Evaluating an Advanced Intensive Management Strategy for Virginia Wheat

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Thesis submitted to the faculty of the Virginia Polytechnic Institute and State University in partial fulfillment of the requirements for the degree of

Master of Science
In
Crop and Soil Environmental Science

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April 29, 2011
Blacksburg, Virginia

Keywords: Winter wheat, Management, Nitrogen, Seeding rate

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ABSTRACT

Current Virginia soft red winter wheat (*Triticum aestivum* L.) management strategies have been in place for over 20 years. A new advanced intensive management (AIM) system has been evaluated in order to improve Virginia wheat yields and attempt to bring state average wheat yields of 4288 kg ha^{-1} more closely in-line with the maximum yield achieved in the Virginia Tech Official Soft Red Winter Wheat Trials of 7400 kg ha^{-1}. Increases in nitrogen (N) fertilizer application rates and splits, a chelated micronutrient blend, increased seeding rates, and a "no tolerance" pest control methodology were compared to current intensive management practices in this study. Additional fall N application and an increased seeding rate resulted in an increased number of tillers m^{-2} at growth stage (GS) 25 and biomass at GS 30. This increased number of tillers may lead to a greater amount of viable grain head production and increased wheat yields. Higher seeding and N application rate resulted in dramatically increased lodging in 2009 with resultant yield loss. Grain yield was significantly affected by management type in three of six instances. The number of heads m^{-2} was the yield component factor most influenced by factors tested in these studies.

Dedication

I dedicate this thesis to my parents, Floyd and Mary Childress, who have always been there to encourage me in whatever I pursue.

Thank you for the love and support.

Acknowledgements

I would like to thank all who have aided and influenced me in this project. Thank you!

Floyd and Mary Childress

Dr. Wade Thomason

Dr. Mark Alley

Dr. Carl Griffey

Dr. Dave Parrish

Harry Behl

Liz Hokanson

Steve Nagle

Mike Brosius

Hunter Frame

Virginia Crop Improvement Association Foundation Seed Farm

Virginia Small Grains Board

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LIST OF ABBREVIATIONS

a.i. – active ingredient

AIM – advanced intensive management

BYDV – barley yellow dwarf virus

CT – conventional tillage

SIM – standard intensive management

GLM – general linear model

GS – growth stage

IPM – intensive pest management

NT – no-tillage

SR – seeding rate

UAN – urea ammonium nitrate

General Introduction

Since the early 1980s, when state wheat (*Triticum aestivum* L.) yields averaged 2680 kg ha^{-1}, Virginia wheat producers have seen an increase in average yields up to the current level of 4288 kg ha^{-1} (NASS, 2010). The increases in yield can be attributed to many factors, including genetic gains, which have led to greater stress tolerance and disease resistance, and also improved management practices. The improvements in management practices include optimizing plant populations, tailoring N fertilizer applications to better meet plant needs, and implementing integrated pest management guidelines (Herbert et al., 2005). However, the intensive management practices currently in use were created in the early 1990s, prior to extensive adoption of minimum or no-till production practices; and they may need to be updated to further take advantage of genetic improvements, new pest management tools, as well as improved planting equipment that can potentially increase yield. Since 2001, the average overall yield measured from Virginia Tech Official Variety Trials for wheat has increased; but the maximum yields attained have remained near 7400 kg ha^{-1} without any appreciable changes in management practices (Thomason et al., 2009a), indicating that genetic yield potential and disease resistance improvement may not be the primary limiting factors in improving the state maximum wheat yield, since these high yields are achieved in nurseries that are not treated for disease. There is a need to re-evaluate current management practices in order to drive further increases in overall production and to narrow the “gap” between yields that approach the species’ biological potential and what is produced under Virginia conditions. The intent of this study is to re-evaluate the management of high-yield wheat and demonstrate the effect of intensive management practices and strategies on wheat production.

Literature Review: Effect of Management Practices and Strategies on Wheat Production

The Yield Gap

Wheat is the third most-produced cereal after corn (*Zea mays* L.) and rice (*Oryza sativa* L.) and together provide about two-thirds of all energy in human diets (FAO STAT, 2011). Currently a yield gap exists between yields achieved by farmers and yield potential of wheat. While maintaining a sizable yield gap is necessary for sustaining steady increases in average wheat yields, there exists a need to close this deficit to better meet world demand for wheat. It is projected that the world population will grow from 6 billion in 1999 to 9 billion by 2044, an increase of 50 percent (U.S. Census Bureau IDB, 2011). The projected increase in population will create greater food demand, while the amount of cultivatable land will diminish. In order to meet this demand, greater yields are needed per unit of land and time. Intensive management of wheat allows consistent production at high yield levels without causing environmental damage (Cassman, 1999). This requires improvements made in soil fertility to be made precisely and in an as-needed basis rather than widespread applications of inputs. As such, developing the scientific knowledge, technology, and farmer education to allow diagnosis of yield limiting factors, prediction of expected yields and input requirements, and the implementation of field-specific management are crucial to food security.

Wheat Management

Management, not simply additional inputs, is the key to improving wheat productivity and decreasing risk from negative environmental impacts. Management strategies have been created to optimize the grain yield potential for soft red winter wheat in Virginia and the southeast, but much remains to be done to truly realize maximum yield potential. According to Alley et al. (1993), ability of the producer to remain flexible and make management decisions appropriate to their situation is key to optimizing yield.

To truly be a successful manager, a producer must first be able to identify in the field the various growth stages of soft red winter wheat. Timing, as indicated by growth stage, is critical to achieving maximum results from inputs. For example, N applications need to be made at the growth stages that are critical to continued plant growth and development, not at a calendar date convenient for the producer (Hucklesby et al., 1971; Hargrove et al., 1983). Regardless of whether the Feekes' growth scale (Large, 1954) or the Zadoks' decimal code (Zadoks et al., 1974) for growth is used, wheat development may be divided into five main categories, each of which plays an important role in yield formation. These developmental periods are seedling emergence, tillering, stem elongation, flowering, and grain-fill (Alley et al., 1993).

Awareness of wheat growth stages enables effective management. Management can affect the number of wheat spikes per unit area via canopy manipulation during initial tillering. Proper use of effective management strategies may allow optimal numbers of vigorous tillers to emerge, and, in later stages, maintenance of these tillers. Kernels per spike may be influenced by proper management decisions during stem elongation, pollination, and grain fill.

Cultivar selection is paramount when maximum grain yield is desired. Cultivars should be chosen on the basis of heading date, resistance to major diseases known to be present in the specific area, plant height, lodging rating, test weight, and yield potential (Thomason et al., 2009b). Due to the wide climatic variation across Virginia, there is not a single best cultivar. Wheat cultivars should be adapted to the area in which they are to be planted. In eastern

Virginia, producers may choose to double-crop wheat with soybeans (*Glycine max L.*). To effectively manage this, wheat cultivars are chosen that have earlier heading and maturity dates and are planted later in the fall to take advantage of optimum environmental conditions during the spring grain fill period. Producers in western Virginia, however, do not typically double-crop after winter wheat. Wheat cultivars grown in the western portion of the state need to be planted earlier in the fall to minimize the chance for freeze damage and winter kill. Producers should plant multiple cultivars to reduce the risk of the total crop being susceptible to a single major disease outbreak or adverse weather. Choosing cultivars that match the climatic variations, disease pressures, and producer's needs is a necessary and profitable yield-building strategy.

