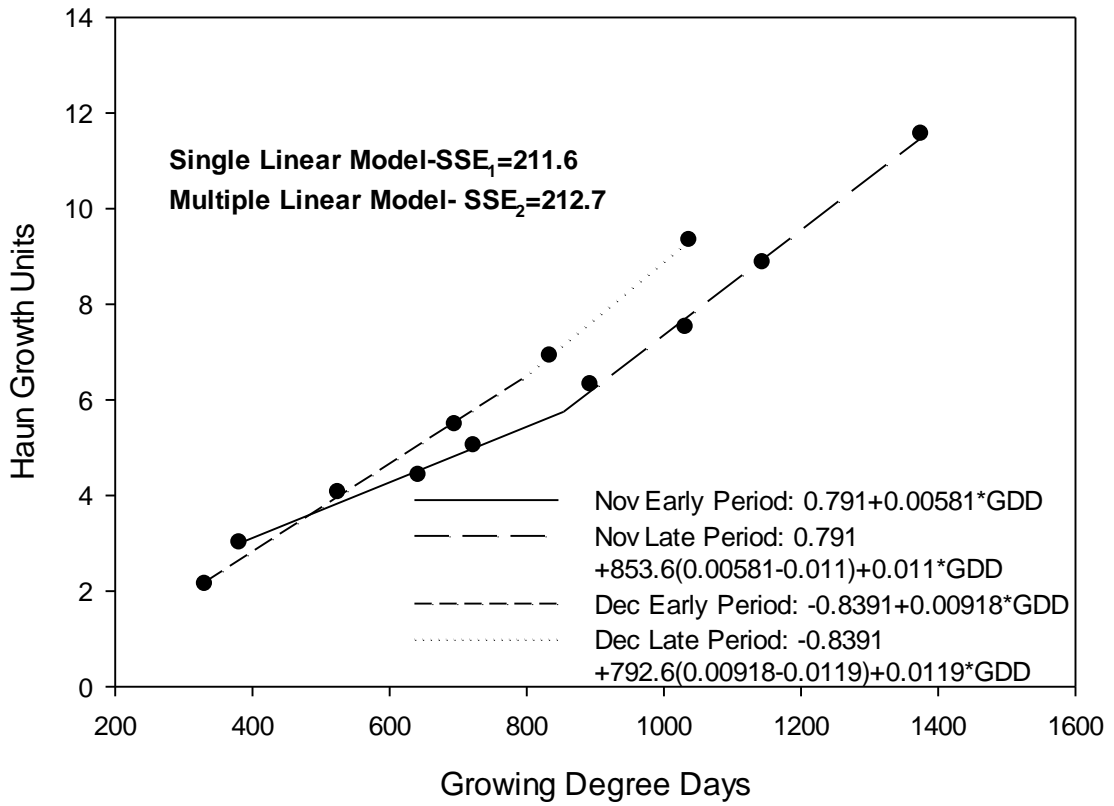


Figure 1.1: Relationship between Haun growth stage and accumulated GDD at Hertford in 2012-13.

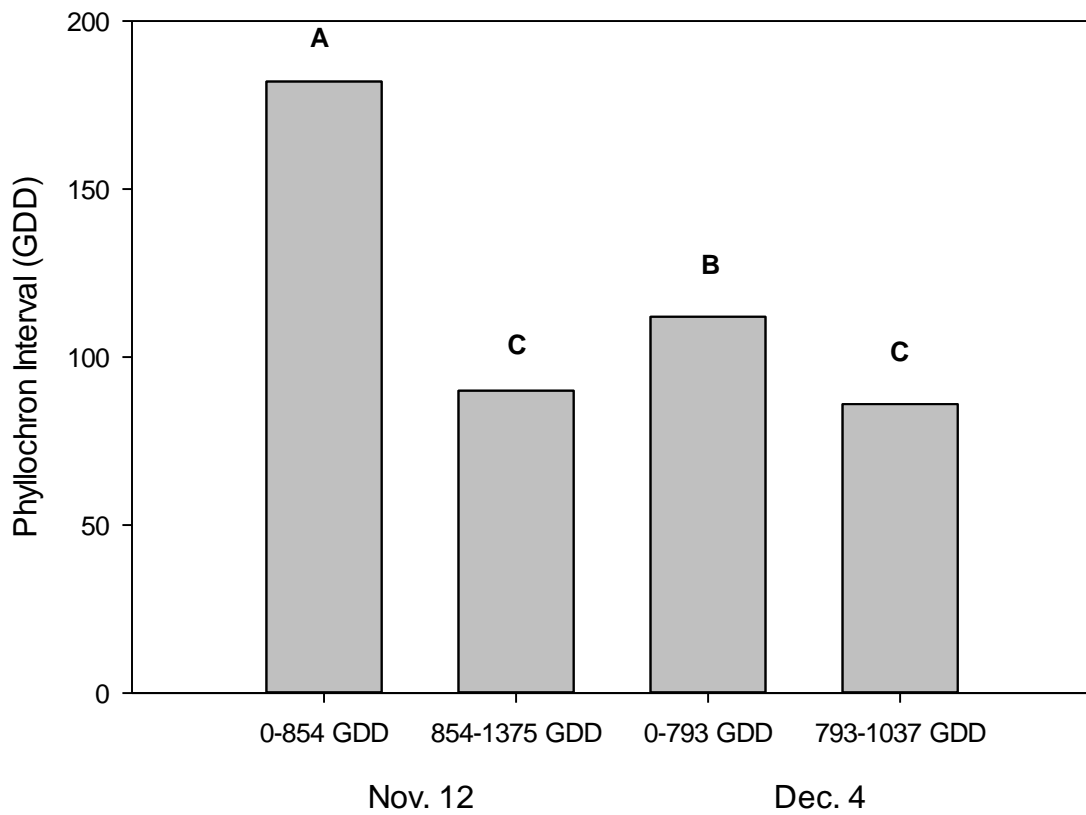


Figure 1.2: Phyllochron interval response to planting date at Hertford, in 2012-13. Differing letters represent LSD at  $p < 0.05$ .

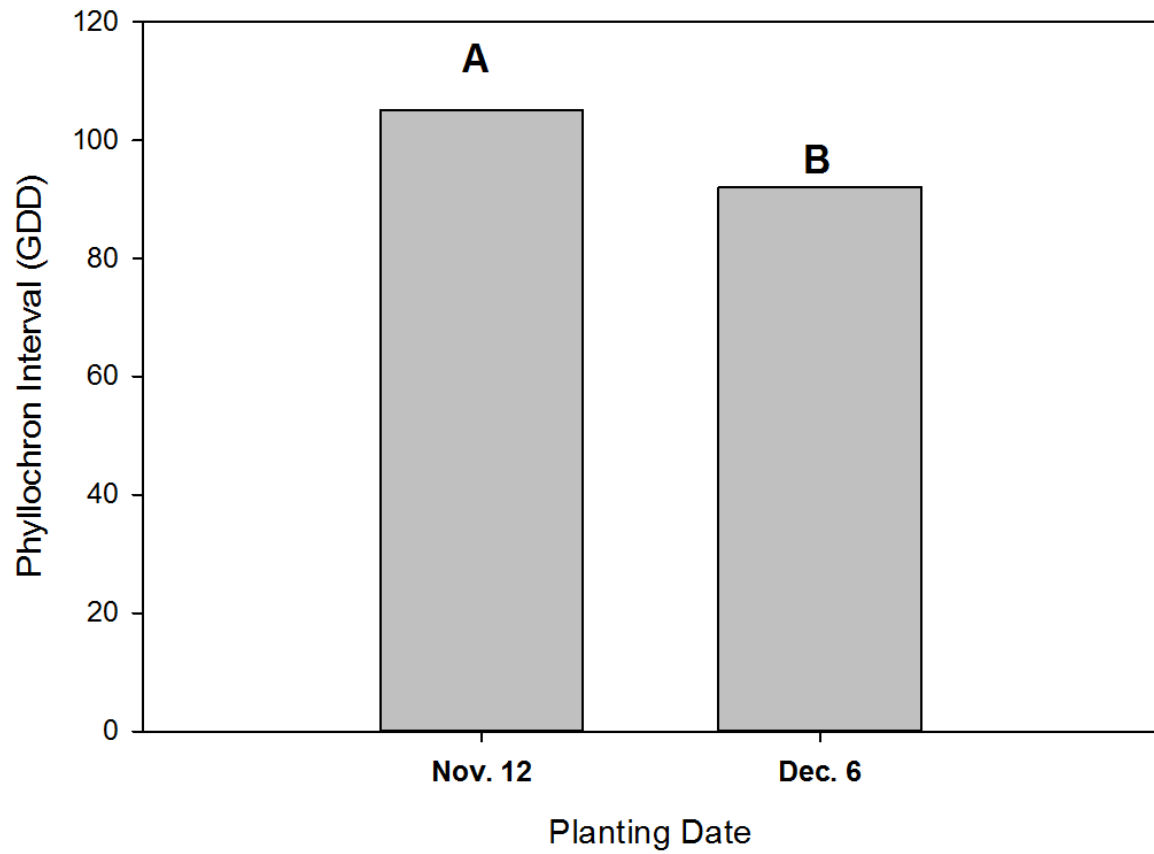


Figure 1.3: Phyllochron interval response to planting date at Tidewater Research Station in 2013-14. Differing letters represent LSD at  $p < 0.05$ .



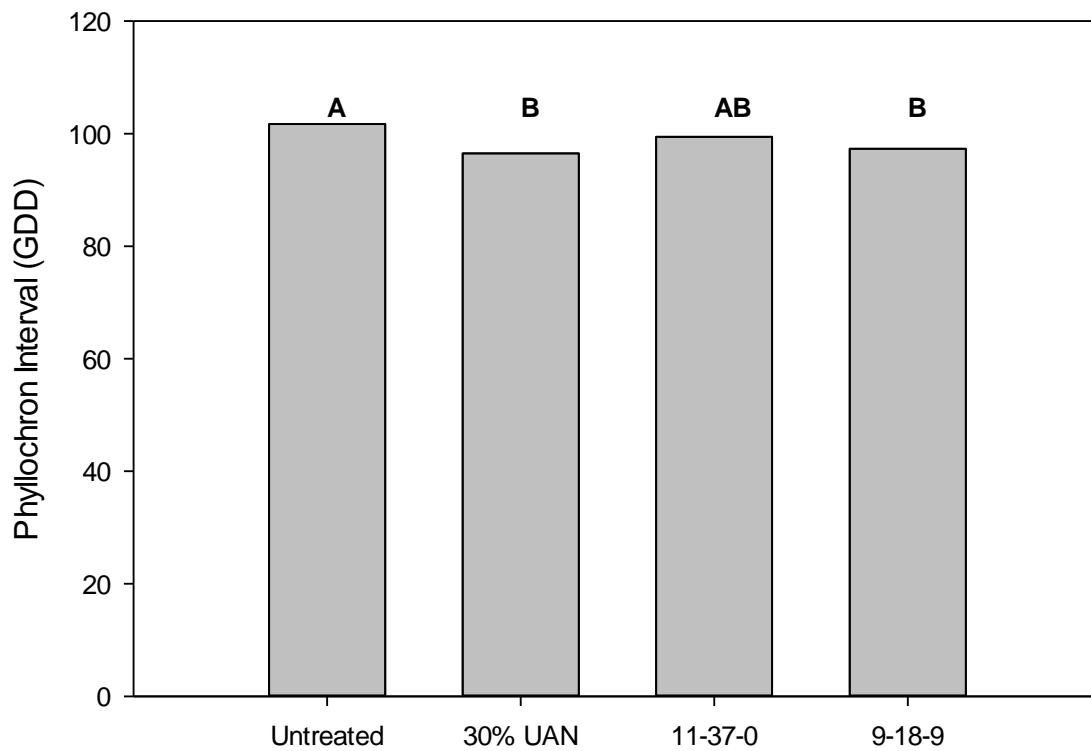


Figure 1.4: Phyllochron interval response to fertilizer at Tidewater Research Station in 2013-14. Differing letters represent LSD at  $p < 0.05$ .

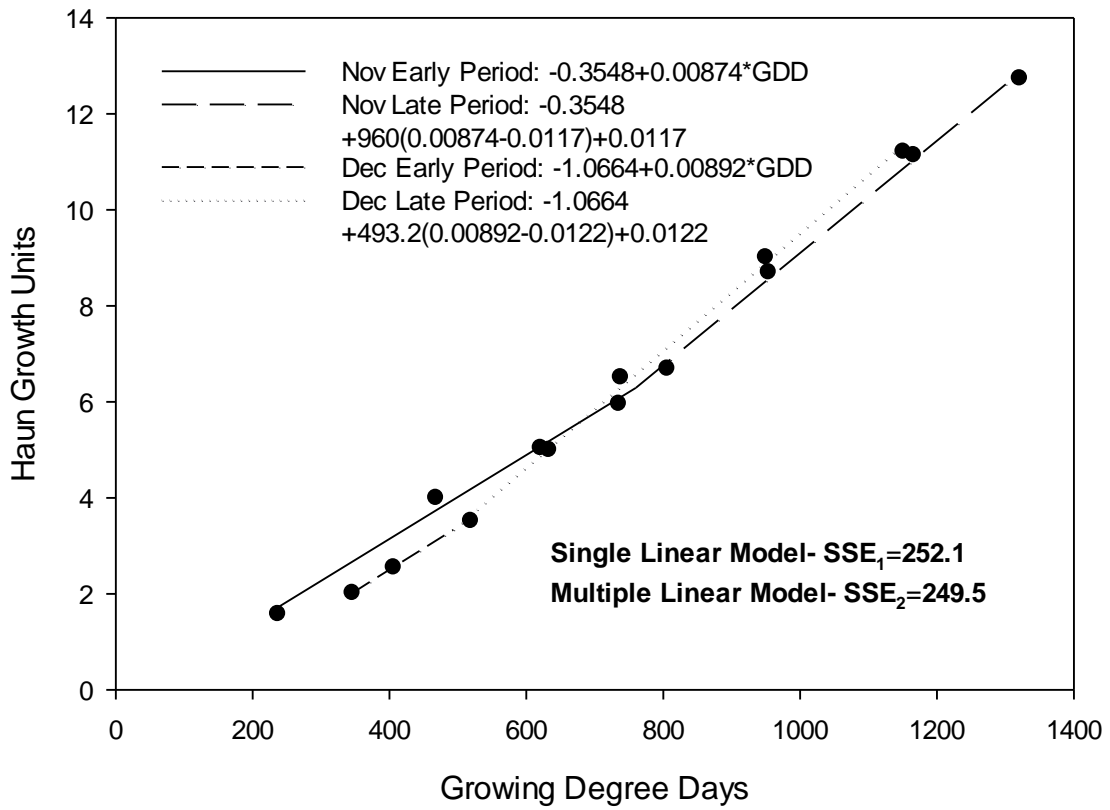


Figure 1.5: Relationship between Haun growth stage and accumulated GDD at Chowan in 2013-14.

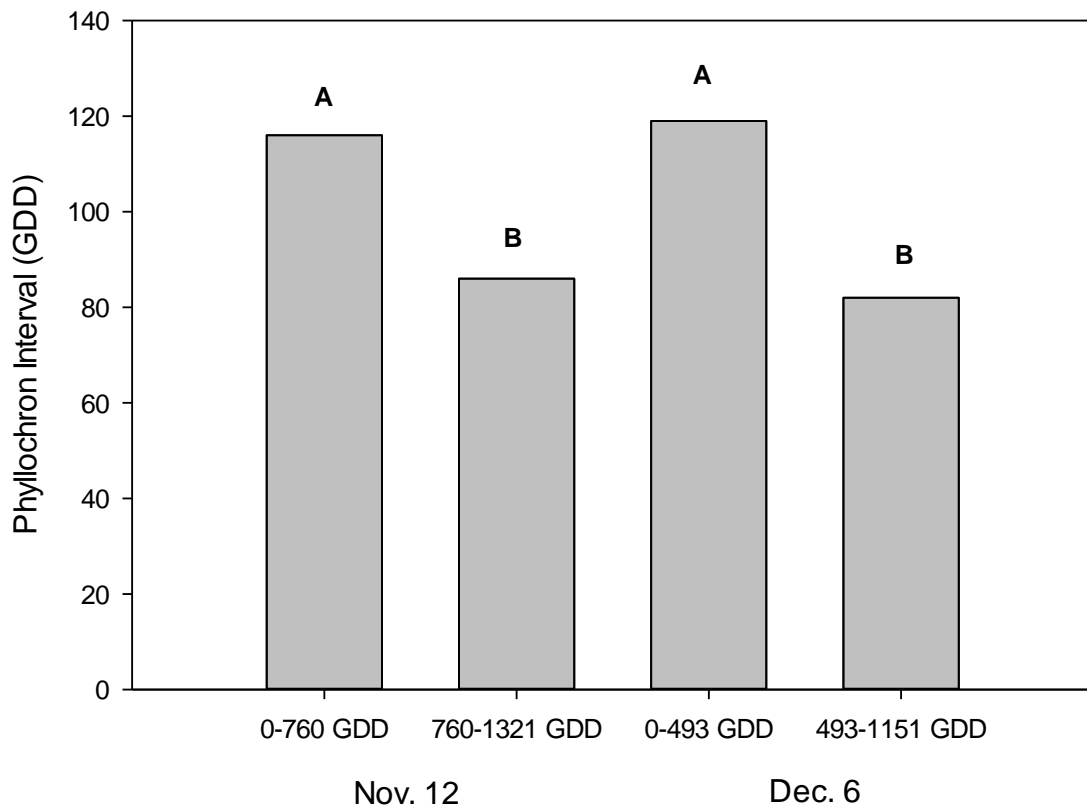


Figure 1.6: Phyllochron interval response to planting date at Chowan in 2013-14. Differing letters represent LSD at  $p < 0.05$ .

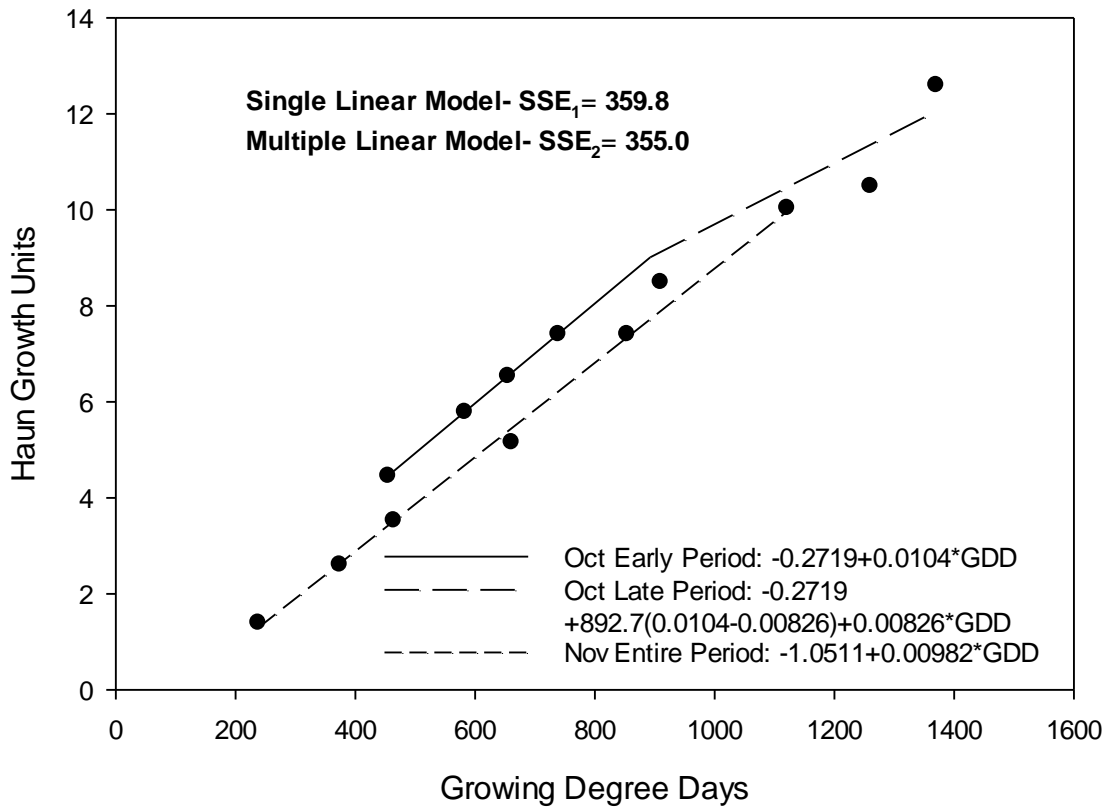


Figure 1.7: Relationship between Haun growth stage and accumulated GDD at Piedmont Research Station in 2013-14.