Virginia has a humid subtropical climate (Hayden and Michaels, 2000), which is favorable to a number of diseases that can cause a significant amount of economic damage to wheat. Diseases that occur yearly in a humid climate such as this can be grouped into foliar, head, and root and crown diseases. Intensive management calls for selection of disease resistant cultivars and regular scouting of fields to identify potential problems and timely applications of appropriate disease control practices to reduce the potential impact of yield-limiting diseases.

Disease pressure causes major losses in yield for wheat producers in Virginia and other areas having humid climates (Roth and Marshall, 1987). Management strategies such as planting multiple cultivars to reduce the risk of yield loss from a major disease outbreak and timing planting, fertilization, and insecticide and fungicide applications are essential to minimizing losses associated with disease. The Virginia Tech Pest Management Guide (Hagood and

Herbert, 2009) provides suggestions for products and application rates for insecticides and fungicides. Diseases such as powdery mildew (*Blumeria graminis* f. sp. *tritici*), leaf rust (*Puccinia persistens.*f. sp. *triticina*), and Stagnospora glume blotch (*Phaeosphaeria nodorum* f. sp. *tritici*) typically cause a reduction in photosynthetic leaf area and cause a general increase in respiration and transpiration within the colonized host tissues (Broscious et al., 1985). Yield losses may be great due to reduced plant vigor, growth, and seed fill, which result in a loss of profit for producers (Everts et al., 2001). Producers trying to increase grain yield components and grain yield by increasing the total N application rate may run the risk of increasing powdery mildew and leaf rust incidence and severity (Boquet and Johnson, 1987; Krupinsky et al., 2002). Kelley (2001) and Ransom and McMullen (2008) found that the impact of foliar diseases may be reduced and monetary return may be salvaged by integrating fungicides and plant genetic resistance.

Head diseases are generally more prevalent in wet seasons due to favorable conditions for infection. Two common examples of head diseases that affect Virginia producers are glume blotch and fusarium head blight (*Fusarium graminearium*). Fusarium head blight can cause wheat grain to be shriveled or killed, replaced by the pathogen, and have an increased chance for mycotoxin contamination (Ransom and McMullen, 2008). Fusarium head blight is best managed through multiple strategies, as a single strategy often fails when environmental conditions favor severe infections. Strategies that have proven effective in managing fusarium head blight include selecting resistant cultivars, using high quality seed that has been treated with a systemic fungicide, minimization of pathogen-colonized crop residue in the field, crop rotation, implementing a fungicide spray program, and staggering planting dates. Any combination of these strategies may reduce the severity of fusarium head blight.

Wheat glume blotch causes brown glume lesions and sometimes complete darkening of wheat heads as the plants approach maturity. Initial infection of glume blotch resembles other diseases, which often makes diagnosis difficult. The fungus that causes wheat glume blotch is distributed in all wheat-growing areas of the world (Buhariwalla, et al., 2008). In Virginia, glume blotch is most commonly found in the western portion of the state, because it is favored by high rainfall (Stromberg, 2000). The most effective management strategy for controlling wheat glume blotch is planting resistant cultivars. Cultivars with disease ratings of "good" or better provide adequate resistance to glume blotch. Wheat cultivars that are taller also tend to be less prone to glume blotch infection, because rain-splashed spores cannot reach the heads as easily. Foliar fungicides and systemic fungicide seed treatments may also be used to control glume blotch.

Root and crown diseases can be very common in Virginia, because such diseases thrive at moderate temperatures and high moisture levels during the initial infection and colonization of the wheat plant (Alley et al., 1993). The most common root disease in the region is take-all disease (*Gaeumannomyces graminis* var. *avenae*), which is a fungal disease that attacks the bases of the main stem and tillers, causing complete or partial rotting (Bowden, 2000). Stems and tillers that have been compromised cannot adequately supply nutrients and water to the developing heads. Reducing the nutrient and water supply causes the heads to dry up and die prematurely. Scouting in an infected field may reveal "whiteheads", or prematurely dead heads among healthy flowering heads. The simplest and most cost effective measure for control of take-all is crop rotation (Alley et al., 1993). Rotating a field from wheat production to another crop that is not a host for the take-all organism for several growing seasons or allowing the crop field to lie fallow reduces the presence of the fungus in any infected crop residue, such as the crowns and roots, and in the soil. In continuous wheat production, Christensen and Brett (1985) found that take-all severity was reduced when soil micronutrients and pH were managed correctly. Their study found that the addition of Chloride (Cl) and maintaining a pH of 5.0 to 5.5 in organic soils and 6.0 to 6.4 in mineral soils reduced take-all symptoms and increased grain yield.

Control of viral diseases after infection occurs is generally not possible, so management must focus on preventing infection (Cisar et al., 1982). Typical characteristics of viral infection in winter wheat include plant stunting and leaf mosaics and yellowing. The most widely distributed and destructive viral diseases in Virginia wheat are *barley* and *cereal yellow dwarf viruses* (Luteovirus) (Stromberg, 2009). Symptoms are often confused with various nutritional or non-biological disorders. Severe stunting and yellowing or purpling of leaves is indicative of these aphid-vectored (*Rhopalosiphum padi* L. and *Sitobion avenae* F.) diseases. A study by Kieckhefer and Gellner (1992) revealed that yield reductions due to aphids and *barley yellow dwarf virus* (BYDV) can be as high as 35 to 40%. Implementing a thorough scouting and management strategy is the cornerstone to preventing grain yield loss and maximizing producer profits (Krupinsky et al., 2002). Delaying fall planting until aphid populations decline and using resistant or tolerant cultivars may reduce the risk for BYDV by reducing the window and likelihood of aphid feeding. Systemic insecticide seed treatments and foliar-applied products reduce aphid populations through the fall, which minimizes the number of primary infections.

Foliar insecticide treatments may need to be applied if spring aphid counts reveal levels above threshold infestation of 450 aphids per meter of row in several locations within a field (Day, 2009).

Tillage Selection, Integrated Pest Management, and Seeding Rate

Many recent studies on wheat have dealt with the introduction of intensive no-till systems (Decker et al., 2009) and its impact on wheat grain yield (Young et al., 1994; Diaz-Zorita et al., 2004, Kumudini and Grabau, 2007; Kumudini et al., 2008), conservation of nutrients for the following crop (Johnston and Fowler, 1991; Halvorson et al., 2004), and the retention of water (Tompkins et al., 1991; Bonfil et al., 1999; Nielsen et al., 2002). Traditionally, preparation of seedbeds using plows, discs, and culti-packers was required to achieve proper seed to soil contact and allow grain drills to penetrate the soil and place the seed at an optimum rate and depth. No-till methods of planting were created to minimize the amount of soil disturbance and increase producer efficiency by reducing the number of trips across the field. A typical no-till cropping system uses a grain drill specifically designed to cut through the previous crop residue, place the seed in a narrow seedbed, and close the furrow with minimum impact on the surrounding area (Ganzter and Blake, 1978). Various studies have reported that no-tillage wheat production has the potential to increase yields, reduce yields, or maintain yields relative to conventional methods of tillage (Ciha, 1982; Hall and Cholick, 1989; Carr et al., 2003). This inconsistency can be attributed to variations in previous crop residue, water infiltration and holding capacity, weed control, and increased seeding rates with no-till systems.

Crop residues can result in cooler soil temperatures in the fall and slower soil warming in the spring (Kumudini et al., 2008). Cooler soils may cause a delayed emergence, slower seedling development, and reduced tillering. There is also speculation that no-till cropping systems may alter the far-red/red light ratio at the crop crown, which can lead to a reduction of photosynthate partitioning and decrease tillering capacity (Kasperbauer and Karlen, 1986). A study performed by Kumudini et al. (2008) in Kentucky indicates that no-till wheat production, when environmental conditions are unfavorable, can result in reduced yields due to reduced fall tillers and increased spring tiller production. This increases the number of grain heads produced and decreases the number and size of the kernels, resulting in decreased yields. Rasmussen et al. (1997) noted that yield potential in no-till systems is directly linked to environmental effects, seeding rate, and cultivar choice, providing evidence that the no-till system may well be more affected by environmental influences than conventional tillage systems. Virginia producers have begun to appreciate the use of no-till cropping systems to reduce their labor and fuel inputs, allow an earlier planting date, reduce erosion, and improve soil conservation (Thomason et al., 2009a). No-till wheat production does not always achieve higher yields than conventional tilled production, but the advantages make the adoption of no-till very practical in reaching sustainable maximum wheat yields.

Increased utilization of no-till wheat production has created greater disease, pest, and weed pressure and incidence than normally seen in conventional till production (Stromberg, 2009). This is especially true when residue left on the soil surface is from a previous corn or wheat crop. Usually the increase in disease incidence and severity occurs because a greater amount of inoculum of the pathogen is present on the wheat residue left above the soil surface. Examples of increased disease pressure from leftover wheat residue include Fusarium head blight, glume blotch, and tan spot (*Pyrenophora tritici-repentis* D.). The fruiting bodies of these fungi overwinter on the remaining corn and/or wheat residue and provide a large amount of spores to infect the subsequent wheat crop. Pests such as the Hessian fly (*Mayetiola destructor* S.) and aphids may overwinter, and oversummer, in crop residue. Undisturbed residue provides a better habitat for the overwintering/oversummering life cycles of these pests to survive (Herbert et al., 2005). In no-till systems, both annual and perennial weeds such as henbit (*Lamium amplexicaule* L.), chick weed (*Ageratum conyzoides* L.), shepherd's purse (*Capsella bursa-pastoris* L.), ryegrass (*Lolium temulentum* L.), and common burdock (*Articum minus* B.) are major problems. Due to the absence of tillage, initial weed control before and immediately following planting is accomplished solely with herbicides. However, upon establishment of the wheat crop, weed control methods are the same as in conventional systems. Despite the potential challenges associated with using no-till production, effective management guidelines and tactics are available to counter increased disease, pest, and weed threats. Utilizing crop rotations and integrated pest management (IPM) programs can make no-till wheat production very successful.

Seeding rate also influences wheat grain yield under intensive management. Ciha (1983) and Roth et al. (1984) report that increased seeding rates may be beneficial when germination and emergence conditions are less than optimal. However, Joseph et al. (1985) noted that increasing seeding rate to supraoptimal levels such as 700 seeds m^{-2} or greater resulted in a linear decrease in soft red winter wheat yield in Virginia. Johnson et al. (1988) found that grain yield of soft red winter wheat did not respond to increases in seeding rate beyond the normal recommended seeding rate of 300 to 400 seeds m^{-2} in conventional tillage and 400 to 600 seeds m^{-2} in no-tillage situations in field studies conducted in Georgia. In Virginia, it is recommended to increase seeding rates in no-tillage systems by 10% over conventional seeding rates when planting into heavy residue, such as corn stalks, or when soil conditions make it difficult to maintain a constant planting depth (Thomason et al., 2009a). This suggests that achieving the appropriate seeding rate along with planting date is necessary to optimize potential wheat grain yield.

Plant Nutrition

Typically, N fertilizer is necessary for reaching the potential maximum grain yield. The impact that N has on wheat yield goes much further than total yield (Nielsen and Halvorson, 1991). Nitrogen affects the three yield components of wheat: heads per unit area, kernels per head, and kernel size, by influencing vegetative plant growth. Traditionally in Virginia, N is applied in the fall at planting and in two in-season splits, usually occurring at Zadoks growth stage (GS) 25 and 30, or sometime during the early and late spring (Roth et al., 1987; Alley et al., 1996; Flowers et al., 2001; Weisz et al., 2001). Each split should not exceed more than 67 kg ha^{-1} to avoid foliar damage and maximize N use efficiency (Alley, et al., 1996). Applying N in two applications has become the norm in Virginia, because this better matches crop demand with nutrient availability. Cooke (1982) found that applying N in split or delayed applications would be most effective in soils where residual N is low and leaching risk is high. Roth et al. (1987) state that wheat is most responsive to split N applications if: (i) the field has a high N requirement, and (ii) there is a substantial risk of N loss due to leaching or denitrification. These situations are applicable to Virginia producers, especially those located in the Coastal Plain, the main wheat producing area in the state.

To effectively create and implement a multiple split N application program, the producer must understand why the application splits are timed accordingly and what stands to be gained from proper utilization of an N management plan. The GS 25 application is used to maintain and stimulate formation of tillers, which may lead to an increase in harvestable heads and, hence, grain yield. If tiller density is below the level necessary to achieve optimum yields, the N application rate may be adjusted upwards to satisfy the plant needs for tillering (Flowers et al., 2001). The second spring application of N is made at, or just after, GS 30, which is the beginning of stem elongation and the most rapid period of wheat growth. During this time, the potential number of kernels per head is being established during embryonic head development. The purpose of this second application is to provide the wheat with N during the time of maximum uptake and use while leaf area is increasing and reproductive structures are forming (Alley et al., 1996). If N is limiting to the wheat plant during this period, tiller abortion may occur, which reduces the number of heads per acre at harvest. At this point in the growing season and beyond, management must be directed at maintaining the developing heads and the supporting yield-forming structures.

In an intensive wheat management program, soil micronutrients are closely monitored due to their potential impact on yield components and grain yield. Typically, micronutrient deficiencies can be identified through the use of soil sampling and analysis, plant tissue testing at various growth stages, and the careful review of previous crops' needs for micronutrient fertilization (Brann et al., 2000). Micronutrient deficiencies are most likely to occur when the soil pH falls below 5.0 or is above 7.0. This is particularly a problem in a crop that requires intensive N inputs. Nitrogen fertilizers are slightly acidic, and regular applications of N may lower soil pH below the optimum range for micronutrient uptake (Alley et al., 1993). Soil pH may also be lowered as basic cations such as Ca, Mg, and K are leached or removed from the soil. For example, manganese (Mn) deficiency can limit growth at pH levels above 6.5 and cause toxicity to wheat at pH levels of 5.2 or lower (Ohki, 1984). Micronutrient uptake may be limited by other means as well. In wheat-producing areas throughout the state that either use animal manure containing high amounts of P or have high soil levels of P, there can be severe limitations to the uptake of copper (Cu), Mn, and zinc (Zn) (Brown, 1965; Singh et al., 1986). The effect of micronutrient deficiencies in wheat can be seen in yield components and in grain yield, making the management of soil micronutrient composition extremely important to maximizing Virginia wheat yields.