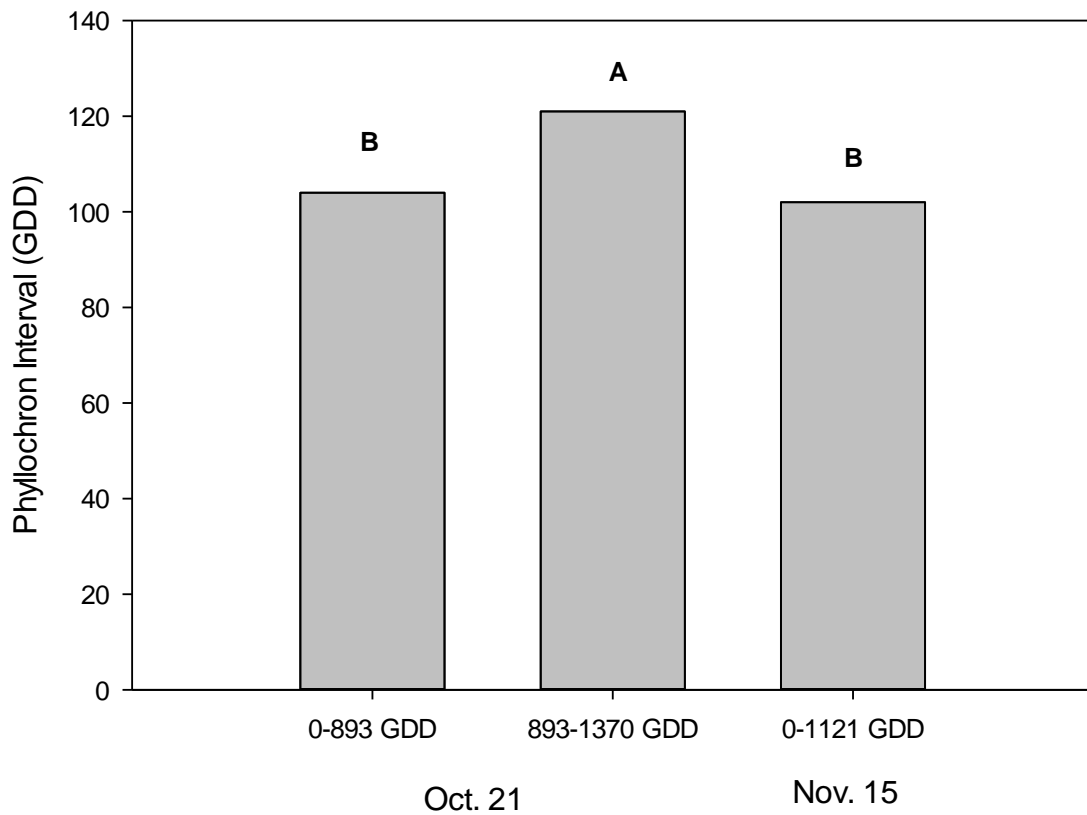


Figure 1.8: Phyllochron interval response to planting date at Piedmont Research Station in 2013-14. Differing letters represent LSD at  $p < 0.05$ .

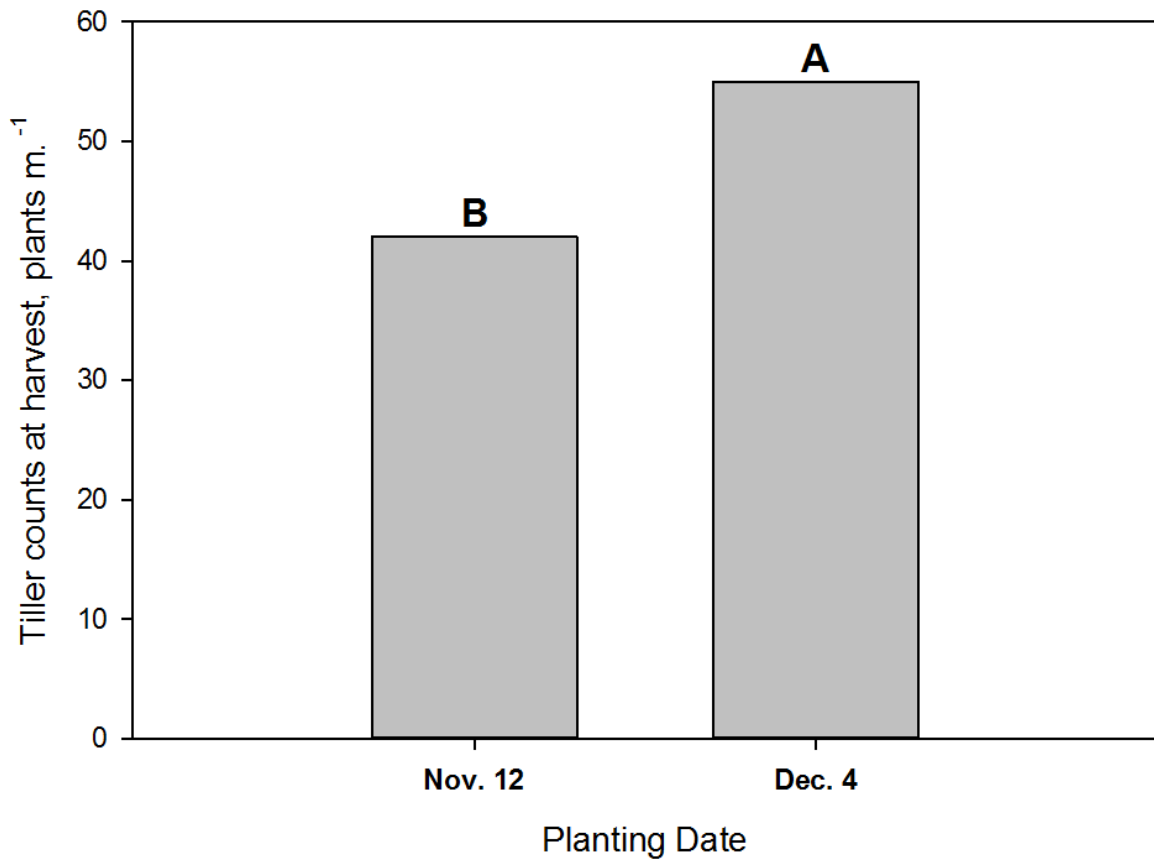


Figure 1.9: Tiller response to planting date at Hertford in 2012-13. Differing letters represent LSD at  $p < 0.05$ .

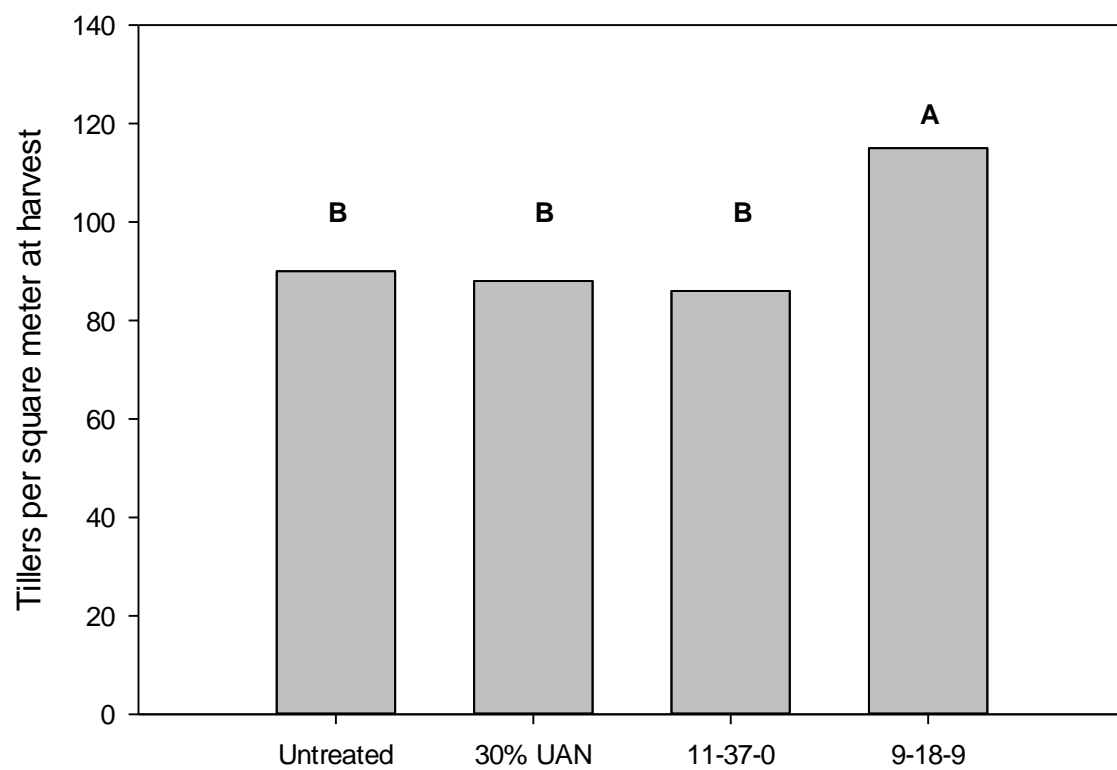


Figure 1.10: Tiller response to fertilizer at Hertford in 2012-13. Differing letters represent LSD at  $p < 0.05$ .

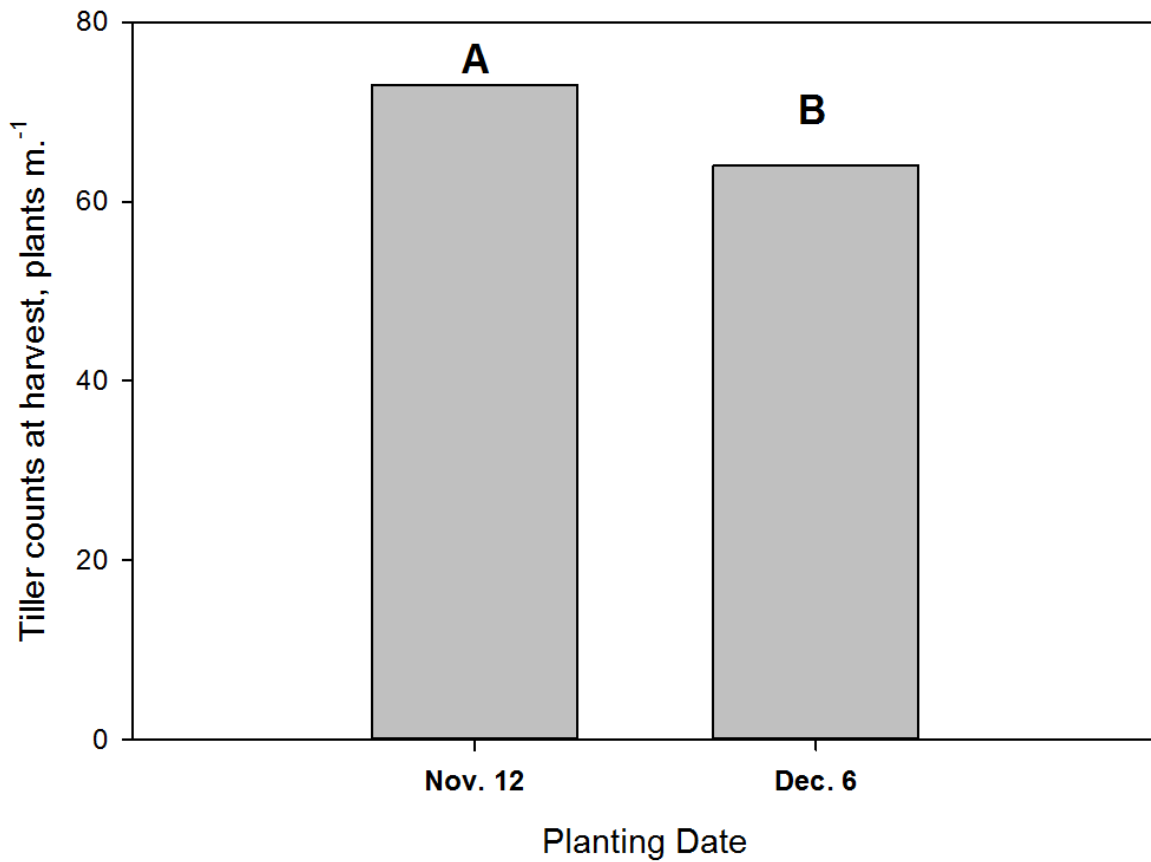


Figure 1.11: Tiller response to planting date at Tidewater Research Station 2013-14. Differing letters represent LSD at  $p < 0.05$ .



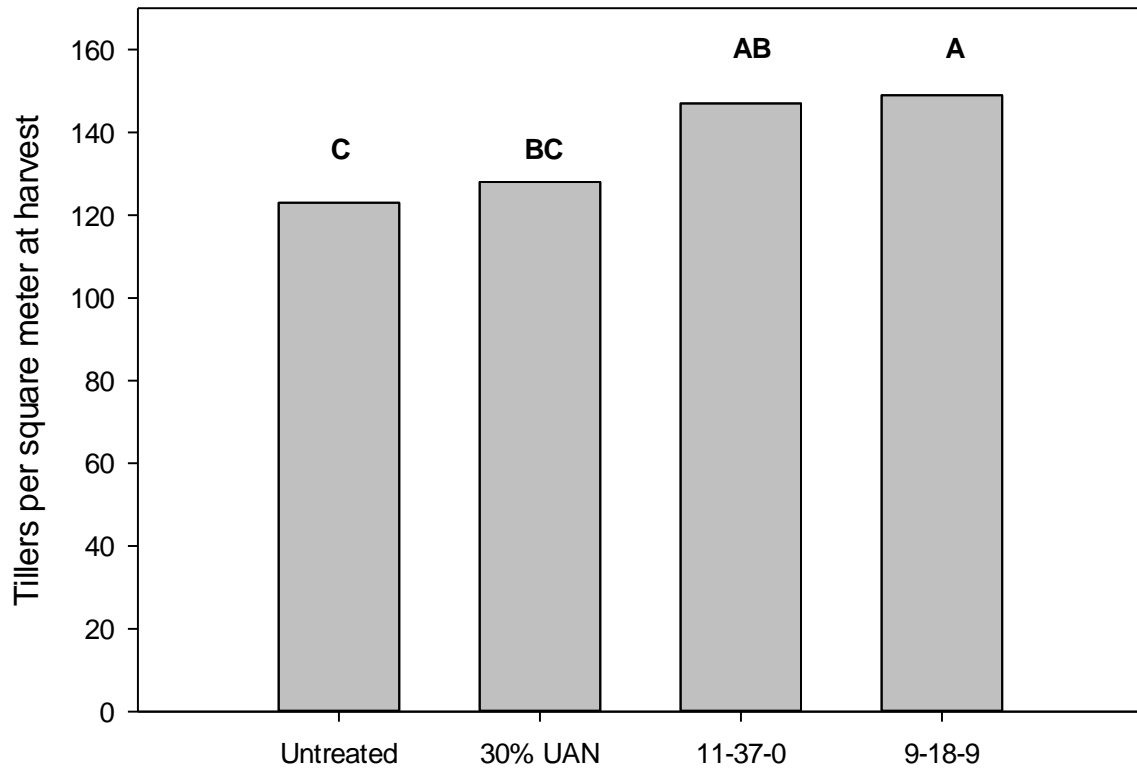


Figure 1.12: Tiller response to fertilizer at Tidewater Research Station in 2013-14. Differing letters represent LSD at  $p < 0.05$ .

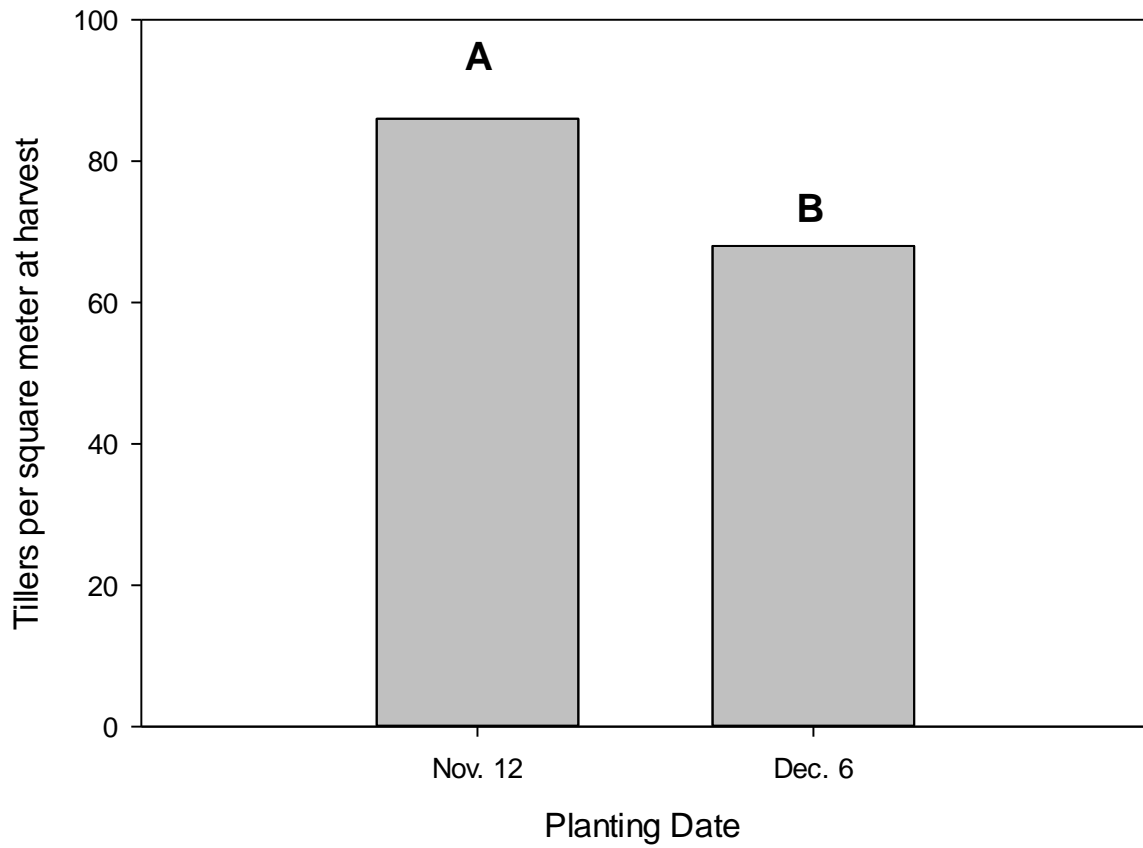


Figure 1.13: Tiller response to planting date at Chowan in 2013-14. Differing letters represent LSD at  $p < 0.05$ .

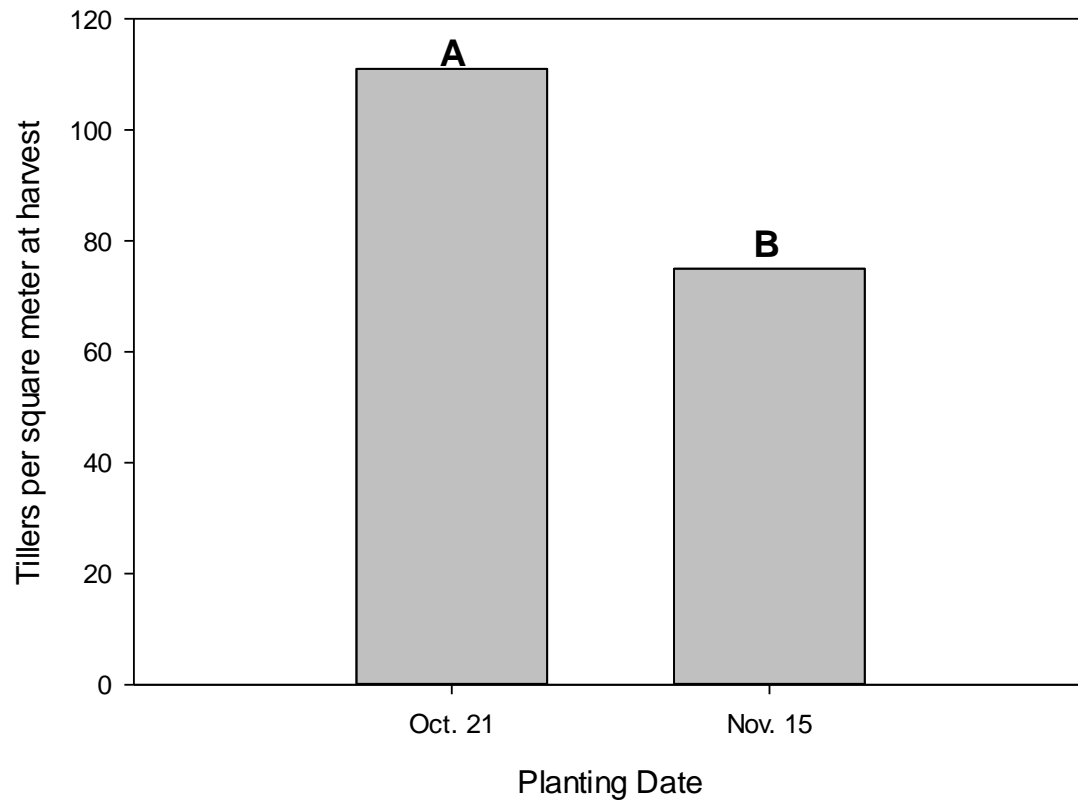


Figure 1.14: Tiller response to planting date at Piedmont Research Station in 2013-14. Differing letters represent LSD at  $p < 0.05$ .