Objectives

The overall objective of this study is to evaluate an advanced intensive management strategy for impact on grain yield and yield components of Virginia wheat. This study will help determine where yield formation can be most affected and what measures need to be taken to improve wheat yields.

Materials and Methods

Field experiments were conducted at Mt. Holly, Virginia, under conventional-tillage and no-tillage management and Blacksburg, Virginia, under conventional tillage, in 2009 and 2010. These sites were selected because they provide a direct comparison of proposed management strategies in different climatic and soil types. Soil series for Blacksburg were a Guernsey silt loam (fine-loamy, mixed, active, mesic Ultic Hapludalf) in 2009 and a Hayter loam (fine, mixed, superactive, mesic Aquic Hapludalf) in 2010. Plots in Mt. Holly were grown on a State fine sandy loam (fine-loamy, mixed, semiactive, thermic Typic Hapludalf) during both the 2009 and 2010 seasons (Table 1). The Blacksburg location was planted with a Great Plains 605NT no-till grain drill, while the Mt. Holly site was planted with a John Deere 1590 no-till grain drill, both with 19 cm row spacing. At Mt. Holly, plots were 14.6 m long and 3 m wide. Plots located in Blacksburg were 14.6 m long and 3.6 m wide. In 2009, the soft red winter wheat cultivar Shirley was used at both Blacksburg and Mt. Holly, while in 2010, 'Shirley' was used at Blacksburg and 'Merl' was used in both the conventional and no-tillage studies at Mt. Holly (Table 1). Treatments consisted of two seeding rates under standard intensive management (SIM) (Alley et al., 1993) and advanced intensive management (AIM) practices, with and without supplemental irrigation. Experimental design was a split-split plot with four and six replications at Mt. Holly and Blacksburg, respectively. Main plots were irrigation or no irrigation, sub-plots were seeding rate, and sub-sub-plots were management; either SIM or AIM practices. Supplemental irrigation was supplied via a surface drip system when soil moisture in the 0-to-30-cm depth dropped to 70% field capacity. Seeding rates were 379 or 482 seeds m^{-2} when planted in conventional tillage and 482 or 551 seeds m^{-2} when planted no-till.

SIM Treatments

Standard intensive management is based on current Virginia Tech/Virginia Cooperative Extension recommendations for wheat production (Alley et al., 1993). Standard N management was 34 kg N ha^{-1} at planting, GS 25 N rate based on tiller density, and GS 30 N rate based on tissue N concentration (Table 1). Pre-plant applications of P, K, S, and lime were based upon soil testing recommendations. Weed control was maintained using thifensulfon-methyl and tribenuron-methyl herbicide at 0.021 kg a.i. ha^{-1}. Pest control was based on current Virginia Cooperative Extension IPM (Herbert et al., 2005) thresholds. To control aphid populations in the SIM plots, lambda-cyhalothrin insecticide was used when IPM thresholds were exceeded in either the fall or spring. Lambda-cyhalothrin was applied in the late fall (GS 15) at a rate of 0.034 kg a.i. ha^{-1} to prevent aphid infestation. Prothioconazole plus tebuconazole fungicide was applied at early to mid-flowering (GS 58) at 0.017 kg a.i. ha^{-1} to control fusarium head blight, glume blotch, and leaf and stem rust.

AIM Treatments

Advanced intensive management consisted of an overall winter/spring N rate increase of 20% beyond standard recommended rates, with four instead of two in-season splits (late fall, GS 25, GS 30, and GS 45) (Table 1), a micronutrient fertilizer blend of 0.5% B, 2% Cu, 1.5% Mn, and 1.5% Zn applied at 1500 ml ha^{-1} with each spring N application, and "no tolerance" prophylactic pest management. Lambda-cyhalothrin insecticide was applied to the AIM plots in the fall at GS 15 at 0.034 kg a.i. ha^{-1}, while prothioconazole plus tebuconazole fungicide was applied at mid-flowering (GS 58) at 0.017 kg a.i. ha^{-1} Weed control was maintained using thifensulfon-methyl and tribenuron-methyl herbicide at 0.021 kg a.i. ha^{-1}. Urea ammonium nitrate solution (UAN) was used as the N source for both the SIM and AIM tests.

Irrigation and Chemical Application

Irrigation was supplied to the wheat through the use of 6 mil T-Tape drip tape (Deere & Company, Moline, IL), with a line spacing of 0.4 meters. Water was carried to the drip tape through 5-cm diameter Vinylflow Layflat™ tubing (Kuriyama of America, Schaumburg, IL). The irrigation system was designed to deliver 300 and 525 liters per minute at Blacksburg and Mt. Holly, respectively. At Blacksburg, 3.8 cm of water per irrigation was applied, while 1.9 cm was applied at Mt Holly. This difference was due to differences in soil water holding capacity between the two sites. It should be noted that no irrigation was applied at the Blacksburg location in 2009 due to more than adequate rainfall. All applications of liquid fertilizer and herbicides were made with a CO_2- powered backpack sprayer. Thifensulfon-methyl and tribenuron-methyl herbicide was applied to the plots at 0.021 kg a.i. ha^{-1}. The application of lambda-cyhalothrin insecticide was performed at the same time as fall UAN and herbicide applications. The rate of insecticide application depended upon the management system and the severity of aphid infestation. SIM plots were applied with 0.034 kg a.i. ha^{-1} of insecticide. AIM plots were applied with 0.034 kg a.i. ha^{-1} of insecticide as part of the “no tolerance” pest management strategy. All treatments received an application of ethephon at 0.175 kg a.i. ha^{-1} at GS 48 to reduce lodging potential.

Site Measurements

Early season stand was assessed by counting total plants from 1 m of row from three locations within each plot at GS 11. At GS 25, the number of tillers m^{-2} was determined for each plot by counting all tillers from 1 m of row from three random locations within each plot. At GS 30 biomass was sampled from each plot from similar areas as the GS 25 tiller counts, but clipping occurred outside the area to be used for grain harvest. Plant tissue was dried in a forced air oven at 60°C for 48 hr and then weighed to determine dry matter. At GS 80, the number of heads in 1 m of the centermost row of the plot, measured approximately 1 m from the end of the plot, was counted to estimate the total number of heads m^{-2}. Grain was harvested from the center 1.2 m of the 3.6-m wide plot, using a Kincaid 8XP plot combine. Plot grain weight, grain moisture, and test weight were determined using a HarvestMaster™ system (Juniper Systems, Logan, UT). A grain subsample was taken from each plot upon which test weight and moisture were determined using a Dickey-John GAC 2100 (Dickey-John, Auburn, IL) grain analyzer. Kernel weight based on 1,000 kernels was also determined from this subsample. The number of kernels $head^{-1}$ was calculated as the quotient of kernels per plot and heads per plot.

Climatic data

Hourly air temperature, soil moisture, and climatic information was gathered during the growing season using Watchdog™ (Spectrum Technologies Inc., Plainfield, Il) weather stations at Blacksburg (Figures 1a and 1b) and Mt. Holly (Figures 2a and 2b). Thirty-year mean precipitation and temperature data were obtained from the National Weather Service, Eastern Region Center (NOAA, 2010).

Statistical analysis

Data were analyzed as a split-split plot design using the GLM procedure available from SAS (SAS Inst., 2008). Due to interactions of treatment effects with years and locations, data are presented by year, by site. At Blacksburg in 2009, rainfall was more than adequate so no irrigation was supplied and just the split plot of seeding rate and the subplot of management type were evaluated. Mean comparisons using a protected LSD test were made to separate irrigation, seeding rate, and management effects where F-tests indicated that significant differences existed ($P \leq 0.05$).

Results and Discussion

Analysis of variance of vegetative measures, lodging, grain yield, and yield components are presented in Table 2 for Blacksburg in 2009 and 2010; in Table 3 for the conventional tillage study at Mt. Holly in 2009 and 2010; and in Table 4 for the Mt. Holly no-tillage study in 2009 and 2010. Providing supplemental irrigation generally had no effect on yield or yield components, however seeding rate and management type significantly affected tillers, aboveground biomass, grain yield, and yield components in some sites and years.

Weather

Climatic conditions varied considerably over the two cropping seasons. The spring of the 2009 season was unseasonably wet during pollination and grain fill, especially in Blacksburg, where rainfall totals were 130 mm greater than the 30-year average for the spring (Figures 1a and 1b). The average monthly temperature during the month of June, 2010 at Mt. Holly was 3°C higher than historical averages, while rainfall was 120 mm less than the 30-year average (Figures 2a and 2b). These weather conditions likely contributed to the reduced yields observed at Mt. Holly in 2010. A reduction in yield due to increased average temperatures was reported by Gibson and Paulsen (1999) who found that for every 1°C increase above 15°C after anthesis and during grain fill there would be 3% to 5% decrease in yield. Yield reduction is attributed to greater physiological stress placed upon the plant, especially if the plant is growing during a period of high temperatures and water deficit (Porter and Gawith, 1999). This stress leads to lessened photosynthetic ability and a decrease in photosynthate transfer and accumulation in the filling grain head (Wheeler et al., 2000; Lanning et al., 2009).

GS 25 Tiller density

Growth stage 25 tillers were significantly influenced by management in all instances except at the Blacksburg 2010 site (Tables 2-4). Tiller density was also affected by seeding rate at Blacksburg in 2009. Growth stage 25 tiller counts ranged from 1080 to 1515 tillers m^{-2} in 2009 and 1376 to 1446 tillers m^{-2} in 2010 in Blacksburg. In Mt. Holly, tiller counts in 2009 ranged from 1190 to 2040 tillers m^{-2}, while in 2010 tillers varied from 1108 to 1842 tillers m^{-2}. Spring (GS 25) tiller counts for the 2009 and 2010 harvest seasons in Blacksburg and Mt. Holly as affected by management system are shown in Figure 4. The AIM system resulted in greater tiller density at five of the six site years, with an average of 300 tillers m^{-2} than the SIM system. Tiller counts at Blacksburg in 2009 in response to seeding rate are shown in Figure 5. At this site, the higher seeding rate resulted in more tillers (>1350 m^{-2}) than the normal seeding rate of 379 seeds m^{-2} (Figure 5). Fall-developed tillers are capable of producing larger and more productive grain heads than are spring tillers; and, according to Darwinkel et al. (1977), both the number of kernels per head and kernel weight decrease gradually from the main shoot to successive tillers produced throughout the vegetative period of growth. This indicates that optimizing the seeding rate to most effectively utilize resources and to produce adequate fall tillers is a key component to yield formation. The advanced intensive management system produced, on average, higher tiller counts than the standard intensive management system during both years and in both locations. In Blacksburg, 147 more tillers m^{-2} were produced using the advanced intensive management, while in Mt. Holly, 243 more tillers m^{-2} were produced using this system (Figure 4). This can most likely be attributed to the early winter N application in addition to the pre-plant application of 34 kg N ha^{-1}.

GS 30 biomass

Growth stage 30 biomass accumulation in Blacksburg ranged from 1881 to 2160 kg ha^{-1} in 2009 and 1102 to 1321 kg ha^{-1} in 2010. Biomass at GS 30 at Mt. Holly in 2009 varied from 833 to 1257 kg ha^{-1} and in 2010 ranged from 1020 to 1558 kg ha^{-1}. However, GS 30 wheat biomass was only affected significantly by the imposed treatments at the Mt. Holly CT location in 2010 (Table 3). At this site, the main effects of seeding rate and management type were significant. The higher seeding rate of 482 seeds m^{-2} resulted in over 1300 kg ha^{-1} of dry biomass, which was > 300 kg ha^{-1} more than the amount collected from the normal seeding rate plots (Figure 6). It is hypothesized that this increase occurred because higher plant densities make more efficient use of available light space and resources (Hay and Porter, 2006; Kumudini and Grabau, 2007). Similarly, AIM resulted in > 300 kg ha^{-1} additional biomass at GS 30 compared to SIM (Figure 7). Like the increase in tillers at GS 25 associated with AIM, the increased biomass production can be attributed to the early winter application of 40 kg N ha^{-1}, which promoted late fall and winter crop growth. The increased biomass could also be linked to reduced potential for pest damage with the more intensive management. However, we speculate that this is unlikely because pest pressure was not severe in the plots with SIM management.

Grain yield

Wheat grain yield was significantly affected by the interaction of seeding rate and management type at Blacksburg in 2009 and at Mt. Holly no-till in 2010 (Tables 2 and 4). The main effect of management type was significant for the Mt. Holly conventional till site in 2010 and the no-till site in 2009 (Tables 3 and 4). Grain yields at Blacksburg averaged 5789 to 6799 kg ha^{-1} in 2009 (Figure 8) and 6419 to 6695 kg ha^{-1} in 2010 (Figure 9). In Mt. Holly, grain yields ranged from

5452 to 7132 kg ha^{-1} in 2009 (Figure 8) and 3869 to 4790 kg ha^{-1} in 2010 (Figure 9). Over both growing seasons and locations, utilizing the higher seeding rates of 482 and 551 seeds m^{-2} resulted in grain yields that were 130 kg ha^{-1} more than the lower seeding rate, however, in 2010 this effect was significant only at the Mt. Holly conventional site (Figure 9). Plots receiving advanced intensive management had a yield increase of 109 kg ha^{-1} over plots receiving standard intensive management (Figures 8 and 9). Management variations included providing an additional N application of 40 kg N ha^{-1} in late fall, which promoted fall tillering, and a "no tolerance" pest control methodology, which prevented insect infestation and aphid vectored viral disease inoculation. As part of the advanced intensive management system, the wheat also received multiple in-season splits of N. Multiple small doses of N can provide adequate and sustained plant nutrition throughout the growing season and are more likely to be beneficial in sandier soils where leaching would be more likely to occur. The addition of the chelated micronutrient blend may have also contributed, especially on sandy soils where B, Cu, Mn, and Zn are more likely to be deficient (Mortvedt, 1996). However, no visible micronutrient deficiencies were observed and winter wheat response to micronutrient application is not common in Virginia. The interaction between seeding rate and management observed at two locations (Tables 2 and 4) may be explained by increased plant density and nutrition, which presumably created more favorable conditions for fall tiller production and grain head formation. Plots receiving both higher seeding rates as well as advanced intensive management produced higher grain yields in 3 of the 6 site years than plots receiving a lower seeding rate and standard intensive management.