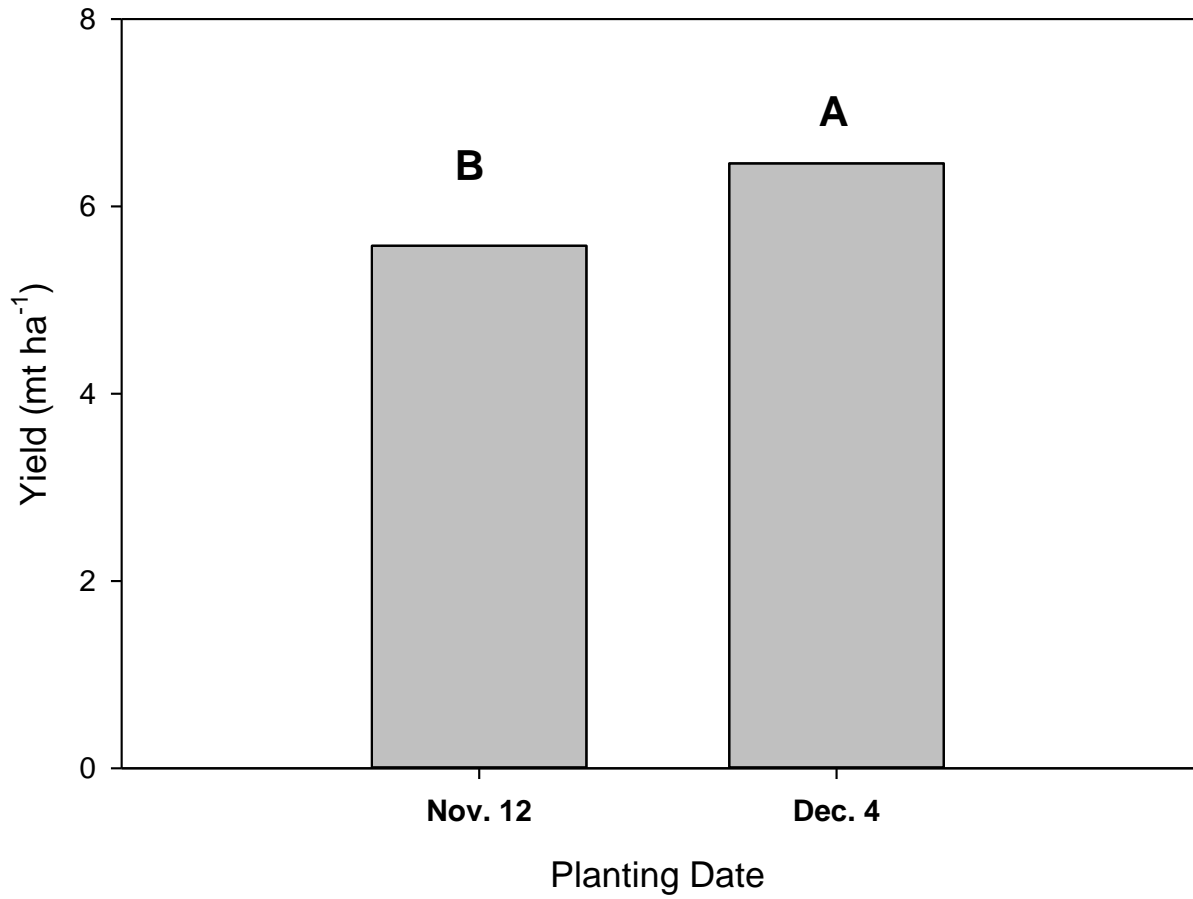


Figure 1.15: Grain yield response to planting date at Hertford in 2012-13. Differing letters represent LSD at  $p < 0.05$ .

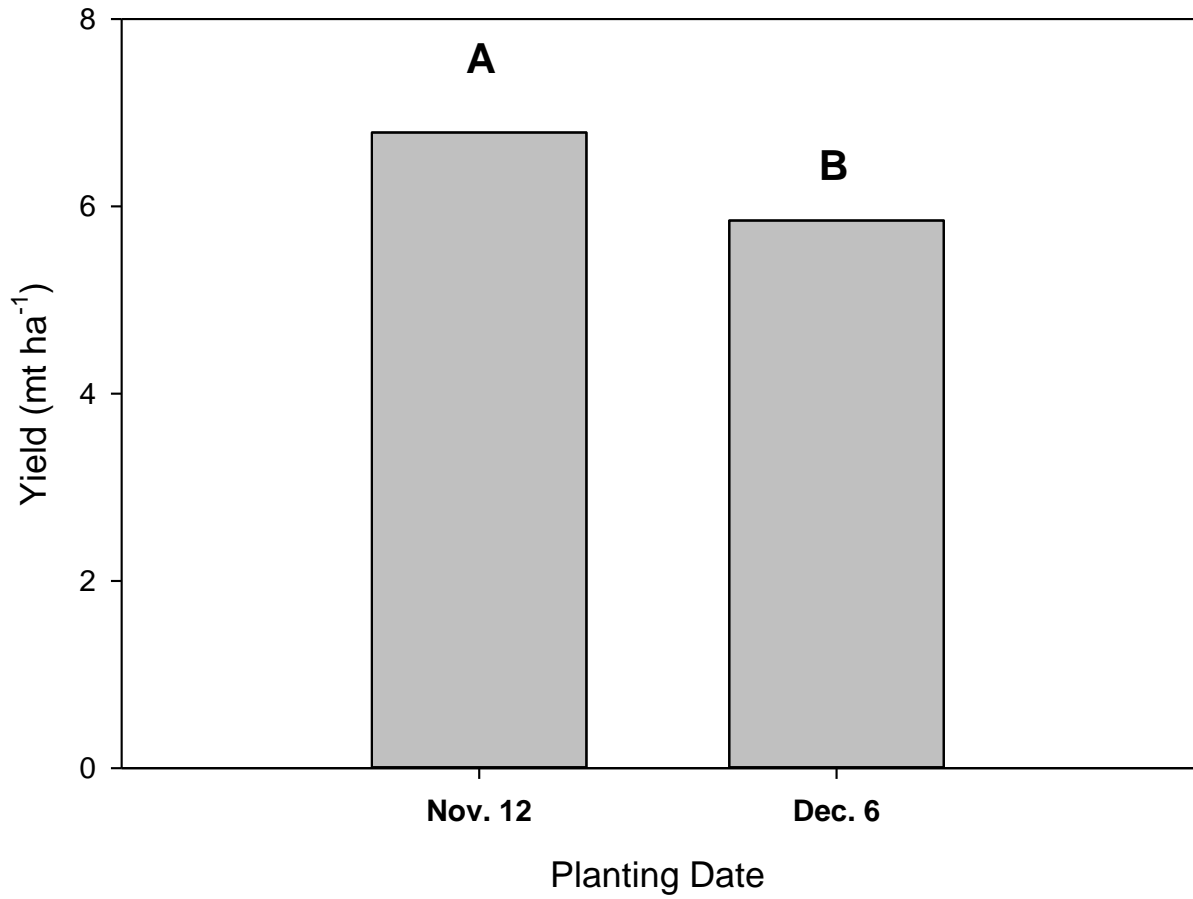


Figure 1.16: Grain yield response to planting date at Tidewater Research Station in 2013-14. Differing letters represent LSD at  $p < 0.05$ .

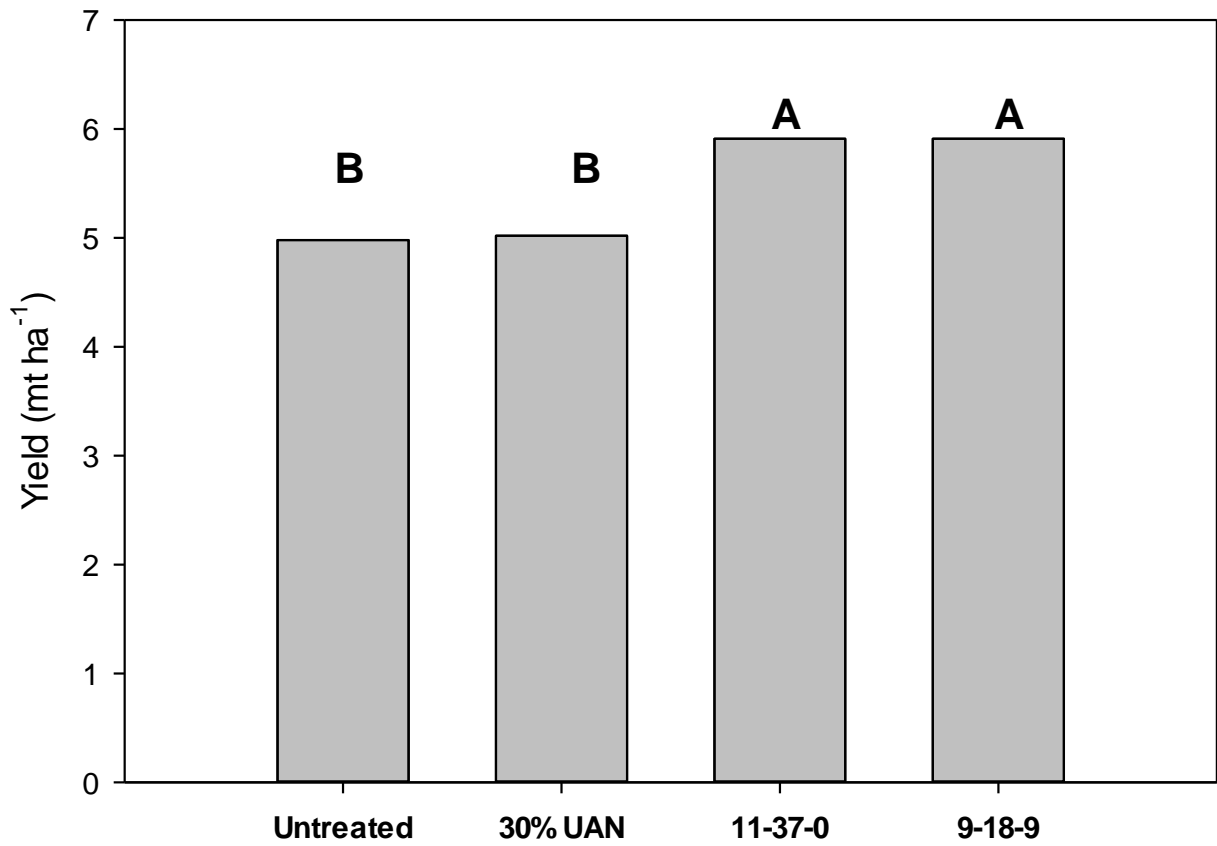


Figure 1.17: Grain yield response to fertilizer at Tidewater Research Station in 2013-14. Differing letters represent LSD at  $p < 0.05$ .

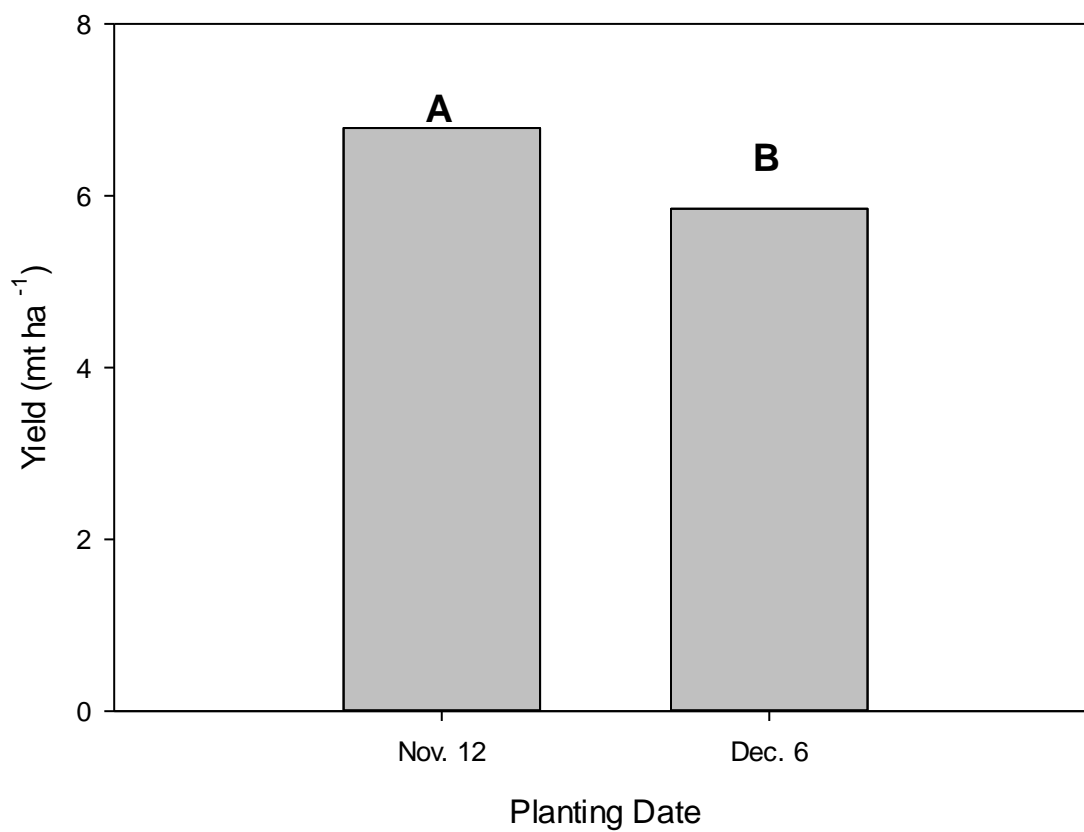


Figure 1.18: Grain yield response to planting date at Chowan in 2013-14. Differing letters represent LSD at  $P < 0.05$ .

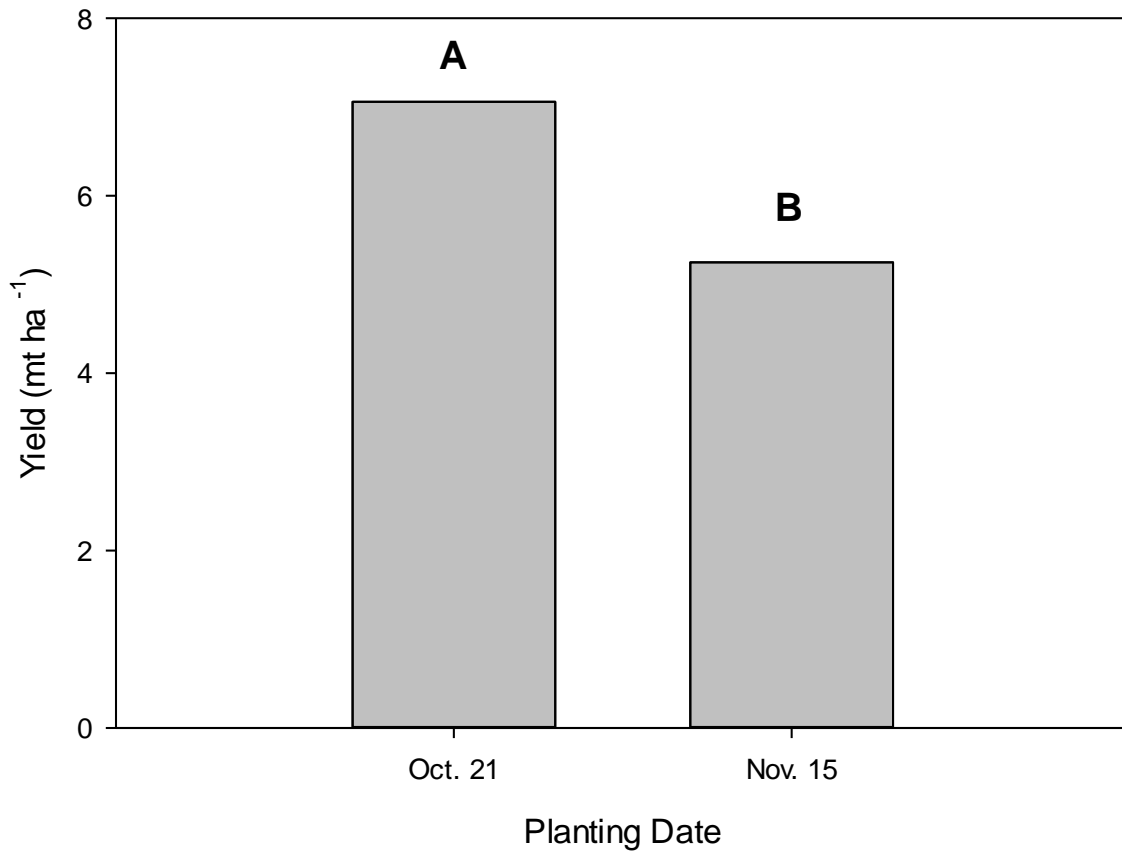


Figure 1.19: Grain yield response to planting date at Piedmont Research Station in 2013-14. Differing letters represent LSD at P < 0.05.



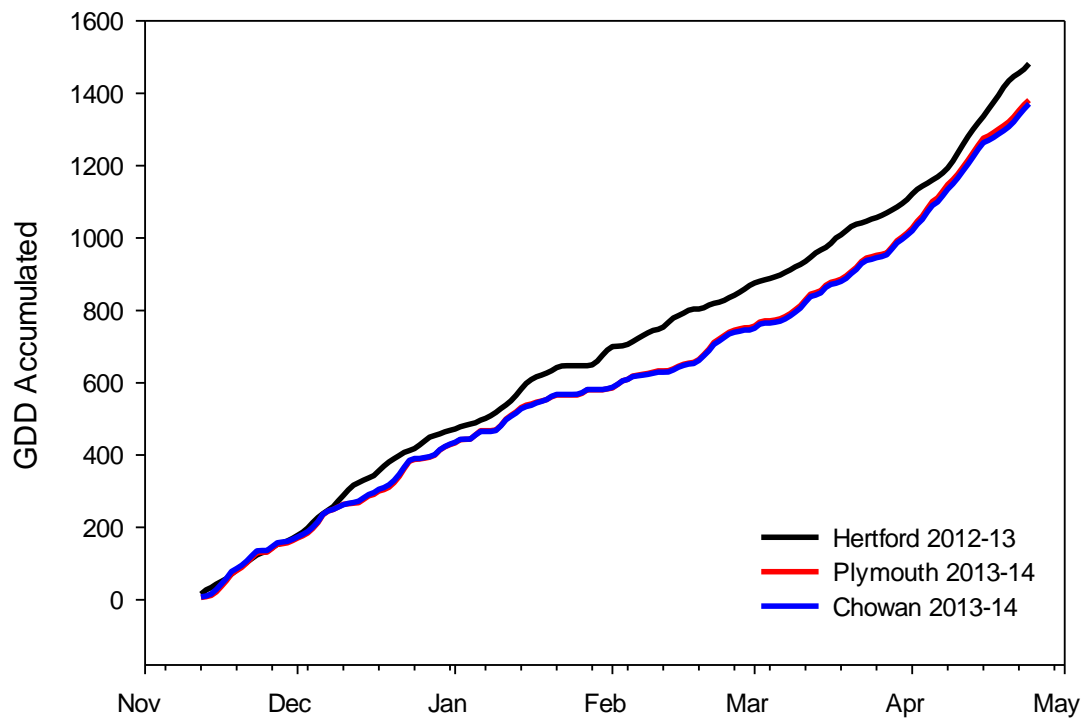


Figure 1.20: Total GDD accumulation since planting at three locations in two different growing seasons.

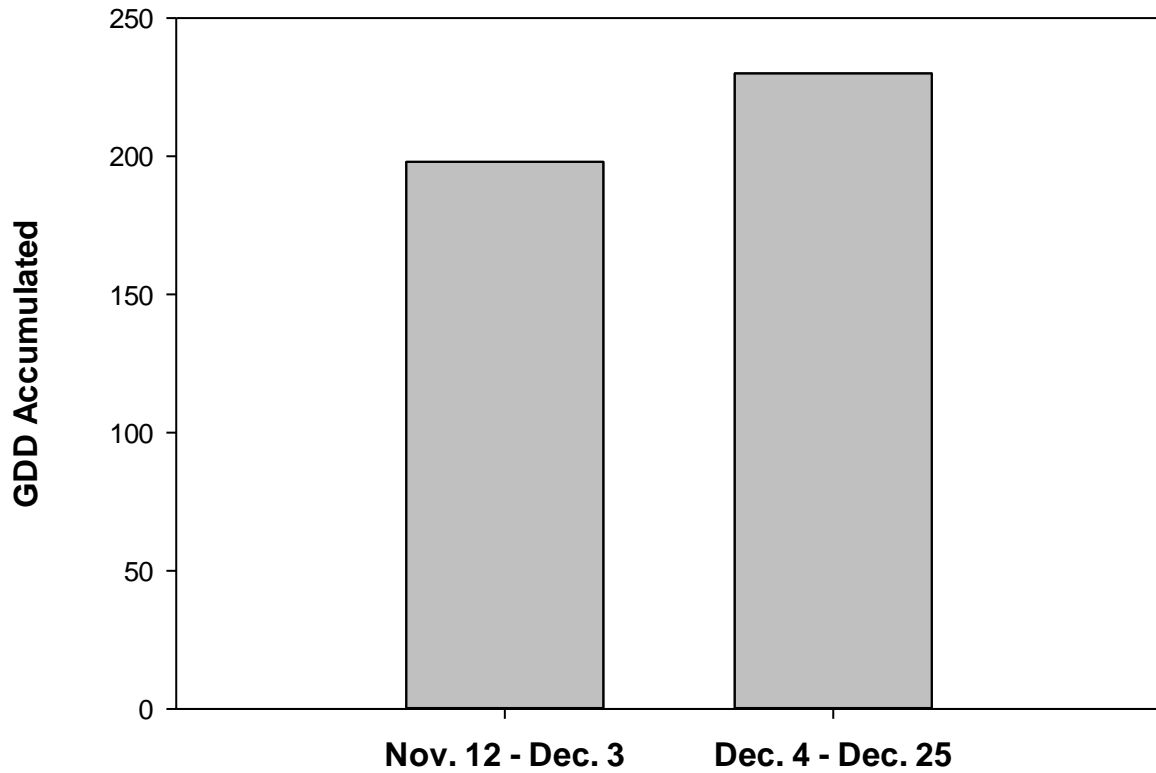


Figure 1.21: Total GDD accumulated the first 21 days after each planting date (11/12 & 12/4) at Hertford in 2012-13.