Heads at harvest

Growth stage 65 heads m^{-2} at Blacksburg varied from 638 to 740 heads m^{-2} in 2009 and 699 to 763 heads m^{-2} in 2010 over treatments (Table 5). Head counts at Mt. Holly ranged from 225 to 930 heads m^{-2} in 2009 and 267 to 904 heads m^{-2} in 2010 (Table 5). Heads m^{-2} was significantly affected by seeding rate at the Mt. Holly no-till location in 2010 and the conventional trials at Mt. Holly in both years (Tables 3 and 4). The higher seeding rates, 482 and 551 seeds m^{-2}, had 40 fewer heads m^{-2} compared to the normal seeding rates of 379 and 482 seeds m^{-2} averaged over management type at all sites. This indicates that, at the higher seeding rates, plants developed fewer spring tillers and fewer small heads, whereas with less interplant competition, plants sown at a lower seeding rate had an increase in the number of spring tillers and small grain heads. This result has also been reported by Holen et al. (2001), who stated that increasing plant densities increased heads m^{-2}, while kernels $head^{-1}$ and kernel weight decreased. This indicates that, with higher seeding rates and/or conditions that favor fall tillering, the number of heads m^{-2} likely has the greatest effect on grain yield, an observation also reported by Blue et al. (1989).

Kernels per head

The number of kernels $head^{-1}$ ranged from 25.8 to 34.3 in 2009 and 27.4 to 30.3 in 2010 at the Blacksburg site. At Mt. Holly, kernels $head^{-1}$ varied from 18.5 to 31.6 in 2009 and 23.1 to 27.6 in 2010 across treatments (Table 6). The reduction in kernels $head^{-1}$ seen in 2010 at Mt. Holly can likely be attributed to the unseasonably warm and dry conditions encountered during the grain fill period (Figures 1a to 2b). Kernel number was influenced by the interaction of irrigation and seeding rate at the Mt. Holly conventional site in 2009 and by management type at the Mt. Holly no-till sites in both years (Tables 3 and 4). At the conventional tillage site at Mt.

Holly in 2009, the higher seeding rate resulted in a greater number of kernels head^{-1} when no irrigation was supplied, however no effect was observed with supplemental irrigation (Table 6). The irrigation by seeding rate interaction that was observed during 2009 at the Mt. Holly conventional site may be explained by increased plant density and more available moisture, which created a more favorable environment for development of a greater number of grain heads in the spring (Table 6). In response to management type, AIM resulted in greater numbers of kernels head^{-1} in 2009 but few kernels than SIM in 2010 (Table 6). A general trend observed was that, as the number of heads m^{-2} increased, the number of kernels head^{-1} decreased for both the Blacksburg and Mt. Holly sites over both years. This inverse relationship has been observed in other research (Darwinkel et al., 1977; Weisz et al., 2001), and the most probable explanation is that the amount of light, space, and nutrients intercepted by a single plant sown at higher seeding rates is comparatively low, while at lower seeding rates more of these resources are available per plant due to decreased inter- and intra-plant competition.

Kernel weight

A similar trend to kernels head^{-1} and heads m^{-2} was observed with kernel weight. In five of six site years, kernel weight increased as the number of heads m^{-2} decreased (Table 7).

Kernel weight was significantly influenced by supplemental irrigation at the Mt. Holly no-till site in 2009 (Tables 2 and 4). In both instances, kernel weight was significantly increased when irrigation was supplied. The main effect of seeding rate also affected kernel weight at the Mt. Holly sites in 2009 (Tables 3 and 4). Over locations, the higher seeding rate resulted in an average increase of 2 mg kernel^{-1} compared to the normal rate (Table 7). Darwinkel (1978) found that kernel weight increased as the number of heads m^{-2} produced decreased. It was also noted by Shanahan et al. (1983) that increased kernel weight is more closely associated with additions of N than any other input, which agrees with the influence of AIM on kernel weight. In Blacksburg, kernel weight varied from 28.6 to 32.5 mg^{-1} in 2009 and 29.9 to 31.4 mg^{-1} in 2010, while Mt. Holly kernel weight ranged from 29.3 to 32.4 mg^{-1} in 2009 and 27.6 to 31.1 mg^{-1} in 2010.

Lodging

Lodging scores for Blacksburg and Mt. Holly are presented in Table 8. Lodging was significantly influenced by management type at all sites in 2009, as well as the interaction of seeding rate and AIM at Blacksburg in 2009 (Tables 2 to 4). As seeding rates and N rates were increased, the incidence of lodging also generally increased (Table 8). In comparison, plots that were planted with lower seeding rates and received lower N rates received lodging scores that were 1.3 units lower. Results similar to these were also seen by Easson et al. (1993), who reported that, at higher seeding rates and high N fertilizer rates, wheat plants had smaller diameter basal internodes with fewer support roots per stem and a lower root dry weight per stem. This indicates that, as seeding rates are increased, competition for space for root production is increased. It also indicates that, at higher N rates, the wheat plants are allocating more resources to tiller production. Easson et al. (1993) speculated that this reallocation resulted in tillers with smaller and weaker stems, which decreased the ability of the wheat plant to stay upright during periods of high wind. Neither tiller size nor stem strength, per se, was measured in these studies. In 2010, lodging values were not significant at either location (Tables 3 to 5). This can be attributed to above-average temperatures and drought conditions, which reduced plant growth.

Summary and Conclusion

The field studies carried out during 2008-2009 and 2009-2010 in Blacksburg and Mt. Holly showed that wheat grain yield and yield components were significantly affected by two main variables: seeding rate and management type. Increased seeding rates and advanced intensive management increased wheat yields, but not consistently over sites and years. Increasing seeding rates resulted in greater numbers of tillers m^{-2} produced in the fall and greater amounts of GS 30 biomass. The increased number of fall tillers and early spring biomass showed the ability to influence grain yields by controlling the development of grain heads. Utilizing advanced intensive management allowed plants sown at higher seeding rates to not only produce a greater number of fall tillers, but permitted tillers to be carried through the winter and become grain producing heads. Current Virginia Cooperative Extension IPM recommendations were observed to be adequate for maintaining insect and disease control in wheat, since yield losses were not observed when IPM recommendations (SIM) were followed. In 2009 in Blacksburg, the combination of higher N rates and increased plant density, as well as unfavorable weather, contributed to greater lodging and a reduction of 220 kg ha^{-1} in grain yield. The addition of supplemental irrigation generally had no positive effect. This can be attributed to higher than average rainfall in 2009 and above average temperatures in 2010. There was no influence of irrigation in 2010 due to air temperatures being 3°C warmer than 30-year averages and rainfall being 40 mm less than 30-year averages, resulting in soil moisture deficit (Figure 3a and 3b). The one component of the AIM system that was consistently beneficial was the late fall N application, especially under no-till conditions. This application had the effect of increasing or maintaining tiller numbers through the winter, thereby increasing wheat yield potential.

However, the cost effectiveness of increased N applications and possibly seeding rates needs to be considered on an individual field basis before adoption.