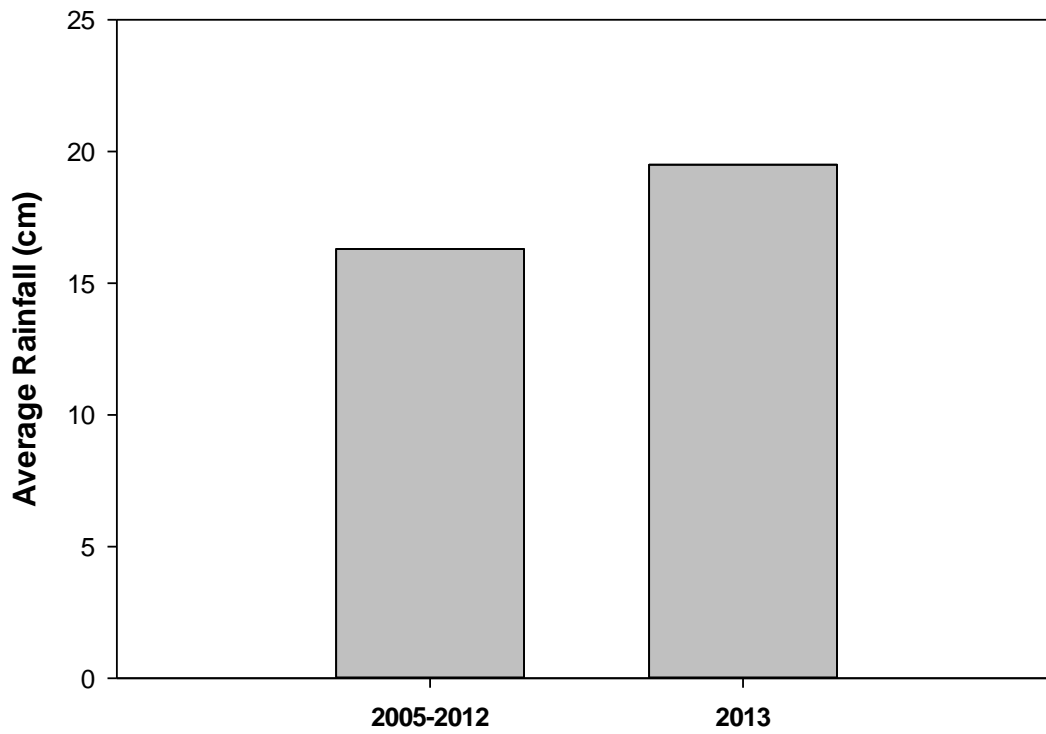


Figure 1.22: Average rainfall in November and December from 2005-2012 compared to 2013 at Plymouth, NC.

## CHAPTER TWO

### Kernel Development in Wheat

JOSEPH C. OAKES and RONNIE W. HEINIGER

#### ABSTRACT

Kernel weight and test weight are two important components of wheat (*Triticum aestivum* L.) yield and quality. However, little research has been done in North Carolina to quantify kernel development in response to environmental conditions and management conditions. Therefore, this study was conducted to examine how factors such as plant density, light interception, fungicide, and nitrogen influence kernel development during the grain fill period and its impact on grain yield. Field research was conducted at seven locations from 2011-2014 to investigate these factors. The shaded treatment had the lowest rate of grain fill at each location ( $0.0604 \text{ mg GDD}^{-1}$ ); however, there was no consistent difference among the untreated control, fungicide, nitrogen, and low seeding rate treatments. The low rate of grain fill resulted in the shade treatment having either the lowest yield across all locations ( $5.18 \text{ mt ha}^{-1}$ ). The impact of the shade indicates the importance of proper light interception during the grain fill period. When light interception or green leaf area is reduced, both the rate of grain fill and the yield are severely reduced. Therefore, anything that reduces light interception during the grain fill period, such as disease or early senescence, will result in a yield reduction. While a fungicide application at GS 70 did not show a significant increase in the rate of grain fill or yield, it may be beneficial when there is intense disease pressure which will inhibit light interception during the grain fill period.

## **INTRODUCTION**

Grain growth in wheat (*Triticum aestivum*) follows an overall sigmoidal pattern (Wiegand and Cuellar, 1981) and can be characterized by three different stages: a lag phase, a linear phase, and a tailing-off phase (Hunt et al., 1991). The linear grain filling phase begins a few days after anthesis and lasts until grain fill is nearly complete (Bingham, 1967). This linear phase in grain growth is characterized by two parameters: the rate and duration of grain fill (Hunt et al., 1991). In turn, these two parameters have a direct impact on final grain weight (Evans and Wardlaw, 1976), and ultimately yield. Sofield et al. (1977) found that a reduction of the duration of grain growth imposed a major limitation on wheat yields. Environmental and management factors such as temperature, light interception, and nitrogen (N) or fungicide application have the potential to influence the rate and duration of grain fill. To achieve higher wheat yield a thorough understanding of how these factors impact grain fill is required.

### **Temperature**

One of the most important environmental factors affecting plant growth and development is temperature (Grass and Burris, 1995). Several studies have shown temperature has an impact on the linear grain filling period. While an increase in post anthesis air temperatures causes a moderate increase in the rate of grain growth (Chowbury and Wardlaw, 1978), many studies have shown that increased temperatures have a negative impact on yield (Grass and Burris, 1995; Woodruff and Tonks, 1983)

Optimum development temperature in wheat is 15°C (Chowbury and Wardlaw, 1978). Nevertheless, in many of the wheat-producing regions of the world, temperatures

exceed this optimum during part of the growing season and reduce grain yield and quality (Grass and Burris, 1995). Banowitz et al. (1999) performed a post anthesis (1-7 days) treatment at a day/night temperature of 35/25°C, which reduced kernel weight and number on the primary spike. At 12 days after anthesis, kernel weight was reduced by 23% in the treated plants. While genotypic differences in heat tolerance exist, temperatures greater than 15°C reduce yield by 3-4% per degree (Woodruff and Tonks, 1983).

Grass and Burris (1995) examined the effect of heat stress on durum wheat and found that regardless of cultivar differences, seeds maturing under temperatures 8 to 16°C higher weighed less than those produced under cooler conditions. Hunt et al. (1991) also found that wheat plants exposed to high temperatures shortly after anthesis produced smaller kernels. Seed width was reduced in the warmer conditions, as well (Grass and Burris, 1995). Leaf senescence and loss of green color in flag leaves were also noted; and the authors concluded that leaf senescence caused a reduction in duration of the grain filling period. Similar results were noted by Tashiro and Wardlaw (1990). However, no effect was noted with 9°C higher temperatures beginning seven days after anthesis. In contrast, grain weight per spike was reduced by high temperature stress at all stages, and showed the greatest response 12-15 days after anthesis. The stage of grain development 7-12 days after anthesis was the most sensitive stage for grain weight (Tashiro and Wardlaw, 1990). This is the stage of rapid cell division and enlargement in the endosperm when the water content and length of grain increase rapidly.

Temperature strongly influences grain fill (Hunt et al., 1991). However, temperature has been shown to have the opposite effect on the duration of grain fill when compared to the

rate of grain growth. While an increase in temperature causes a moderate increase in the rate of grain growth, numerous studies have shown an inverse relationship between an increase in temperature and the duration of grain filling. Chowbury and Wardlaw (1978) found that there was an inverse relationship between temperatures over 15°C and the duration of grain fill. In phytotron experiments, Sofield et al. (1977) observed that a temperature increase during the grain fill period from 15/10°C day/night temperature to 30/25°C reduced grain fill duration from approximately 60 to 40 days. Meanwhile, Wiegand and Cuellar (1981) showed that for each degree Celsius increase in mean temperature, a 3.1 day decrease in the duration of grain fill occurred.

### **Light Interception**

The period following anthesis is critical to grain fill in terms of light interception (Jenner, 1979). Ford and Thorne (1976) observed the effects of light intensity on different times of growth in spring wheat in Great Britain. Light intensity treatments were applied both before and after anthesis. Differences in radiation imposed two weeks before anthesis did not affect grain yield (Ford and Thorne, 1976). Neither the supply of carbohydrate for grain filling nor the sink capacity was affected. However, differences in radiation after anthesis did affect grain yield, mainly through modification of carbohydrate availability for grain filling (Ford and Thorne, 1976). Ford and Thorne (1976) also noted that extra radiation did indeed increase growth in all parts of the plant including grain growth and final grain yield. Asana et al. (1969) observed similar results in response to shading. A shading treatment imposed fifteen days after anthesis was severe enough to cut down on the accumulation of kernel dry matter and reduce head weight by 30%. Shade treatments (Ford and Thorne, 1976) caused a

16% decrease in ear weight while grain growth was not affected after shading ceased. Jenner (1979) performed shade treatments where the wheat was subjected to brief periods of shading just after the ears showed the first signs of anthesis, and afterwards were grown to maturity in full illumination. Shading resulted in smaller grains, slower rates of accumulation of kernel dry matter, and ultimately lower final grain weight.

The effect of thinning was complimentary to that of shading (Fischer and Laing, 1976). While reducing irradiance lowered the accumulation of kernel dry matter per plant, thinning the crop increased it. In northwest Mexico, thinning the crop at, or soon after, anthesis increased stem weight during the first half of the grain filling period, and increased grain growth rate during the latter half (Fischer and Laing, 1976). Thinning largely relieved the competition for light, thereby increasing photosynthesis levels in plants remaining. As was the case with shading, the effect of thinning again depended on when the treatment was applied.

### **Fungicide**

Fungicides may impact grain fill by helping to maintain green leaf area and, potentially, increase seed weight. In Western Europe, improved disease control has accounted for yield increases by increasing the duration of the grain fill period (de Wit, 1977). Gooding et al. (2000) showed that when fungicides delay senescence, the rate of grain fill increases. Fungicides applied at flag leaf and ear emergence increased mean grain weight 15% for every day that they delayed senescence of the flag leaf (Gooding et al., 1994). However, extending green leaf life does not always increase grain size. Davies et al. (1984) observed that substantial gains were made in green flag leaf area duration through fungicide



use; however, there was no parallel gain in yield. Bimmock and Gooding (2002) sought to determine whether fungicides with different modes of action affected grain fill, and whether that effect depended on when senescence occurred relative to the time of grain filling. Their results demonstrated that fungicide treatments often increased the duration of the grain fill period, while the effect on the rate of the grain fill period was small and inconsistent.

Bimmock and Gooding (2002) noted that the relationships between the effects of fungicides on green flag leaf area duration, yield, and grain-filling did not vary substantially between a triazole and a mitochondrial respiration inhibition (MRI) fungicide. However, commercially recommended rates of MRI-containing herbicides did produce larger yields than did equivalent rates of flusilazole. Overall, Bimmock and Gooding (2002) found that grain-filling rates varied according to cultivar and ear position by inconsistent amounts, but significant gains from fungicide treatments were made in grain-filling periods.

### **Nitrogen**

As with fungicides, N has the potential to impact grain fill by maintaining plant nutrition and health and therefore increasing seed weight. Proper management of N is important to ensure that it is available throughout the growing season due to its important role in enhancing vegetative and reproductive development (Frederick and Camberato, 1994). Drought stress, along with other environmental factors, may influence the amount of N utilized by winter wheat. It is already known that application of N to wheat may promote tiller production and survival (Davidson and Chevalier, 1990), as well as increasing kernel numbers per head (Frederick and Camberato, 1994). Research outside the southeastern coastal plain has shown that N has a similar impact to fungicides on grain fill. Simmons

(1987) found applied N delayed leaf senescence, sustained leaf photosynthesis during the grain fill period, and extended the duration of grain fill. Under non-stressed conditions, maintaining high leaf N concentrations during grain fill should increase photosynthate production and final kernel weight (Frederick and Camberato, 1994), which explains why high wheat yields are often associated with extended leaf area duration.

Frederick and Camberato (1995) examined N in relation to drought in South Carolina, and observed that drought stress during pre-anthesis head development can diminish the positive effects of N on kernel number per head. High N fertility can actually exacerbate the severity of drought stress by increasing leaf area indices and the rate of soil water depletion (Frederick and Camberato, 1994). Higher spring N rates combined with irrigation resulted in kernel-weight increases and an extended effective fill period, when compared to lower N rates. These results indicate that soil water must be readily available for spring-applied N to have a positive effect on the effective fill period and individual kernel weight. While irrigation and high spring N applications were successful in extending the duration of grain fill, it was not successful in increasing the rate of grain fill.

The research into the effects of these factors shows how influential they can be both pre and post anthesis. However, the nature of many of these studies required them to be performed in climate-controlled environments. Consequently, many of the field studies were examined in Europe and Australia. Spring wheat rather than winter was also examined in many studies. Therefore, more work is needed on winter wheat in North Carolina to quantify the response of kernel weight to growing conditions during the grain fill period, and to determine how kernel weight is impacted by temperature, light interception, and N

management. Maximizing kernel growth is important in North Carolina due to the possibility for hot and dry conditions in May, which can reduce the grain fill period and ultimately yields. The purpose of this study is to improve understanding of the environmental and management factors that influence the rate and duration of the grain fill period in wheat by examining the influence of plant density, light interception, fungicide, and nitrogen on kernel growth and yield.

## **MATERIALS AND METHODS**

### **Field Experiment**

Research was conducted at five locations in North Carolina to correspond with three major wheat-producing regions of the state: tidewater, coastal plain, and piedmont. In the 2011-12 growing season research was conducted at the Tidewater Research Station (TRS) in Plymouth (Portsmouth fine sandy loam- fine loamy over sandy or sandy skeletal, mixed, semiactive, thermic Typic Umbraquults). During the 2012-13 growing season research was conducted at TRS, the Piedmont Research Station (PRS) in Salisbury (Lloyd clay loam- fine kaolinitic Rhodic Kanhapludults), and at a private farm location in Perquimans County near Hertford (Roanoke silt loam- fine, mixed, semiactive, thermic Typic Endoaquults). In 2013-14, research was conducted at TRS, PRS, and at a private farm location in Chowan County (Altavista fine sandy loam- fine loamy, mixed, semiactive, thermic Aquic Hapludults). This resulted in seven site years of data.

The cultivar ‘Dyna-Gro Shirley’ was planted at each location on 16.9 cm rows, with individual plots being 13.72 m by 1.83 m. Plots were planted in a conventionally-tilled field at each location except PRS, which was planted into no-till corn stubble. Plots were arranged

in a randomized complete block design with six treatments per block and four blocks.

Treatment One represented the untreated control with a standard seeding rate of 82 seeds per meter row. In the second treatment the fungicide Quilt (Azoxystrobin, Propiconazole) was applied at a rate of 1023.09 ml ha<sup>-1</sup> at GS70 (the end of anthesis). Treatment Three consisted of applying 11.21 kg N ha<sup>-1</sup> at GS&). Shading which blocked 50% of incident radiation was applied over plots from GS70 to maturity in Treatment Four. The final two treatments examined the effect of seeding rate on kernel weight. Treatment Five was a low seeding rate of 33 seeds per meter row, while Treatment Six was a high seeding rate of 115 seeds per meter row. To maintain these additional plants from GS30 to maturity an additional 67.26 kg N ha<sup>-1</sup> was applied split to Treatment Six in late Dec or early Jan. At TRS 2011, additional N was applied during the last week of December. In 2012, the additional N was applied on 11 Jan at TRS and Hertford, and on 12 Dec at PRS. In 2013, the additional N was applied on 20 Jan at TRS and Chowan and on 6 Dec at PRS.

Plots were planted on dates considered to be a normal planting date for each location. In 2011 at TRS, plots were planted on 9 Nov. In 2012, plots were planted on 14 Nov at TRS, on 12 Nov at Perquimans County, and on 19 Oct at PRS. In 2013, plots were planted on 11 Nov at TRS and Chowan, and on 21 October at PRS. All plots except Treatment Five received 93.54 L ha<sup>-1</sup> 11-37-0 at planting. At PRS, both Paraquat dichloride and Chlorsulfuron/Flucarbazone-sodium were applied pre-emerge at planting for weed control. Nitrogen was applied at jointing at each location, and rates were adjusted based on previous starter and N applications so that all plots received a total of 134.52 kg N ha<sup>-1</sup>. Top dress N applications were made on 12 March in 2012. In 2013, N applications were made on 20 Mar

at TRS and Hertford and on 11 Mar at PRS. In 2014, N applications were made on 10 Mar at TRS and Chowan and on 13 Mar at PRS.

Beginning at GS70 whole plant samples consisting of thirty plants per plot were collected at weekly intervals from GS70 to maturity. In all, this consisted of five to six sampling dates depending on location. Samples at TRS in 2012 were collected on 30 Apr, 7 May, 14 May, 21 May, and 29 May. At TRS and Hertford in 2013, samples were on 13 May, 20 May, 28 May, 4 June, and 10 June. Samples at PRS in 2013 were collected on 14 May, 21 May, 29 May, 5 June, and 11 June. In 2014, samples were collected on 14 May, 19 May, 27 May, 2 June, and 9 June at TRS and Chowan. Meanwhile, samples at PRS were collected on 20 May, 23 May, 28 May, 4 June, and 16 June. Samples were removed from a section of each plot that was not harvested and grain yield was not measured. Plant samples were dried and weighed, and the heads were separated from the plants. Heads were threshed and kernels from these threshed heads were counted and weighed. Whole plant weight, head weight, kernel number, and individual kernel weight were measured and recorded. Individual kernel weights were calculated by dividing the total kernel weight by the total number of kernels collected. Plots were harvested in mid-June at each location with a Gleaner K2 combine equipped with a Harvestmaster GrainGage to record moisture, grain weight, and test weight. Grain weight was standardized to 13.5% moisture before calculating yield.

### **Statistical Procedure**

Changes in individual kernel weight were used to calculate the rate and duration of the grain fill period. The rate of the grain fill period was calculated by dividing the change in kernel weight by the change in GDD over the entire grain fill period, while the duration of

the grain fill period was calculated by subtracting the number of GDD at the beginning of the grain fill period from the number of GDD at the end of the grain fill period. The start of the grain fill period was characterized as GS70, while the end of the grain fill period was calculated as 95% of the maximum kernel weight (Heiniger et al., 1993). GDD was calculated from the daily maximum and minimum temperatures as indicated in the following formula:

$$Tu=[(Tmax+Tmin)/2]-Tb,$$

where Tu is daily thermal units (GDD), Tmax is the daily maximum temperature, and Tmin is the daily minimum temperature (Baker et al., 1986). In this study the base temperature (Tb) was 0°C.

Due to differences in sampling dates among years and locations, the kernel weight data could not be analyzed across locations. The PROC GLM procedure in SAS (SAS Institute, 2010) was used to determine if there were differences in rate and duration of grain fill among treatments. When differences were detected, Fisher's Protected LSD was used to separate the means. In order to determine differences in kernel weight among sampling periods, the compound symmetry covariance function in PROC Mixed was used to account for differences in variance among sampling periods.

## **RESULTS AND DISCUSSION**

### **Kernel Weight**

At TRS in 2012, no differences were observed in kernel weight at the first sampling date (Figure 2.1). However, at the next three sampling dates, the shaded treatment had significantly lower kernel weights compared to the remaining treatments. Meanwhile, at the

final sampling date, the low seeding rate had the highest kernel weight. The untreated control, nitrogen, and fungicide treatments had the second-highest kernel weights which were all significantly greater than the high seeding rate and the shaded treatment. Again, the shaded treatment had the lowest kernel weight.

At TRS in 2013, differences in kernel weights among treatments were observed at each sampling date. At the first sampling date, the high seeding rate had the highest kernel weight compared to the remaining treatments, but was not significantly different from the untreated control (Figure 2.2). Both the low seeding rate and the shaded treatment had the lowest kernel weight with no significant difference between the two. The high seeding rate had the highest kernel weight at the second sampling date, while the shaded treatment had the lowest kernel weight. There was no difference between the untreated control, nitrogen, fungicide, and the low seeding rate. At the third sampling date, again the high seeding rate had the highest kernel weight. None of the remaining treatments were significantly different from the untreated control. At the fourth sampling date, the high seeding rate had the highest kernel weight but was not significantly different from the untreated control, nitrogen, and fungicide treatments. Again the shaded treatment had the lowest kernel weight. At the final sampling date, no differences were observed among any of the treatments except the shaded treatment which had the lowest kernel weight.

In 2013 at Hertford, differences were observed starting at the second sampling date with the shaded treatment having the lowest kernel weight (Figure 2.3). No differences were observed among the untreated control, low seeding rate, high seeding rate, and nitrogen treatments. At the third sampling date, the high seeding rate had the highest kernel weight,

but was not significantly different from the untreated control or low seeding rate treatment. The shaded treatment had the lowest kernel weight. The only difference at the fourth sampling date was that the shaded treatment had a lower kernel weight than the high seeding rate. Meanwhile at the final sampling date, the shaded treatment had the lowest kernel weight but was only significantly lower than the low seeding rate, high seeding rate, and nitrogen treatments. No other treatment was significantly different from the untreated control.

At PRS in 2013 differences in kernel weight were observed starting at the second sampling date with the high seeding rate having the highest kernel weight and the shaded treatment having the lowest kernel weight (Figure 2.4). This same pattern was observed at the third and fourth sampling dates as well. At the final sampling date, no differences were observed among treatments except for the shaded treatment which had the lowest kernel weight.

In 2014 at TRS, the only difference observed at the first sampling date was that the low seeding had the lowest kernel weight (Figure 2.5). At the second sampling date, the low seeding rate and shade treatments had a significantly lower kernel weight than the high seeding rate, and at the third sampling date the shade and low seeding rate treatments were lower than the high seeding rate, nitrogen, fungicide, and untreated control. At the fourth sampling date, only the shade treatment was significantly lower than the high seeding rate. Meanwhile, no differences were observed among treatments at the last sampling date.

No differences among treatments for kernel weights were observed at the first sampling period at Chowan in 2014 (Figure 2.6). At the second sampling date, the low seeding rate had the lower kernel weight compared to the high seeding rate. There were no



other treatment differences at the second sampling date. At the third, fourth, and fifth sampling dates, the shaded treatment had the lowest kernel weight compared to the remaining treatments. However, no other treatment differences were observed at these final three sampling dates.

At PRS in 2014, there was not a date by treatment interaction as only the date and treatment main effects were significant. Kernel weights increased significantly among sampling dates. Among treatments, there were no differences between the untreated control, nitrogen, fungicide, and high seeding rate treatments (Figure 2.7). The low seeding rate treatment had the second lowest kernel weights, while the shaded treatment had the lowest kernel weights (Figure 2.7).

### **Rate and Duration of Grain Fill Period**

The rate and duration of grain fill was analyzed across the seven site-years. There were both significant location and treatment main effects for rate and duration, but there were no interactions for either rate or duration of grain fill (Table 2.2). Among locations, TRS in 2014 had the highest rate of grain fill ( $8.89 \text{ E}^{-5} \text{ g GDD}^{-1}$ ), but there was no significant difference between it and PRS in 2014 (Table 2.3). PRS in 2013 had the lowest rate of grain fill ( $5.98 \text{ E}^{-5} \text{ g GDD}^{-1}$ ), but it was not significantly different from TRS or Hertford in 2013 (Table 2.3). TRS in 2013 had the longest duration of grain fill (588 GDD), but was not significantly different from PRS in 2013 (Table 2.3). Both TRS and PRS in 2014 had the shortest duration of grain fill.

The shaded treatment had the lowest rate of grain fill among treatments ( $6.04 \text{ E}^{-5} \text{ g GDD}^{-1}$ ). The high seeding rate had the highest rate of grain fill, but it was not significantly

different from either the nitrogen or fungicide treatment (Table 2.4). There was little difference among treatments for the duration of grain fill as there were no significant differences among the untreated control, fungicide, shade, and low seeding rate treatments. Meanwhile, the high seeding rate had the shortest duration of grain fill (435 GDD).

### **Grain Yield**

Both grain yield and test weight were analyzed across the seven site-years (locations). There were only significant location and treatment main effects for grain yield (Table 2.5). However, there was a location by treatment interaction for test weight. The highest yielding site year was PRS in 2014 with an average yield of 7.33 mt ha<sup>-1</sup>, while TRS in 2013 had the lowest average yield of the seven site years (Figure 2.8). Among treatments, there was no difference among the untreated control, fungicide, nitrogen, and high seeding rate treatments (Figure 2.9). These four treatments were the highest yielding treatments, while the low seeding rate had the second lowest grain yield, and the shaded treatment had the lowest grain yield. There was a location by treatment interaction for test weight (Table 2.5). Differences in test weight among locations were observed at Hertford in 2013, PRS in 2013, and TRS in 2014. At each of these locations, the shaded treatment had the lowest test weight among the six treatments. No other treatment differences were observed at these locations.

### **Summary**

Among the six treatments, the shaded treatment had the lowest rate of grain fill. There were no consistent differences in the rate of grain fill among the untreated control, fungicide, nitrogen, and low seeding rate treatments. The shaded treatment was also the lowest yielding treatment (and had the lowest test weight) of the six treatments. This treatment indicates the

importance of proper light interception and leaf area during the grain fill period. Any type of leaf area loss, whether from disease or high temperatures, during the grain fill period which reduces light interception can result in severe yield reductions. Therefore, maintaining green leaf area for as long as possible during the grain filling period is crucial to obtaining high yields. Planting dates and cultivar maturities should be chosen to prevent the grain fill period from occurring after high summer temperatures begin. These high temperatures can cause wheat to turn brown and senesce prematurely, which will cause light interception to be reduced. While there was not a yield response to fungicide, a fungicide applied at GS70 may be necessary if there is intense disease pressure which could restrict light interception during the grain fill period.

Seeding rate also had an impact on yield at each site year. The low seeding rate had the second lowest yield, second only to the shaded treatment. There were instances at certain locations when the kernel weight of the low seeding rate was lower than the other treatments (particular the high seeding rate). The rate of grain fill for this treatment rarely differed from the remaining treatments, so it is not the cause of the reduced yield. The reduction in yield is due to the fact that the plants were unable to produce enough tillers to compensate for the low seeding rate and that kernel weights were lower on average. The remaining three treatments (fungicide, nitrogen, and high seeding rate) were not different from the untreated control in regards to yield.

The results from this study indicate the importance of maintaining green leaf area and light interception in order to foster proper grain fill. Therefore, anything that restricts leaf area and light interception will reduce the rate of grain fill and ultimately yield. Since the

addition of nitrogen or fungicide at GS70 did not increase the rate of grain fill or yield, it is only recommended to apply a fungicide when intense disease pressure is expected to green leaf area and light interception.

## REFERENCES

- Asana, R.D., Parvatikar, S.R., and Saxena, N.P. (1969). Studies in Physiological Analysis of Yield. IX Effect of Light Intensity on the Development of the Wheat Grain. *Physiol. Plant.* 22, 915–924.
- Baker, J.T., Pinter, Jr., P.J., Reginato, R.J., and Kanemasu, E.T. (1986). Effects of Temperature on Leaf Appearance in Spring and Winter Wheat. *Agron. J.* 78, 605–613.
- Banowetz, G.M., Ammar, K., and Chen, D.D. (1999). Postanthesis Temperatures Influence Cytokinin Accumulation and Wheat Kernel Weight. *Plant Cell Environ.* 22, 309–316.
- Bimmock, J.P.R.E., and Gooding, M.J. (2002). The Effects of Fungicides on Rate and Duration of Grain Filling in Winter Wheat in Relation to Maintenance of Flag Leaf Green Area. *J. Agric. Sci.* 138, 1–16.
- Bingham, J. (1967). Investigation on the Physiology of Yield in Winter Wheat by Comparison of Varieties and by Artificial Variation in Grain Number per Ear. *J. Agric. Sci.* 68, 411–422.
- Chowbury, S.I., and Wardlaw, I.F. (1978). The Effect of Temperature on Kernel Development in Cereals. *Australian J. Agric. Res.* 29, 205–223.
- Davidson, D.J., and Chevalier, P.M. (1990). Preanthesis Tiller Mortality in Spring Wheat. *Crop Sci.* 30, 832–836.
- Davies, W.P., Kettlewell, P.S., Green, H.J., Hocking, T.J., and Jarai, M.J. (1984). Senescence and Net Photosynthesis of the Flag Leaf and Grain Growth of Wheat in Response to Fungicide. *Ann. Appl. Bot.* 105, 303–312.
- Evans, L.C., and Wardlaw, I.F. (1976). Aspects of the Comparative Physiology of Grain Yields in Cereals. *Adv. Agron.* 28, 301–350.
- Fischer, R.A., and Laing, D.R. (1976). Yield Potential in a Dwarf Spring Wheat and Response to Crop Thinning. *J. Agric. Sci.* 87, 113–122.
- Ford, M.A., and Thorne, G.N. (1976). Effects of Variation in Temperature and Light Intensity at Different Times on Growth and Yield of Spring Wheat. *Ann. Appl. Bot.* 80, 283–299.
- Frederick, J.R., and Camberato, J.J. (1994). Leaf Net CO<sub>2</sub> Exchange Rate and Associated Leaf Traits of Winter Wheat Grown with Various Spring Nitrogen Fertilization Rates. *Crop Sci.* 34, 432–439.

Frederick, J.R., and Camberato, J.J. (1995). Water and Nitrogen Effects on Winter Wheat in the Southeastern Coastal Plain: I. Grain Yield and Kernel Traits. *Agron. J.* 87, 521–526.

Gooding, M.J., Smith, S.P., Davies, W.P., and Kettlewell, P.S. (1994). Effects of Late-Season Applications of Propiconazole and Tridemorph on Disease, Senescence, Grain Development and Breadmaking Quality of Winter Wheat. *Crop Prot.* 13, 362–370.

Gooding, M.J., Smith, S.P., Davies, W.P., and Jones, S.A. (2000). Green Leaf Area Decline of Wheat Flag Leaves: the Influence of Fungicides and Relationships with Mean Grain Weight and Grain Yield. *Ann. Appl. Bot.* 136, 77–87.

Grass, L., and Burris, J.S. (1995). Effect of Heat Stress During Seed Development and Maturation on Wheat (*Triticum durum*) Seed Quality. *Can. J. Plant Sci.* 75, 821–829.

Heiniger, R.W., Vanderlip, R.L., and Kofoed, K.D. (1993). Caryopsis Weight Patterns within the Sorghum Panicle. *Crop Sci.* 33, 543–549.

Hunt, L.A., van der Poorten, G., and Pararajasingham, S. (1991). Postanthesis Temperature Effects on Duration and Rate of Grain Filling in Some Winter and Spring Wheats. *Can. J. Plant Sci.* 71, 609–617.

Jenner, C.F. (1979). Grain-filling in Wheat Plants Shaded for Brief Periods after Anthesis. *Aust. J. Plant Physiol.* 6, 609–617.

Simmons, S.R. (1987). Growth, Development, and Physiology. ASA CSSA SSSA Madison WI 2nd, 77–113.

Sofield, I., Evans, L.T., Cook, M.G., and Wardlaw, I.F. (1977). Factors Influencing the Rate and Duration of Grain Filling in Wheat. 4, 785–797.

Spietz, J.H.J. (1977). The Influence of Temperature and Light Intensity on Grain Growth in Relation to the Carbohydrate and Nitrogen Economy of the Wheat Plant. *Neth. J. Agric. Sci.* 25, 182–197.

Tashiro, T., and Wardlaw, I.F. (1990). The Effect of High Temperature at Different Stages of Ripening on Grain Set, Grain Set, Grain Weight, and Grain Dimensions in the Semi-Dwarf Wheat “Banks.” *Ann. Bot.* 65, 51–61.

Wiegand, C.L., and Cuellar, J.A. (1981). Duration of Grain Filling and Kernel Weight as Affected by Temperature. 21, 95–101.

De Wit, C.T. (1977). Concluding Remarks. *Acad. Press New York* 365–369.

Woodruff, D.R., and Tonks, J. (1983). Relationship Between Time of Anthesis and Grain Yield of Wheat Genotypes with Differing Developmental Patterns. *Aust. J. Agric. Res.* 34, 1–11.

**Table 2.1: Analysis of variance table for kernel weight. †**

Source of Variation	TRS 2012††	TRS 2013	Perquimans 2013	PRS 2013††	TRS 2014	Chowan 2014	PRS 2014
Date	***	***	***	***	***	***	***
Block	NS	***	NS	*	NS	NS	***
Treatment	***	***	***	***	***	***	***
Date *							
Treatment	***	***	*	***	**	**	NS

† \*, \*\*, \*\*\* indicate significance at the 0.05, 0.01, and 0.001 significance level respectively. NS indicates not significant.

†† TRS: Tidewater Research Station; PRS: Piedmont Research Station

**Table 2.2: Analysis of variance table for rate and duration of grain fill. †**

Source of Variation	Rate	Duration
Location	***	***
Treatment	***	*
Block	NS	NS
Location*Treatment	NS	NS

† \*, \*\*, \*\*\* indicate significance at the 0.05, 0.01, and 0.001 significance level respectively. NS indicates not significant



**Table 2.3: Rate and duration of grain fill among site-years. Differing letters represent LSD at  $p > 0.05$ .**

Location	Rate		Duration	
TRS 12	0.0793	B	463	C
TRS 13	0.0653	CD	588	A
Hertford 13	0.0648	CD	540	B
PRS 13	0.0598	D	565	AB
TRS 14	0.0889	A	372	D
Chowan 14	0.0673	C	477	C
PRS 14	0.0835	AB	338	D

† TRS: Tidewater Research Station; PRS: Piedmont Research Station

†† Rate is in milligrams  $GDD^{-1}$ .

††† Duration is in GDD.

**Table 2.4: Rate and duration of grain fill among treatments. Differing letters represent LSD at  $p > 0.05$ .**

Treatment	Rate†		Duration††	
Untreated Control	0.0722	B	495	A
Fungicide @ GS 70	0.0746	AB	474	AB
Nitrogen @ GS 70	0.0773	AB	456	BC
Shade @ GS 70	0.0604	C	494	A
Low Seeding Rate	0.0729	B	492	A
High Seeding Rate	0.0802	A	435	C

† Rate is in milligrams  $GDD^{-1}$ .

†† Duration is in GDD.

**Table 2.5: Analysis of variance for grain yield and test weight. †**

Source of Variation	Yield	Test Weight
Location	***	***
Treatment	***	***
Block	NS	NS
Location*Treatment	NS	***

† \*, \*\*, \*\*\* indicate significance at the 0.05, 0.01, and 0.001 significance level respectively. NS indicates not significant

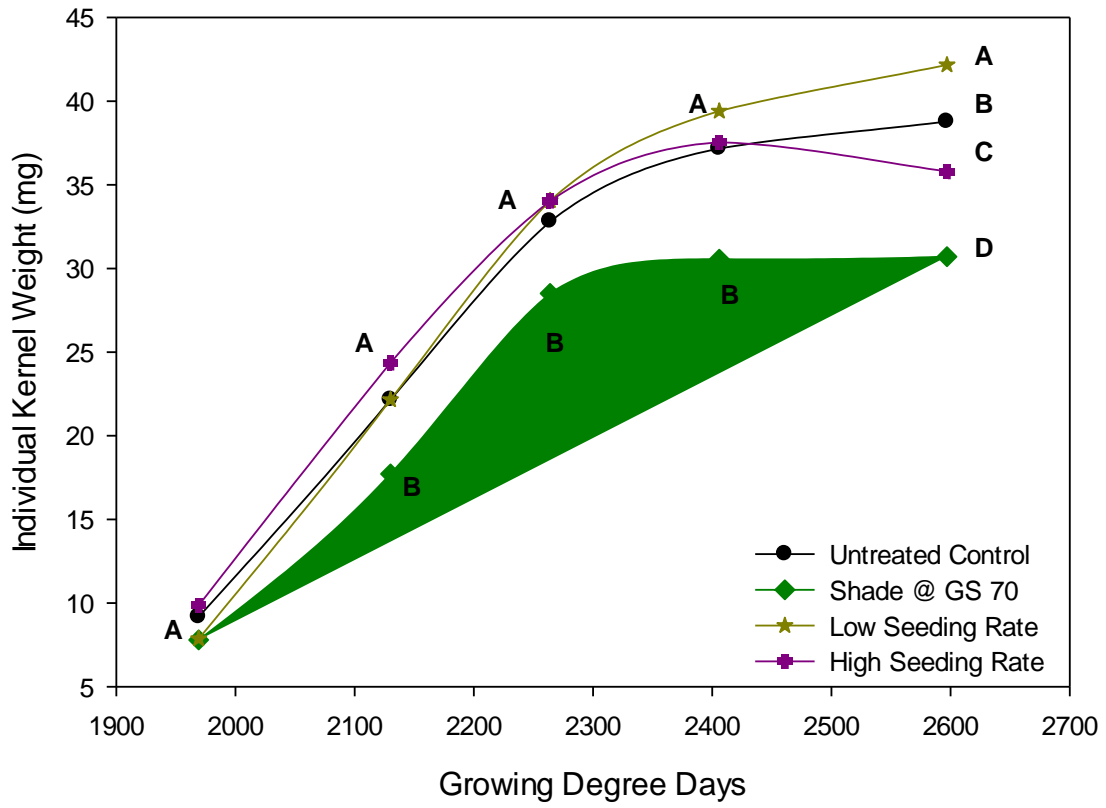


Figure 2.1: Changes in individual kernel weight by sample date at Tidewater Research Station (TRS) in 2012. Differing letters represent  $P < 0.05$ .

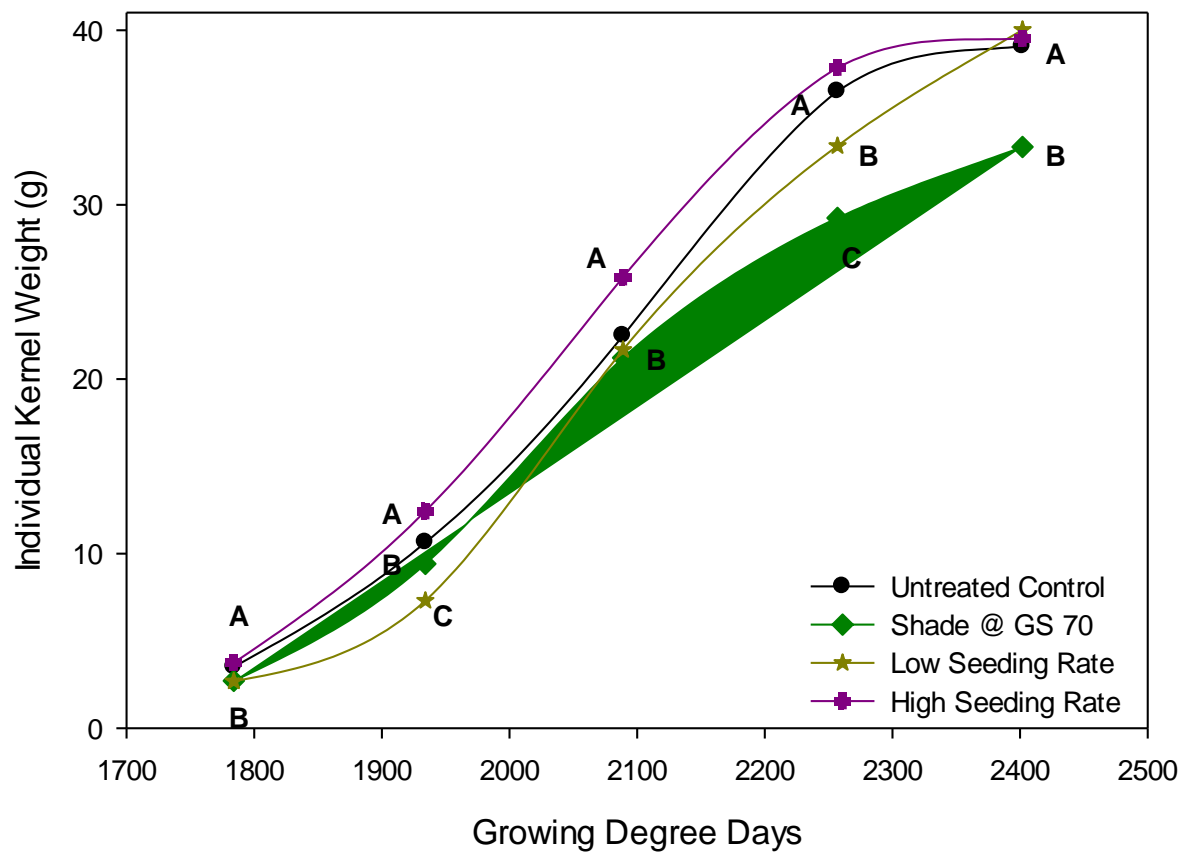


Figure 2.2: Changes in individual kernel weight by sample date at Tidewater Research Station (TRS) in 2013. Differing letters represent  $P < 0.05$ .