Soft red winter wheat grown in Virginia can dramatically respond to N fertilization, especially late fall applications. In five of the six site years, utilizing AIM and the associated late fall N application, tiller density was increased. This creates optimal conditions for tiller proliferation, which influences the number of heads m^{-2}. It has been observed that the number of heads m^{-2} most likely has the greatest effect on grain yield. This work suggests that fall N management may be the key factor in yield building and may lead to improved grain yields.

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Tables

Table 1. Cultivar, planting date, harvest date, and in-season nitrogen applications for wheat studies at Blacksburg and Mt. Holly, Virginia, in 2008-09 and 2009-10.

						-----SIM†-----		---------AIM‡---------			
Year	Site	Cultivar	Soil Series and Texture	Planting Date	Harvest Date	GS 25	GS 30	GS 20	GS 25	GS 30	GS 45
						------------------kg N ha^{-1}------------------					
2008-09	Blacksburg	Shirley	Guernsey sl§	9/26/2008	6/30/2009	62	62	34	45	45	22
	Mt Holly CT¶	Shirley	State fsl#	10/20/2008	6/26/2009	67	67	34	45	56	22
	Mt Holly NT††	Shirley	State fsl	10/20/2008	6/26/2009	67	67	34	45	56	22
2009-10	Blacksburg	Shirley	Hayter loam	9/24/2009	6/22/2010	60	60	34	45	45	22
	Mt Holly CT	Merl	State fsl	10/21/2009	6/18/2010	67	67	34	45	60	22
	Mt Holly NT	Merl	State fsl	10/22/2009	6/19/2010	67	67	34	45	60	22

† Standard Intensive Management
‡ Advanced Intensive Management
§ silt loam
¶ CT = conventional tillage
# fine silt loam
†† NT = no-tillage

Table 2. Analysis of variance for Blacksburg conventional till (CT) GS 25 tillers, GS 30 biomass, GS 65 heads, kernels head^{-1} kernel weight, lodging score and grain yield, 2009 and 2010.

2009

Source of Variation	GS 25 Tillers	GS 30 Biomass	GS 65 Heads	Kernels Head^{-1}	Kernel Weight	Lodging Score	Grain Yield
	----------------	----------------	----------------	----Pr>F----	----------------	----------------	----------------
Irrigation	n/a†	n/a	n/a	n/a	n/a	n/a	n/a
Seeding Rate (SR)	**	ns	ns	ns	ns	ns	**
Irrigation*SR	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Management (Mgmt)	**	ns	ns	ns	*	**	ns
SR*Mgmt	ns††	ns	ns	ns	ns	*	*
Irrigation*Mgmt	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Irrigation*SR*Mgmt	n/a	n/a	n/a	n/a	n/a	n/a	n/a

2010

Source of Variation	GS 25 Tillers	GS 30 Biomass	GS 65 Heads	Kernels Head^{-1}	Kernel Weight	Lodging Score	Grain Yield
	----------------	----------------	----------------	----Pr>F----	----------------	----------------	----------------
Irrigation	n/a	n/a	ns	ns	ns	ns	ns
Seeding Rate (SR)	ns	ns	ns	ns	ns	ns	ns
Irrigation*SR	n/a	n/a	ns	ns	ns	ns	ns
Management (Mgmt)	ns	ns	ns	ns	ns	ns	ns
SR*Mgmt	ns	ns	ns	ns	ns	ns	ns
Irrigation*Mgmt	n/a	n/a	ns	ns	ns	ns	ns
Irrigation*SR*Mgmt	n/a	n/a	ns	ns	ns	ns	ns

* Significantly different at the 0.05 probability level

** Significantly different at the 0.01 probability level

† n/a = not applicable

††ns = non-significant

Table 3. Analyses of variance for Mt. Holly conventional till (CT): GS 25 tillers, GS 30 biomass, GS 65 heads, kernels head^{-1}, kernel weight, lodging score, and grain yield in 2009 and 2010.

2009

Source of Variation	GS 25 Tillers	GS 30 Biomass	GS 65 Heads	Kernels Head^{-1}	Kernel Weight	Lodging Score	Grain Yield
	---------------------------Pr>F---------------------------						
Irrigation	n/a	n/a	ns	ns	ns	ns	ns
Seeding Rate (SR)	ns†	ns	*	ns	*	**	ns
Irrigation*SR	n/a	n/a	ns	*	ns	*	ns
Management (Mgmt)	**	ns	ns	ns	*	*	ns
SR*Mgmt	ns	ns	ns	ns	ns	ns	ns
Irrigation*Mgmt	n/a	n/a	ns	ns	ns	ns	ns
Irrigation*SR*Mgmt	n/a	n/a	ns	ns	ns	ns	ns

2010

Source of Variation	GS 25 Tillers	GS 30 Biomass	GS 65 Heads	Kernels Head^{-1}	Kernel Weight	Lodging Score	Grain Yield
	---------------------------Pr>F---------------------------						
Irrigation	n/a	n/a	ns	ns	ns	ns	ns
Seeding Rate (SR)	ns	*	*	ns	ns	ns	ns
Irrigation*SR	n/a	n/a	ns	ns	ns	ns	ns
Management (Mgmt)	*	*	ns	ns	ns	ns	*
SR*Mgmt	ns	ns	ns	ns	ns	ns	ns
Irrigation*Mgmt	n/a	n/a	ns	ns	ns	ns	ns
Irrigation*SR*Mgmt	n/a	n/a	ns	ns	ns	ns	ns

* Significantly different at the 0.05 probability level

** Significantly different at the 0.01 probability level

† n/a = not applicable

††ns = non-significant

Table 4. Analyses of variance for Mt. Holly no-till (NT): GS 25 tillers, GS 30 biomass, GS 65 heads, kernels head^{-1}, kernel weight, lodging score, and grain yield in 2009 and 2010.

2009

Source of Variation	GS 25 Tillers	GS 30 Biomass	GS 65 Heads	Kernels Head^{-1}	Kernel Weight	Lodging Score	Grain Yield
	---Pr>F---						
Irrigation	n/a	n/a	ns	ns	*	ns	ns
Seeding Rate (SR)	ns†	ns	*	ns	*	*	ns
Irrigation*SR	n/a	n/a	ns	ns	ns	ns	ns
Management (Mgmt)	**	ns	ns	*	*	*	*
SR*Mgmt	ns	ns	ns	ns	ns	ns	ns
Irrigation*Mgmt	n/a	n/a	ns	ns	ns	ns	ns
Irrigation*SR*Mgmt	n/a	n/a	ns	ns	ns	ns	ns

2010

Source of Variation	GS 25 Tillers	GS 30 Biomass	GS 65 Heads	Kernels Head^{-1}	Kernel Weight	Lodging Score	Grain Yield
	---Pr>F---						
Irrigation	n/a	n/a	ns	ns	ns	ns	ns
Seeding Rate (SR)	ns	ns	ns	ns	ns	ns	ns
Irrigation*SR	n/a	n/a	ns	ns	ns	ns	ns
Management (Mgmt)	**	ns	ns	*	ns	ns	**
SR*Mgmt	ns	ns	ns	ns	ns	ns	*
Irrigation*Mgmt	n/a	n/a	ns	ns	ns	ns	ns
Irrigation*SR*Mgmt	n/a	n/a	ns	ns	ns	ns	ns

* Significantly different at the 0.05 probability level

** Significantly different at the 0.01 probability level

† n/a = not applicable

††ns = non-significant

Table 5. Harvestable heads m^{-2} at GS 65 in response to irrigation, seeding rate, and management type at Blacksburg and Mt. Holly, Virginia, in 2009 and 2010. CT = conventional till; NT = no-till; AIM = advanced intensive management; SIM = standard intensive management.