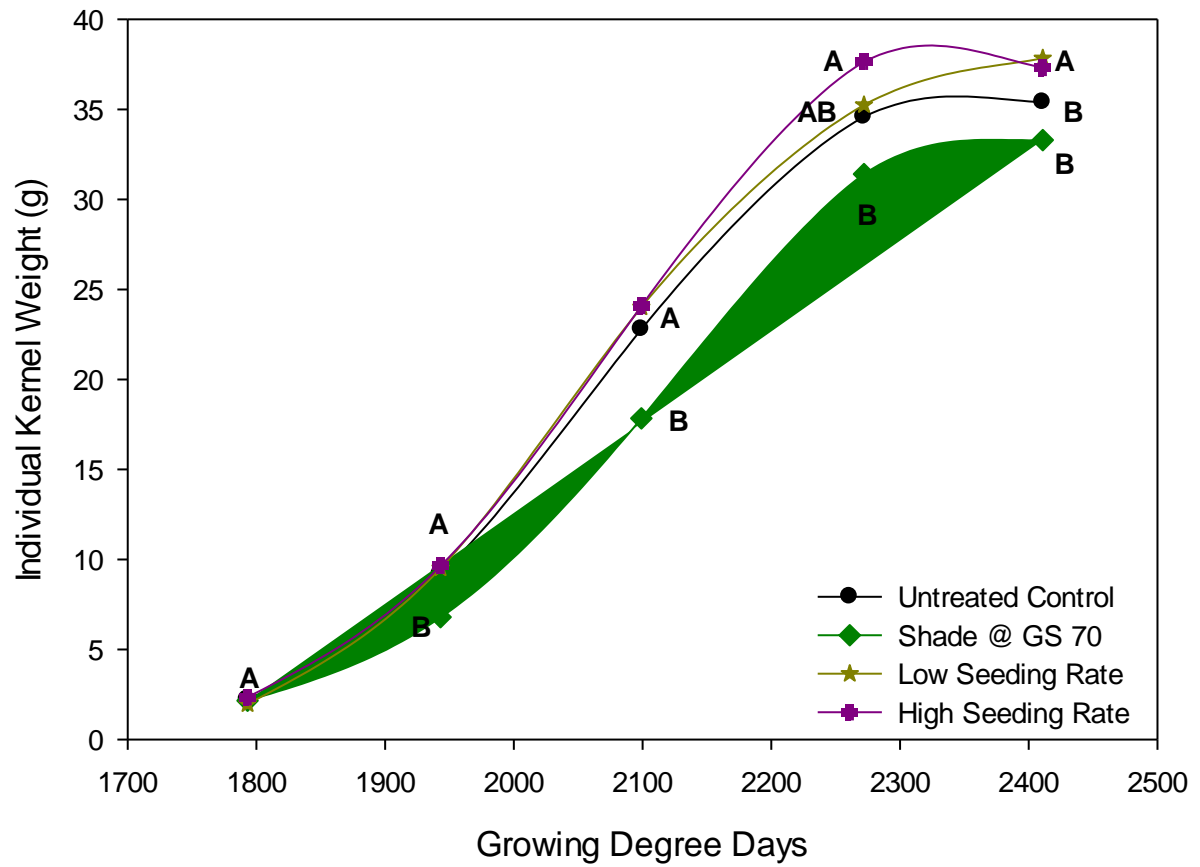


Figure 2.3: Changes in individual kernel weight by sample date at Hertford in 2013. Differing letters represent  $P < 0.05$ .

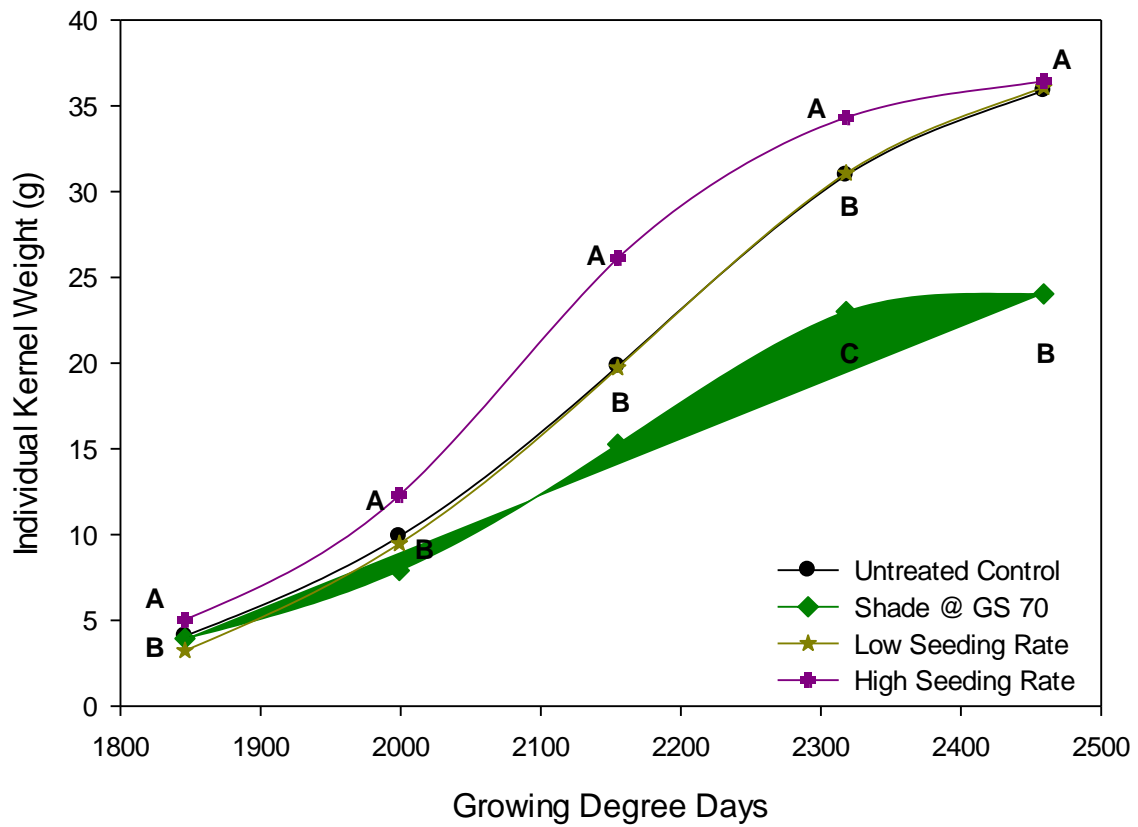


Figure 2.4: Changes in individual kernel weight by sample date at Piedmont Research Station (PRS) in 2013. Differing letters represent  $P < 0.05$ .

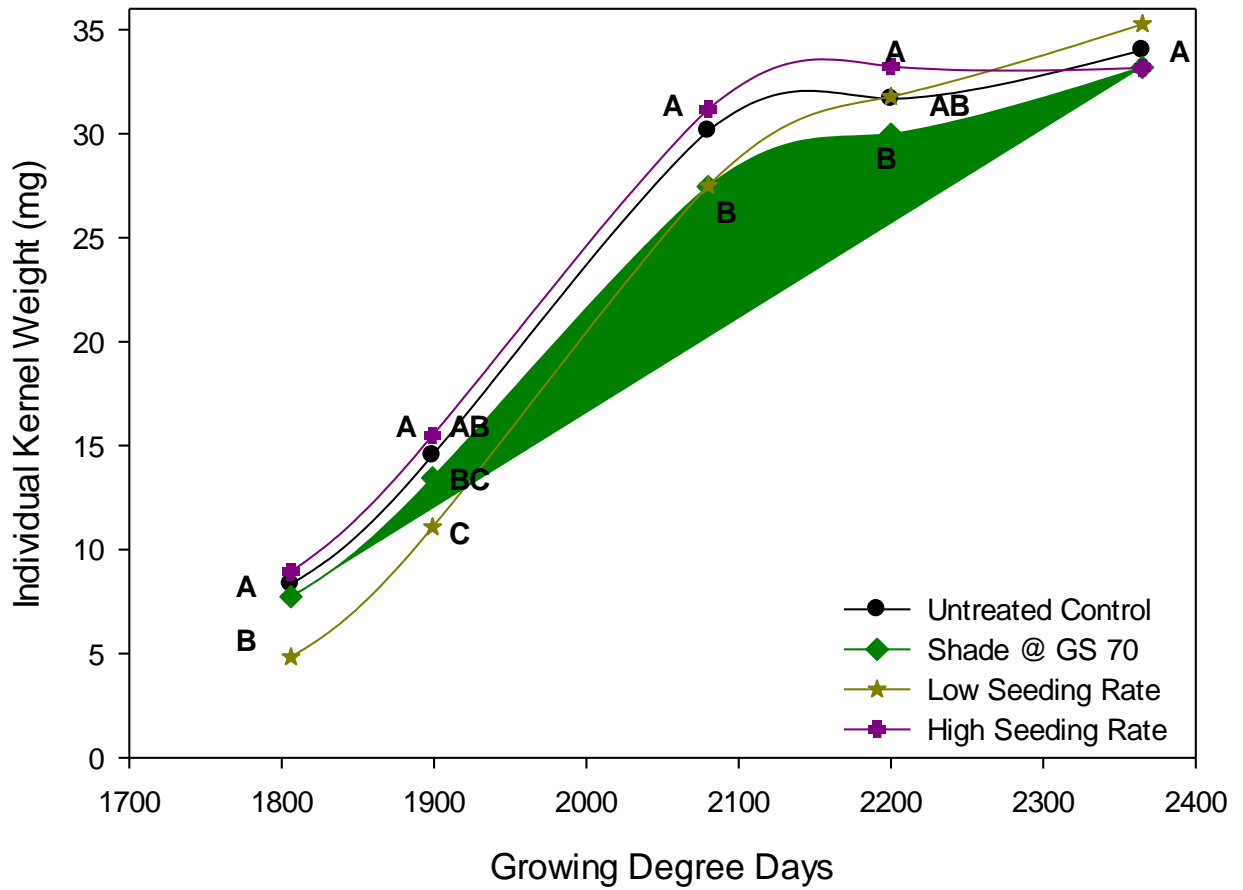


Figure 2.5: Changes in individual kernel weight by sample date at Tidewater Research Station (TRS) in 2014. Differing letters represent  $P < 0.05$ .



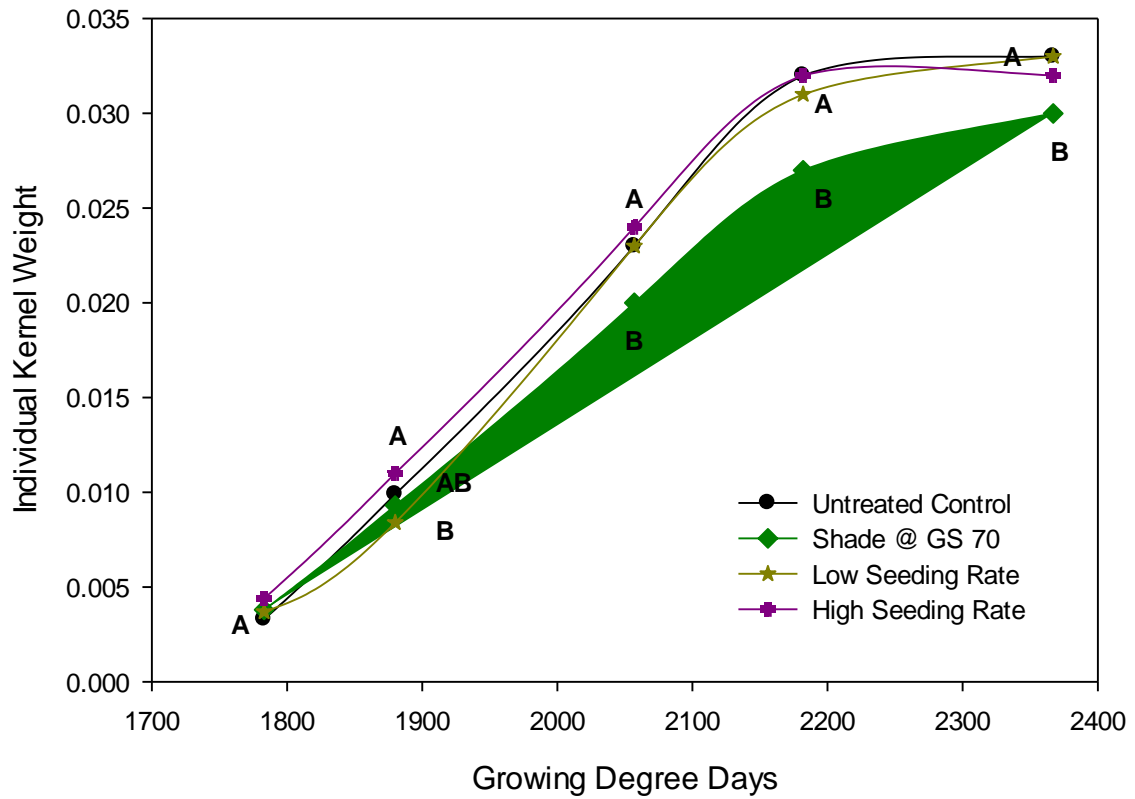
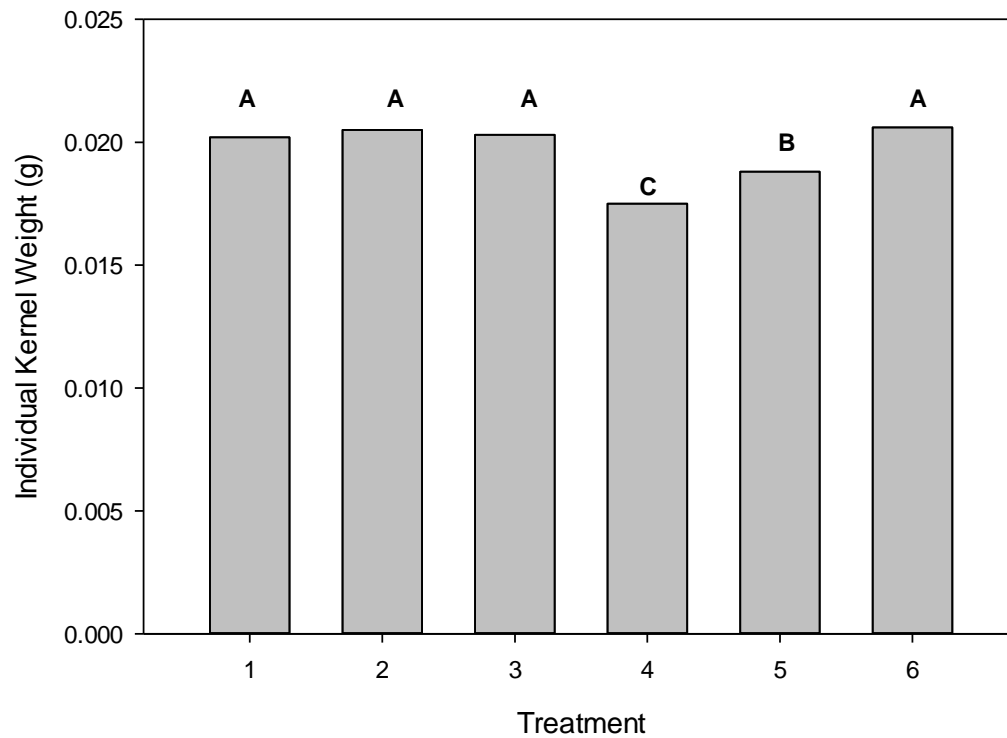


Figure 2.6: Changes in individual kernel weight by sample date at Chowan County in 2014. Differing letters represent  $P < 0.05$ .



Number	Treatment
1	Untreated Control
2	Fungicide @ GS 70
3	Nitrogen @ GS 70
4	Shade @ GS 70
5	Low Seeding Rate
6	High Seeding Rate

Figure 2.7: Individual kernel weights at Piedmont Research Station (PRS) in 2014. Differing letters within sample period represent LSD at  $P < 0.05$ .

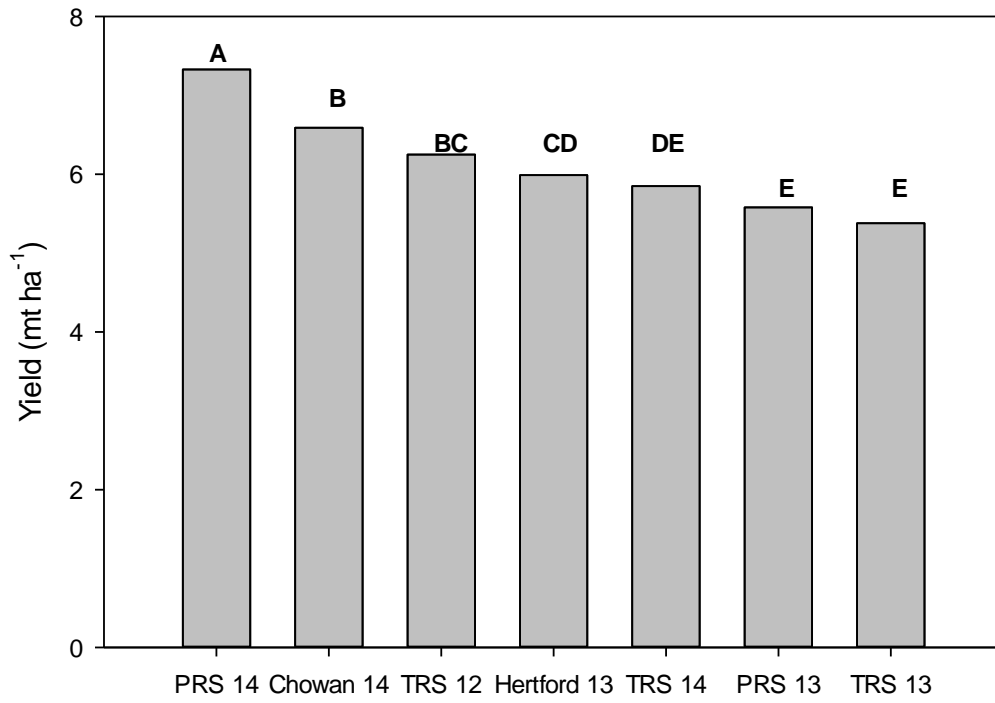
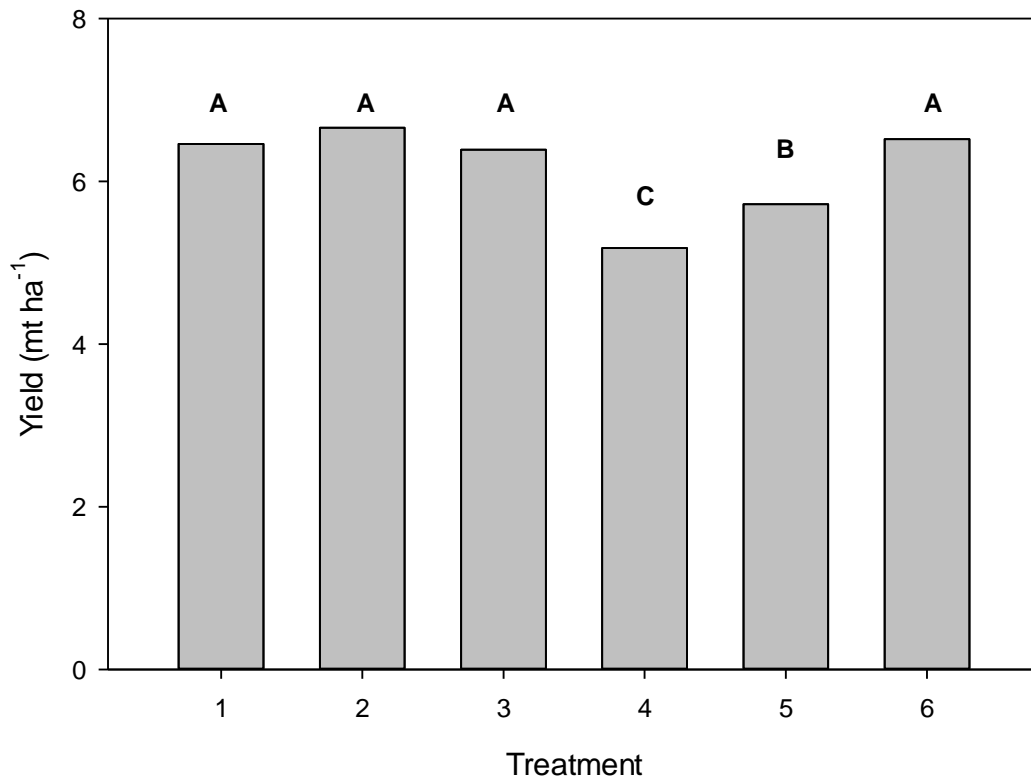


Figure 2.8: Grain yield among location. TRS signifies Tidewater Research Station and PRS signifies Piedmont Research Station. Differing letters within sample period represent LSD at  $P < 0.05$ .



Number	Treatment
1	Untreated Control
2	Fungicide @ GS 70
3	Nitrogen @ GS 70
4	Shade @ GS 70
5	Low Seeding Rate
6	High Seeding Rate

Figure 2.9: Grain yield among treatments. Differing letters within sample period represent LSD at  $P < 0.05$ .

## CHAPTER THREE

### The Impact of Weather Patterns on Planting Date of Wheat in North Carolina

JOSEPH C. OAKES and RONNIE W. HEINIGER

#### ABSTRACT

Planting date is one of the most important decisions that a wheat producer can make because planting date influences early leaf and tiller development in North Carolina. The foundation for high wheat yields is created by early leaf growth and tillers that develop during the fall and early winter. Since it takes approximately 310 GDD for the plant to develop its first tiller growing degree day accumulation (GDD) is essential for tiller development. Years when GDD accumulate rapidly in the fall and early winter result in more leaves and tillers and the potential for greater yield. However, planting too early in these years can result in too much growth and a high likelihood of spring freeze damage. Better selection of planting dates for winter wheat could be achieved if growers knew what late fall and early winter temperatures to expect. Both the El Niño Southern Oscillation (ENSO) and the North Atlantic Oscillation (NAO) were examined in order to determine which phase in each index minimized the time necessary for the plant to develop its first tiller. Consistently more days were required during a neutral ENSO phase to reach 310 GDD than during the El Niño or La Niña phases Pasquotank and Washington Counties for potential planting dates from middle to late November. Potential planting dates from mid-November to mid-December required more days to reach 310 GDD during a Cool October NAO period than during a Warm or Neutral year. This study indicates that wheat growers in North Carolina

should be familiar with these patterns and use them to help determine optimum planting dates.

## **INTRODUCTION**

Wheat (*Triticum aestivum* L.) production in North Carolina is often subject to season to season fluctuations in weather and climate conditions. Management and production practices that are favorable one year may be totally different in the next year when the weather conditions are different. An abnormally warm winter may be present one year, while the following year cold weather may arrive early in the fall and remain cold throughout the winter. Therefore, it is necessary to manage wheat based on yearly conditions rather than making the same decisions each year. Among the management factors that can be controlled by the producer, planting date is one of the most important (Campbell et al., 1991), since it affects several aspects of wheat development. Proper planting date allows the wheat plant to accumulate adequate growing degree days (GDD) throughout the growing season which influences early tiller development (Oakes and Heiniger, 2014). Planting date can also influence the amount of freeze damage around the time of flowering and the amount of heat stress during the grain fill period (Ortiz et al., 2012). Planting too early in a year with a warm winter can result in increased spring freeze damage and increased disease pressure (Weisz and Heiniger, 2013); while planting too late in years with cold winters can result in fewer leaves and tillers and lowered yield potential.

Early, rapid accumulation of GDD allows the plant to develop as many fall tillers as possible. Generally, it takes an average of 310 GDD in order for the plant to establish its first tiller (Oakes & Heiniger, 2014). Tillers that develop in the fall are one of the most essential

factors to high yields since they have two key components of a high yielding crop: large heads with kernels and kernels with a high test weight (Weisz and Heiniger, 2013).

Therefore, the period of time from October to December is one of the most critical periods for North Carolina winter wheat production. Fall tillers also have a stronger root system and are more stress resistant than spring tillers. Warm temperatures produce more tiller growth, while cold temperatures impede growth. Tiller development occurs in the fall until low temperatures stop plant growth (Herbek and Lee). According to Thiry et al. (2002) and Ortiz et al. (2012), an early planting date often promotes increased early leaf and tiller growth during the fall, which contribute more to final grain yield. They also noted that late planting results in less early growth, fewer fall tillers, and more spring tillers which have a low harvest index. However, these two studies were done in Kansas and Alabama, respectively, and results may differ in North Carolina.

In our two-year study on planting date and phyllochron interval (PI), we observed that PI and tiller development is dependent on planting date (Oakes and Heiniger, 2014). A phyllochron interval is defined as the developmental time that it takes for the plant to elongate a new mainstem leaf, and is measured by the number of GDD required to develop a new mainstem leaf (Krenzer, Jr. and Nipp, 1991). Therefore, the shorter the PI, the faster leaves are appearing on the plant. In both years of this study, the later planting date resulted in a shorter PI and faster rate of leaf growth. Despite the PI being consistent between planting dates in both years, tillers per plant and yield differed between years. During the 2012-13 growing season, the second planting date resulted in higher tillers per plant and therefore a higher yield. However, results were different during the 2013-14 growing season, as the

earlier planting date with the longer PI resulted in higher tillers per plant, and a higher yield. Therefore, early leaf and tiller production is dependent on planting date, but it is not necessarily the same each growing season. In 2012, more GDD were accumulated in December than in November. This warmer period in December combined with a shorter PI at the later planting date allowed the plant to develop more leaves in December and to catch up with the November planting which experienced a longer PI and cooler weather in late November which slowed leaf development. As a result, the December planting produced more viable fall tillers and ultimately higher yields. In 2013, more GDD were produced in November than in December, and December was much colder as well. Even though the PI was shorter for the second planting date, the plant was not able to overcome the fewer GDD accumulated after the second planting date. Therefore, yields were higher for the first planting date in 2013-14 despite the faster rate of leaf growth for the second planting date. These data indicate that it would be beneficial to have a way to determine when a particular year will have a warmer December, which would enable a wheat grower to take advantage of the shorter PI that is exhibited when planting later.

One of the strongest drivers of year to year climate variations around the world is the El Niño Southern Oscillation (ENSO) phenomenon (Ropelewski and Halpert, 1986). The ENSO is best known as an increase or decrease in the sea surface temperature in the eastern Pacific Ocean (Fraisse et al., 2007). There are three ENSO phases: El Niño, La Niña, and neutral (Knox and Griffin). When the sea surface temperature is higher than normal in the eastern Pacific, the phenomenon is referred to as El Niño (Fraisse et al., 2007). These warmer sea temperatures cause the atmosphere to be warmer and result in moisture being lifted into



the atmosphere. This moisture in the atmosphere and the warm ocean waters often cause an increase in tropical rain and thunderstorms. Atmospheric and oceanic measurements associated with ENSO provide one of the starting places for climate related agricultural conditions (Fraisse et al., 2008), and have an important and predictable effect on climate in the Southeastern United States (Fraisse et al., 2007). Hansen et al. (2001) studied the effects of ENSO on several crops (peanut, tomato, cotton, tobacco, corn, soybean), and observed that corn and tobacco yields tended to be higher during La Niña years. El Niño generally lasts less than one year, and occurs at semi-regular intervals of 2-5 years (Knox and Griffin). Effects of El Niño are strongest in the Southeast during the winter between October and April since ocean temperatures worldwide are at their warmest, and these warm ocean waters can cause an increase in tropical rain and thunderstorms. During these El Niño years, the southeastern U.S. states tend to be cooler and wetter overall during winter months (Fraisse et al., 2007).

When sea surface temperatures in the Pacific Ocean are lower than normal, the phenomenon is referred to as La Niña and the east to west flow of equatorial trade winds are strengthened (Fraisse et al., 2007). These events stir up the ocean and causes colder water to be brought up from the ocean's floor. La Niña events occur at semi-regular intervals of 2-5 years and can last one to three years (Knox and Griffin). As with El Niño, La Niña effects are strongest in the fall and winter months between October and April. However, with La Niña, the southeast tends to be warmer and drier than normal (Fraisse et al., 2007). During a neutral phase, which occurs around 50% of the time, sea surface temperatures are close to normal and trade winds blow from east to west near the Equator in the Pacific Ocean (Fraisse

et al., 2007). The fact that ENSO has a strong influence on the months of October through April indicates its importance in wheat production. As previously stated, wheat yield is strongly dependent on fall tiller production as these tillers contribute to final grain yield. Therefore, a cold and wet winter could potentially impact fall tiller development negatively. Wet weather could also influence planting date since fields could be too wet to plant when desired.

A second global pattern that may influence the planting date of wheat in North Carolina is the North Atlantic Oscillation (NAO). The NAO is one of the most prominent teleconnection patterns in all seasons (Barnston and Livezey, 1987). It consists of two pressure centers in the North Atlantic: an area of low pressure located near Iceland and an area of high pressure over the Azores. The strength of these two pressure centers often fluctuates, which significantly alters the alignment of the jet stream. This often occurs over the eastern United States and often affects the temperature and rainfall distribution over this area. During a warm NAO period, the low Icelandic and high Azore pressure strengthens, which causes westerlies to increase (Global Patterns-AO&NAO). These increased westerlies allow cold air to drain off rather than letting it build up and moving south. During this pattern, the eastern U.S. often sees stronger storms and more precipitation during the winter due to the increased upper level winds. However, there is also a decreased potential for winter weather during this time as there is a lack of cold air.

A cool NAO period indicates that the Icelandic low and Azores high are weakening, which decreases the pressure gradient in the North Atlantic, and causes the westerlies to decrease (Global Patterns-AO&NAO). The decrease in the westerlies allows cold air to move south

and affect the eastern U.S. During a cool NAO, the eastern U.S experiences colder and drier air masses during the winter. Prolonged periods of several months are often common for both warm and cool phases of the NAO (Climate Prediction Center Internet Team, 2012). Since both ENSO and NAO weather patterns influence both temperature and precipitation in the fall and winter in the southeastern U.S., there is a potential to use these two climate patterns to enable us to make informed planting decisions each year. The objectives of this study were to examine how the ENSO and NAO affect fall and winter weather in North Carolina, and to determine when a grower might delay planting and take advantage of the shorter PI to achieve higher yields. We examine the impact of ENSO and NAO phases on amount of time it takes for the plant to develop its first tiller.

## **MATERIALS & METHODS**

In order to determine how climate patterns affect GDD accumulations, climate data obtained from National Weather Service Cooperative Observed Program (COOP) stations was examined for sixty-two years from 1950 to 2011 at three locations in North Carolina: Pasquotank County, Washington County, and Salisbury. Daily maximum and minimum temperatures were used to calculate the average daily temperature. The August-September-October (ASO) Oceanic Niño Index (ONI) was used to determine ENSO phase. This index consists of a three-month running mean of sea surface temperature anomalies in the Niño 3.4 region of the tropical Pacific from 5°N to 5°S, 120°W to 170°W (Kousky and Higgins 2007; Smith et al. 2008; Dahlman, 2009). El Niño conditions are considered to be present when the ONI is 0.5°C warmer than the average for the base period, while La Niña conditions are

considered to be present when the ONI is 0.5°C cooler than the average. When the ONI is within +0.5°C and -0.5°C of the average, conditions are considered to be ENSO neutral.

The current NAO index corresponds to NAO patterns which generally vary from month to month. When the NAO index is greater than +0.674, a warm NAO period is present. Likewise, when the index is less than -0.674, a cool NAO period is present. When the index is between +0.674 and -0.674, conditions were considered to be NAO neutral. Categories were defined according to the method used by Royce et al. (2011) to categorize MEI. The index values reported consist of the standard deviation from the base period mean value. The thresholds of  $\pm 0.674$  put 25% of values in cool and warm phases.

To determine the target PI at which the first tiller would be initiated, the average PI from two planting dates (on-time and late) was measured at four locations (Hertford, Chowan, Tidewater Research Station, Piedmont Research Station) over two years (2012-13 and 2013-14) (Oakes and Heiniger, 2014). The on-time planting date was 11 November at Hertford, Chowan, and Tidewater Research Station, while the late planting was 4 and 6 December depending on year. At the Piedmont Research Station, the on-time planting date was 21 October, while the late planting date was 15 November. Since three leaves are required for the plant to develop its first tiller, the PI was multiplied by three to determine how many GDD were required for the plant to develop its first tiller. Averaged across planting dates, 310 GDD per tiller was calculated as the point at which tiller development began.

The 62 years of climate data from 1950 to 2011 were segregated into groups according to the ASO ENSO and October NAO phase. For each year at each location, GDD

accumulated each day from 1 October to 15 December was calculated from the daily minimum and maximum as indicated in the following formula:

$$Tu = [(T_{max} + T_{min}) / 2] - T_b,$$

where Tu is daily thermal units (GDD), T<sub>max</sub> is the daily maximum temperature, T<sub>min</sub> is the daily minimum temperature, and the base temperature T<sub>b</sub> was 0°C (Baker et al., 1986). Temperature data from these climate patterns were tested to determine if they minimized the time required to develop the first tiller. For each potential planting date from 1 October to 15 December, we calculated and plotted average days required to achieve 310 GDD for each ENSO and NAO. The number of days required to achieve 310 GDD was plotted and graphed for each day during this time period.

## **RESULTS**

### **El Niño Southern Oscillation**

Table 1 characterizes each year from 1950-2013 based on ENSO and NAO phase. Differences between the La Niña, El Niño and neutral ENSO phases in the number of days required to initiate a tiller were most evident in Pasquotank County (Figure 3.1). Several key differences were observed in the number of days required to initiate a tiller among August-September-October ENSO indexes at certain planting dates. From 7 November to 17 November, La Niña minimized the time it took to reach 310 GDD. During this period, years with a La Niña ENSO index required 2 to 3 less days to reach 310 GDD compared to years with either an El Niño or neutral index. However, from 18 November to 30 November, years characterized with an August-September-October El Niño index required from 1 to 3 days less time to reach 310 GDD compared to years with a La Niña index, and from 1 to 4 days

less time in years with a Neutral index (Figure 3.2). From 2 December until 9 December, La Niña minimized the amount of time required to reach 310 GDD (Figure 3.1). In general, across most of the fall dates tested, years with a neutral ENSO phase required the longest period to reach 310 GDD.

At Washington County, differences among ENSO phases in the days required to initiate the first tiller were similar to the differences found in the Pasquotank County record (Figure 3.3). However, in most cases the differences in tiller initiation were less than a day making it impractical to adjust planting dates based on these differences. The one exception was the period beginning with 18 November and continuing until 2 December. During this period, years in which August-September-October was El Niño, only 19 to 26 days were required to reach 310 GDD compared to 21 to 28 days during La Niña or Neutral years (Figure 3.4).

At Salisbury, there was generally little or no difference in the time required to reach first tiller among years with different ENSO phases (Figure 3.5). For most planting dates, differences of less than one day were found. The exceptions to this were the periods from 6 November to 9 November, when tillering was initiated one day earlier during La Niña years than during El Niño or Neutral years, and the period from 20 November to 24 November when tillering was initiated 1 to 2 days earlier during El Niño years than during Neutral years.

### **North Atlantic Oscillation**

Differences in the number of days required to reach tiller initiation were greater and more consistent when NAO phases were considered than when ENSO phases were used

(Figures 3.6, 3.7, and 3.8). In Pasquotank County, the most consistent pattern observed was that from 21 November to 15 December years with either a Warm or Neutral index in October required from 1 to 8 less days to reach tiller initiation compared to years with a Cool index. Similar observations for an October NAO were made in Washington County. Again, a cool October NAO resulted in much colder temperatures from late November through mid-December as the number of days required to reach 310 GDD rose sharply compared to years with a Warm or Neutral NAO (Figure 3.7). The most consistent pattern was observed from 23 November to 13 December, when 1 to 5 more days were required to reach tiller initiation following a Cool October, than were required following a Warm and Neutral October.

Differences among NAO phases at Salisbury were also similar to those in Washington and Pasquotank Counties. A cool October NAO again resulted in colder weather from mid-November through mid-December, as the number of days required to reach 310 GDD was much higher for the other two phases (Figure 3.8). However, since wheat is planted earlier in the piedmont than in the coastal plain, this increase in the cool NAO phase is unlikely to affect planting date in the piedmont since wheat is generally planted mid-late October. Very little differences among the three NAO periods are observed in Salisbury before the middle of November.

## **CONCLUSION**

The observations from this study show some important trends in fall and winter weather and how they influence wheat planting in North Carolina. Both ENSO and NAO phases have an effect on temperatures in November and December, and thus both can potentially impact the accumulation of GDD and the start of tiller initiation. In this study, the

use of the August-September-October ENSO phase to predict differences in days to 310 GDD was less useful than the use of the October NAO. The only location where the ENSO index indicated differences of more than 1 or 2 days among the phases in reaching 310 GDD was in Pasquotank County during the period from 18 Nov to 30 Nov. Furthermore, other than the fact that years with a Neutral August-September-October index consistently required more days to reach 310 GDD in Pasquotank County, there were no consistent differences. On some dates, years with a La Niña index resulted in slightly shorter periods to tiller initiation, and on other potential planting dates the years with an El Niño index resulted in slightly shorter period to tiller initiation.

In contrast, the October NAO resulted in larger and more consistent differences among potential planting dates in the time required to reach 310 GDD. At all three locations, analysis indicated that potential planting dates from mid-November to mid-December resulted in 1-8 more days to reach 310 GDD when the Cool October NAO phase was present. This consistent pattern would indicate that the NAO would have some potential for helping growers avoid late planting during years when the October NAO was rated “Cool”. This study underscores the importance of a wheat grower in North Carolina being familiar with NAO phases and using them as a decision aid when selecting a planting date.



## REFERENCES

- Baker, J.T., Pinter, Jr., P.J., Reginato, R.J., and Kanemasu, E.T. (1986). Effects of Temperature on Leaf Appearance in Spring and Winter Wheat. *Agron. J.* 78, 605–613.
- Barnston, A.G., and Livezey, R.E. (1987). Classification, seasonality and persistence of low-frequency atmospheric circulation patterns. *Mon. Weather Rev.* 115, 1083–1126.
- Campbell, C.A., Selles, F., Zetner, R.P., McLeod, J.G., and Dyck, F.B. (1991). Effect of Seeding Date, Rate, and Depth on Winter Wheat Grown on Conventional Fallow in S.W. Saskatchewan. *Can. J. Plant Sci.* 71, 51–61.
- Climate Prediction Center Internet Team (2012). North Atlantic Oscillation.
- Dahlman, L. (2009). Climate Variability: Oceanic Niño Index.
- Fraisse, C., Paz, J.O., and Brown, C.M. (2007). Using Seasonal Climate Variability Forecasts: Crop Yield Risks. *Univ. Fla. IFAS Ext. CIR1498*, 1–8.
- Fraisse, C., Cabrera, V., Breuer, N., Baez, J., Quispe, J., and Matos, E. (2008). El Niño-Southern Oscillation influences on soybean yields in eastern Paraguay. *Int. J. Climatol.* 28, 1399–1407.
- Global Patterns - Arctic & North Atlantic Oscillations. State Climate Office of North Carolina. <http://nc-climate.ncsu.edu/climate/patterns/NAO.html>
- Hansen, J., Jones, Irmak, A., and Royce, F. (2001). El Niño-Southern Oscillation impacts on crop production in the southeast United States. *ASA Spec. Publ. Number 63* 57–78.
- Herbek, J., and Lee, C. Growth and Development. In *A Comprehensive Guide to Wheat Management in Kentucky*, (UK Ag Extension), pp. 6–12.
- Klepper, B., Rickman, R.W., and Belford, R.K. (1983). Leaf and Tiller Identification on Wheat Plants. *Crop Sci.* 23, 1002–1004.
- Knox, P., and Griffin, M. ENSO Impacts on Southeastern Agriculture. *Southeast Clim. Ext.*
- Kousky, V., and Higgins, R., 2007. An alert classification system for monitoring and assessing the ENSO cycle. *Weather Forecasting* 22, 353–371.
- Krenzer, Jr., E.G., and Nipp, T.L. (1991). Mainstem Leaf Development and Tiller Formation in Wheat Cultivars. *Agron. J.* 83, 667–670.
- Oakes, J.C., and Heiniger, R.W. (1991). Phyllochron Interval and Yield Response to Planting Date and Starter Fertilizer in Wheat. Unpublished data.

Ortiz, B.V., Tapley, M., and van Santen, E. (2012). Planting Date and Variety Selection Effects on Wheat Yield. Ala. Coop. Ext. Syst. ANR-1442 1–4.

Ropelewski, C.F., and Halpert, M.S. (1986). North American Precipitation and Temperature Patterns Associated with the El Niño/Southern Oscillation (ENSO). *Mon. Weather Rev.* 114, 2352–2362.

Royce, F.S., Fraisse, C.W., and Baigorria, G.A., 2011. ENSO classification indices and summer crop yields in the Southeastern USA. *Agricultural and Forest Meteorology* 151, 817–826.

Smith, T., Reynolds, R., Peterson, T., Lawrimore, J., 2008. Improvements to NOAA’s historical merged land–ocean surface temperature analysis (1880–2006). *J. Climate* 21, 2283–2296.

Thiry, D.E., Sears, R.G., Shroyer, J.P., and Paulsen, G.M. (2002). Planting Date Effects on Tiller Development and Productivity of Wheat. *Keep. Res. Ser.*

Weisz, R., and Heiniger, R.W. (2013). Nitrogen Management for Small Grains. In *North Carolina Small Grain Production Guide*, (NCSU), pp. 25–31.

**Table 3.1: El Nino Southern Oscillation (ENSO) and North Atlantic Oscillation (NAO) phases for each year from 1950-2013.**

ENSO Phase			NAO Phase		
El Nino	La Nina	Neutral	Cool	Warm	Neutral
1951	1954	1950	1955	1950	1952
1953	1955	1952	1960	1951	1966
1957	1956	1958	1968	1953	1967
1963	1964	1959	1973	1954	1970
1965	1970	1960	1980	1956	1975
1968	1971	1961	1981	1957	1976
1969	1973	1962	1992	1958	1979
1972	1975	1966	1997	1959	1982
1976	1983	1967	2002	1961	1984
1977	1985	1974	2003	1962	1987
1982	1988	1978	2004	1963	1988
1986	1995	1979	2006	1964	1989
1987	1998	1980	2012	1965	1991
1991	1999	1981	2013	1969	1993
1994	2000	1984		1971	1994
1997	2007	1989		1972	1996
2002	2010	1990		1974	1998
2004	2011	1992		1977	2001
2006		1993		1978	2005
2009		1996		1983	2008
2012		2001		1985	2009
		2003		1986	2010
		2005		1990	
		2008		1995	
				1999	
				2000	
				2007	
				2011	

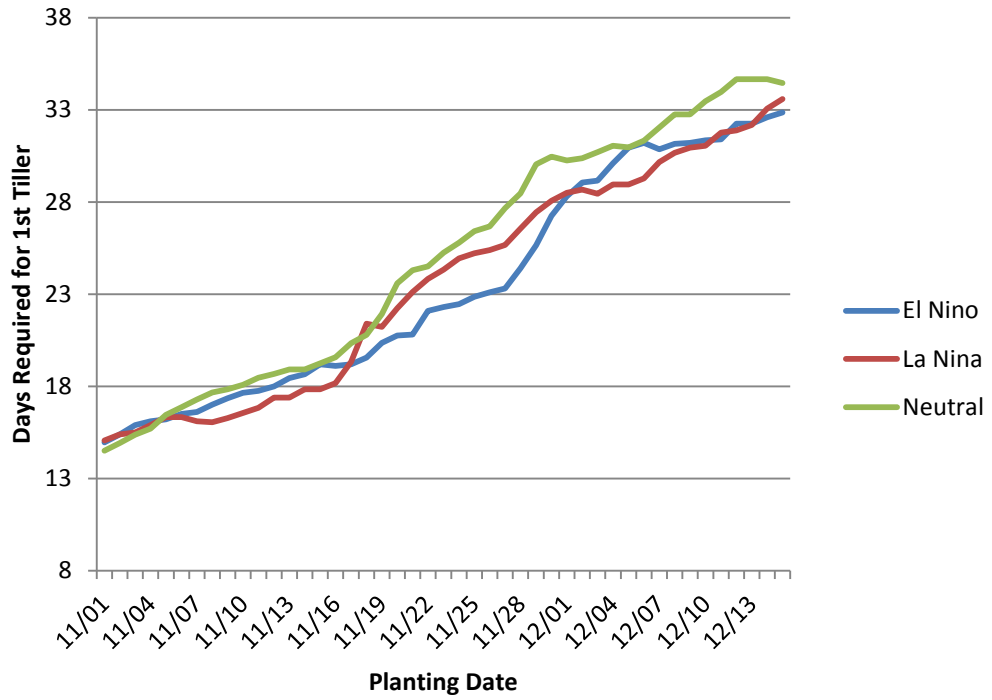


Figure 3.1: Days required to reach 310 GDD (1<sup>st</sup> tiller) based on temperatures averaged over the period from 1950 to 2011 for the three ENSO phases in Pasquotank County.

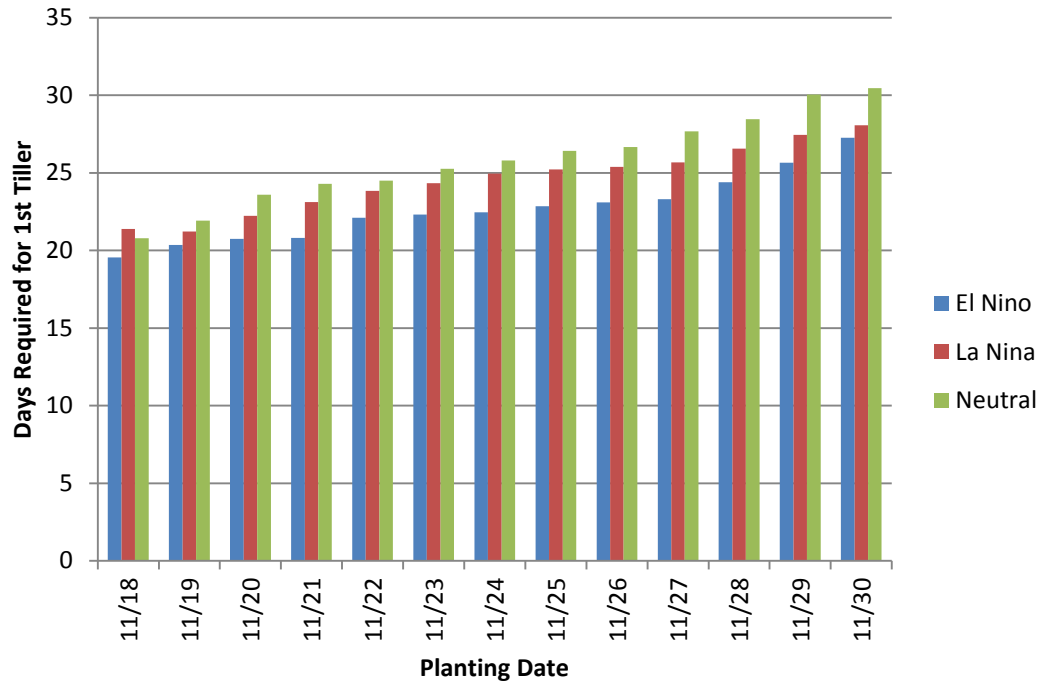


Figure 3.2: Days required to reach 310 GDD (1<sup>st</sup> tiller) based on temperatures averaged over the period from 1950 to 2011 for the three ENSO phases between November 18 and November 30 at Pasquotank County.

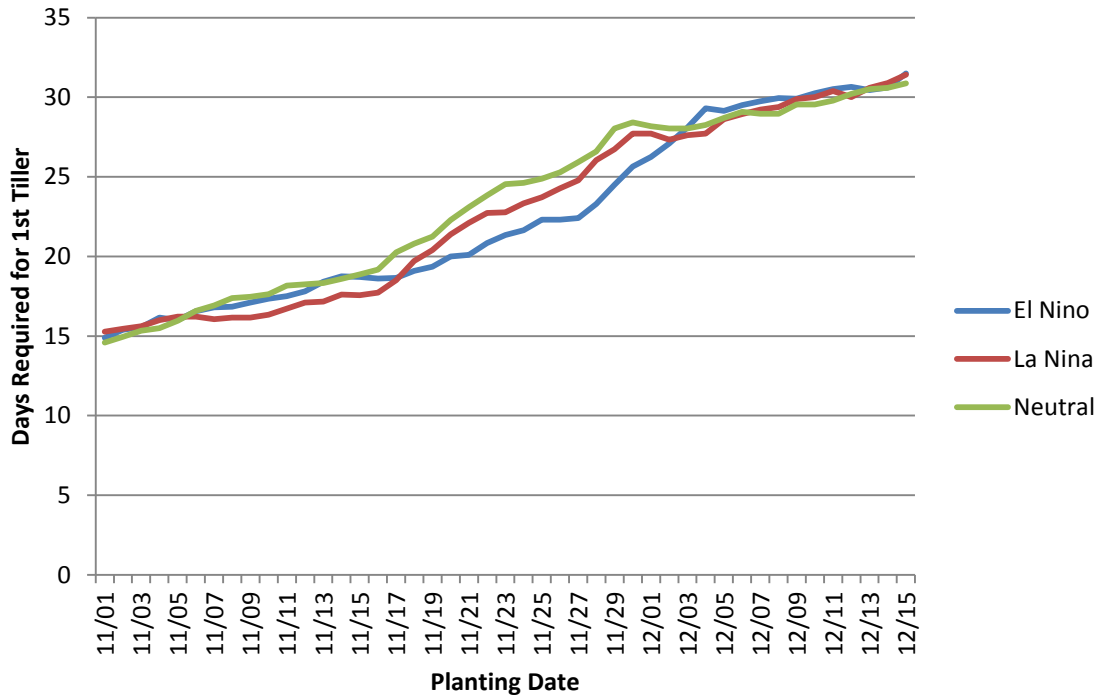


Figure 3.3: Days required to reach 310 GDD (1<sup>st</sup> tiller) based temperatures averaged over the period from 1950 to 2011 for the three ENSO phases at Washington County.

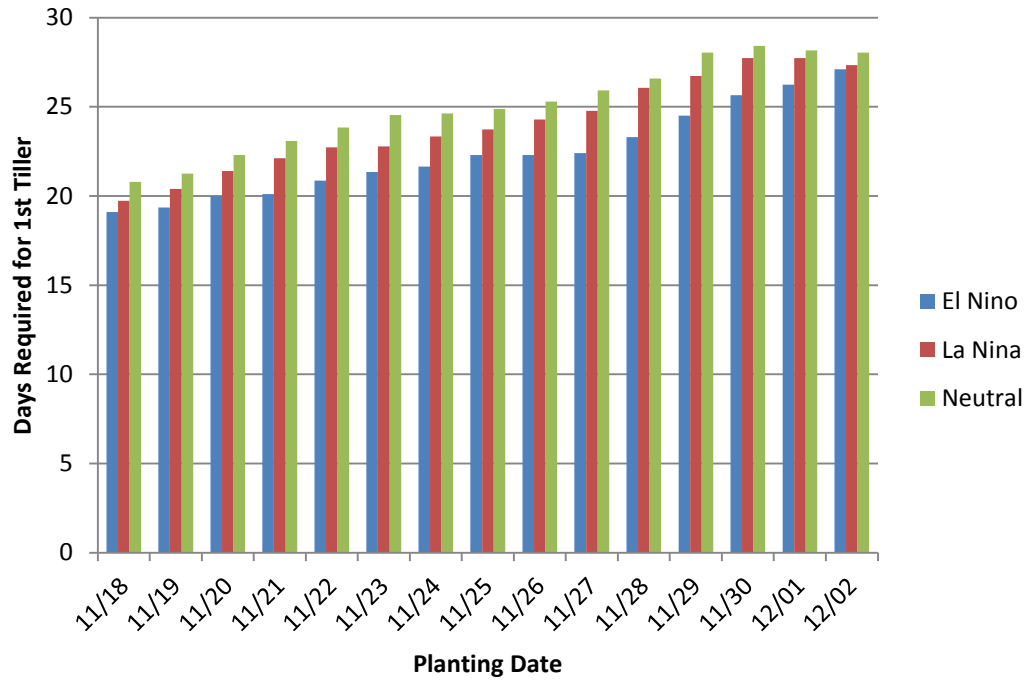


Figure 3.4: Days required to reach 310 GDD (1<sup>st</sup> tiller) based on temperatures averaged over the period from 1950-2011 for the three ENSO phases between November 18 and December 2 at Washington County.

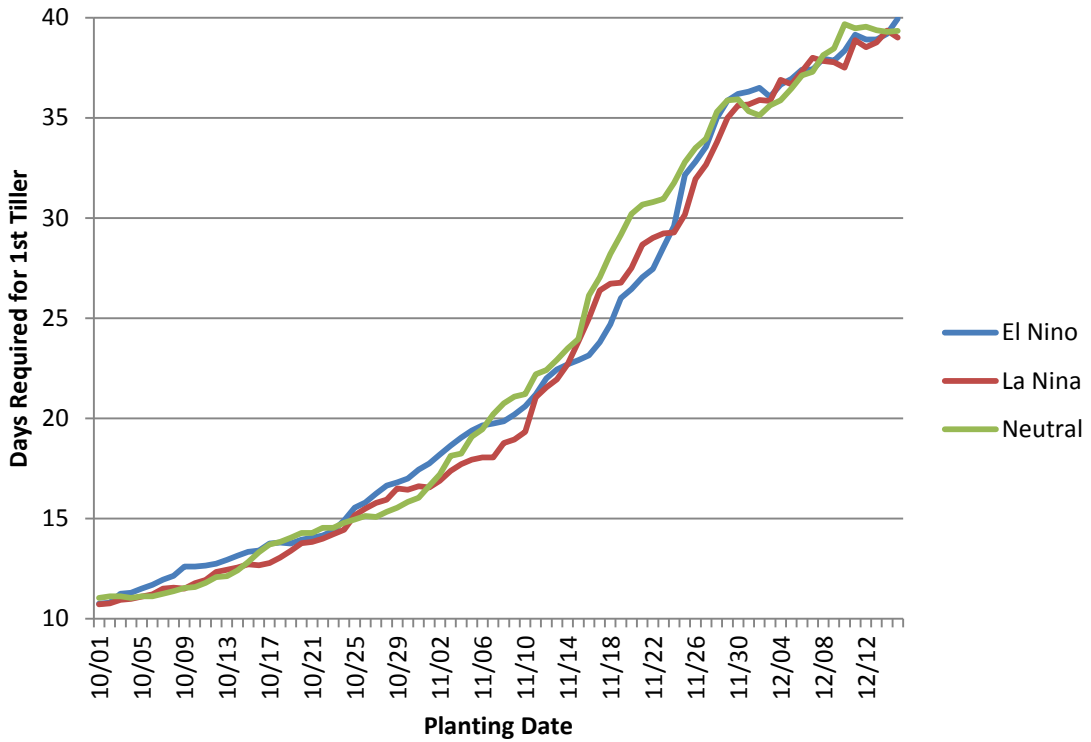


Figure 3.5: Days required to reach 310 GDD (1<sup>st</sup> tiller) based on temperatures averaged over the period from 1950 to 2011 for the three ENSO phases at Salisbury.



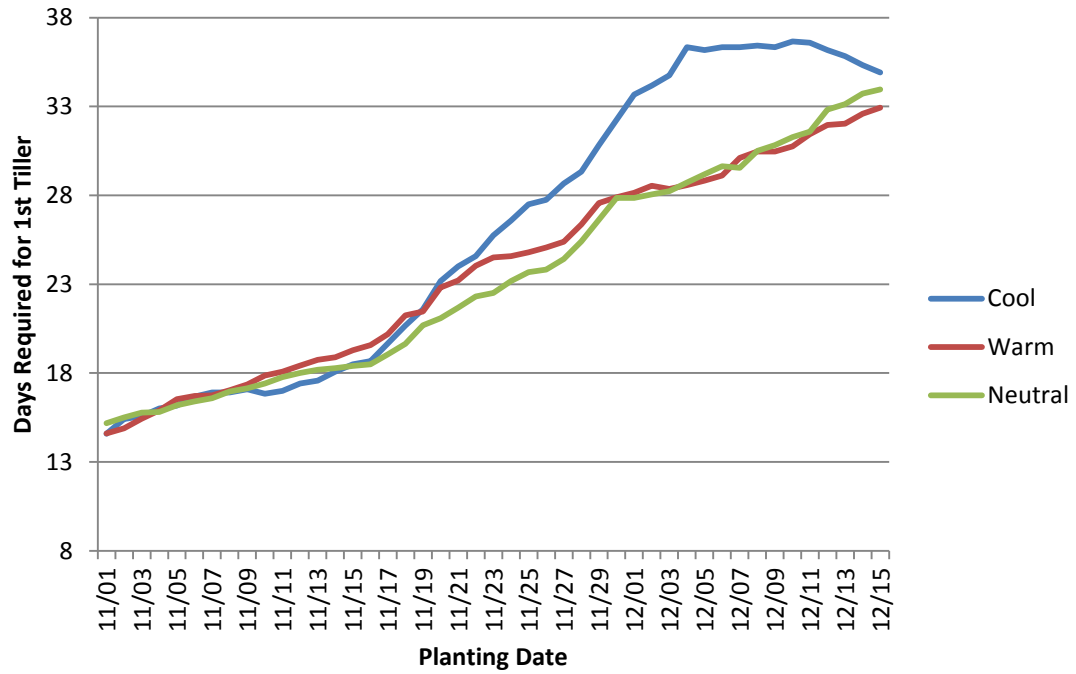


Figure 3.6: Days required to reach 310 GDD (1<sup>st</sup> tiller) based on temperatures averaged over the period from 1950 to 2011 for the three October NAO phases at Pasquotank County.

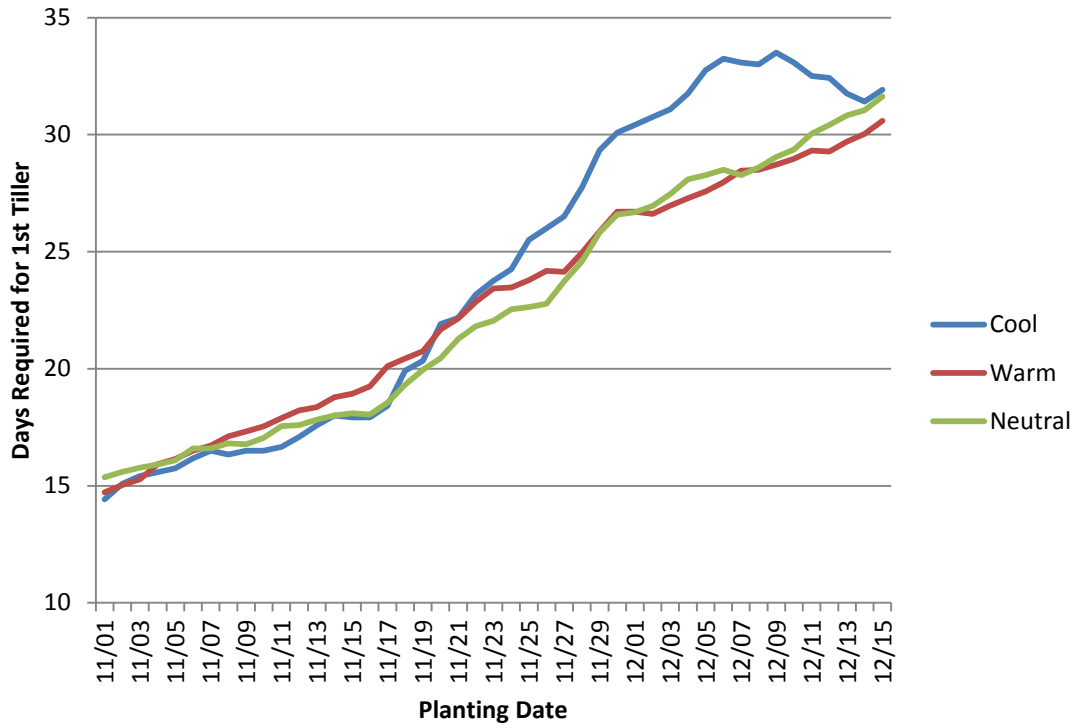


Figure 3.7: Days required to reach 310 GDD (1<sup>st</sup> tiller) based on temperatures averaged over the period from 1950 to 2011 for the three October NAO phases at Washington County.

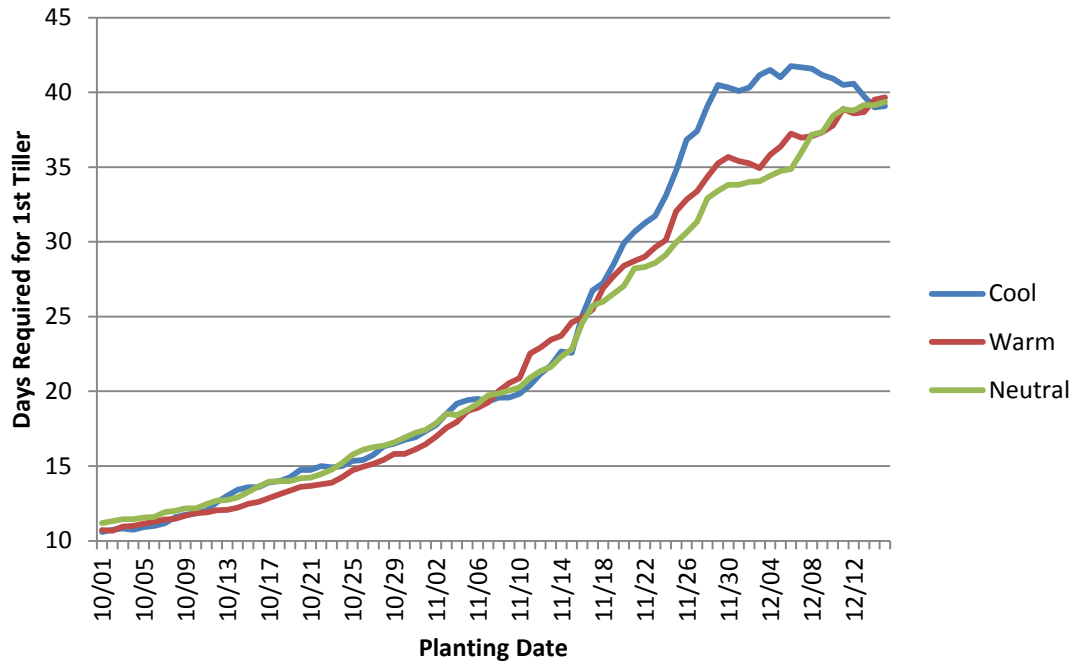


Figure 3.8: Days required to reach 310 GDD (1<sup>st</sup> tiller) based on temperatures averaged over the period from 1950 to 2011 for the three October NAO phases at Salisbury.