			2009			2010		
Irrigation	Seeding Rate	Management	Blacksburg	Mt. Holly CT	Mt. Holly NT	Blacksburg	Mt. Holly CT	Mt. Holly NT
			heads, m2					
N	Normal†	AIM	697	835	818	719	255	303
		SIM	646	930	878	723	249	283
	High‡	AIM	638	783	654	763	282	277
		SIM	681	680	603	732	286	267
Y	Normal†	AIM	727	801	766	735	225	302
		SIM	710	792	904	706	262	317
	High‡	AIM	740	766	689	723	274	284
		SIM	703	809	723	699	268	288
		LSD = 0.05	48.9	96.8	144.7	ns	26.9	ns

†Normal SR = 379 seeds m^{-2} at Blacksburg and Mt Holly CT, 482 seeds m^{-2} at Mt. Holly NT

‡High SR = 482 seeds m^{-2} at Blacksburg and Mt Holly CT, 551 seeds m^{-2} at Mt. Holly NT

Table 6. Kernels head^{-1} in response to irrigation, seeding rate, and management type in Blacksburg and Mt. Holly, Virginia, in 2009 and 2010. CT = conventional till; NT = no-till; AIM = advanced intensive management; SIM = standard intensive management.

			2009			2010		
Irrigation	Seeding Rate,	Management	Blacksburg	Mt. Holly CT	Mt. Holly NT	Blacksburg	Mt. Holly CT	Mt. Holly NT
					kernels, head^{-1}			
N	Normal†	AIM	28.2	23.3	22.5	29.0	25.4	24.1
		SIM	32.8	22.1	20.9	28.2	26.7	26.7
	High‡	AIM	34.3	24.2	29.0	28.0	24.7	27.1
		SIM	29.4	31.4	31.6	27.6	24.8	27.6
Y	Normal†	AIM	25.8	24.8	23.9	27.4	27.2	24.2
		SIM	26.3	24.0	18.5	29.5	25.6	23.1
	High‡	AIM	22.8	25.1	28.6	27.9	25.1	26.8
		SIM	26.0	24.2	24.8	30.3	25.3	26.6
		LSD= 0.05	3.7	3.6	5.9	ns	ns	0.62

†Normal SR = 379 seeds m^{-2} at Blacksburg and Mt Holly CT, 482 seeds m^{-2} at Mt. Holly NT

‡High SR = 482 seeds m^{-2} at Blacksburg and Mt Holly CT, 551 seeds m^{-2} at Mt. Holly NT

Table 7. Wheat kernel weight in response to irrigation, seeding rate, and management type at Blacksburg and Mt. Holly, Virginia in 2009 and 2010. CT = conventional till; NT = no-till; AIM = advanced intensive management; SIM = standard intensive management.

			2009			2010		
Irrigation	Seeding Rate	Management	Blacksburg	Mt. Holly CT	Mt. Holly NT	Blacksburg	Mt. Holly CT	Mt. Holly NT
			kernel weight, mg^{-1}					
N	Normal†	AIM	29.1	29.4	29.3	31.4	29.0	29.2
		SIM	31.1	28.8	28.9	31.0	31.1	29.6
	High‡	AIM	30.3	30.3	31.7	30.5	27.6	30.0
		SIM	28.6	31.6	32.4	30.7	27.9	30.4
Y	Normal†	AIM	31.3	30.5	30.8	31.4	30.8	29.7
		SIM	32.3	31.9	28.4	31.3	29.2	29.4
	High‡	AIM	30.2	32.2	32.6	32.0	29.8	30.7
		SIM	32.5	31.0	31.4	29.9	30.0	30.3
		LSD = 0.05	1.24	2.76	1.39	ns	ns	ns

†Normal SR = 379 seeds m^{-2} at Blacksburg and Mt Holly CT, 482 seeds m^{-2} at Mt. Holly NT

‡High SR = 482 seeds m^{-2} at Blacksburg and Mt Holly CT, 551 seeds m^{-2} at Mt. Holly NT

Table 8. Lodging score at harvest in response to irrigation, seeding rate, and management type at Blacksburg and Mt. Holly, Virginia, in 2009 and 2010. CT = conventional till; NT = no-till;. AIM = advanced intensive management; SIM = standard intensive management.

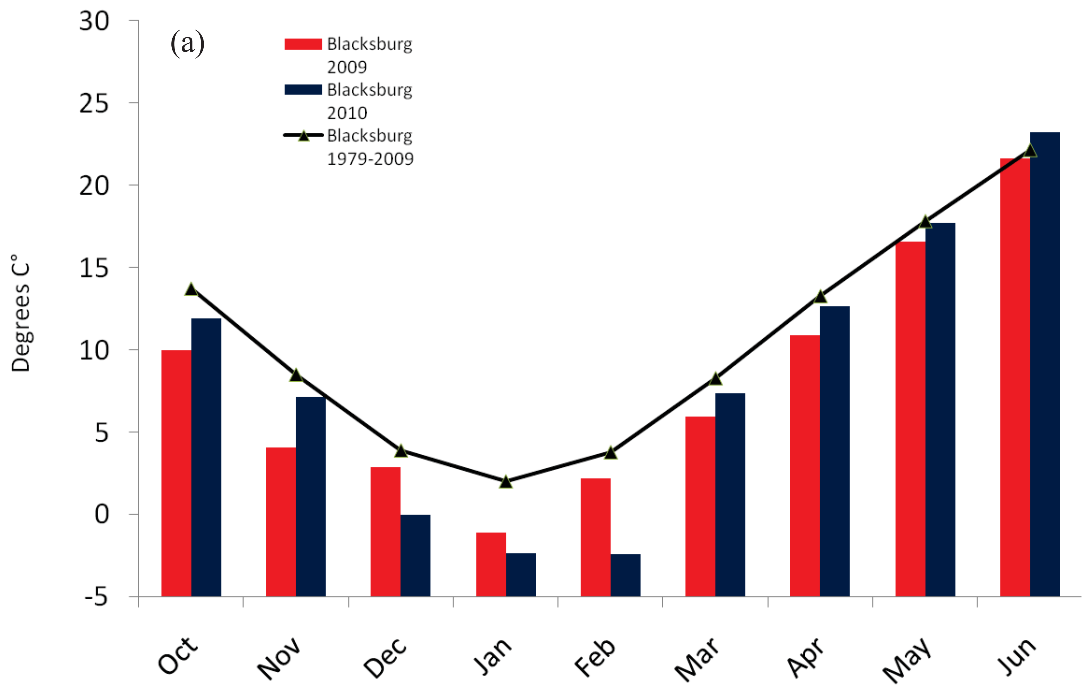
			2009			2010		
Irrigation	Seeding Rate	Management	Blacksburg	Mt. Holly CT	Mt. Holly NT	Blacksburg	Mt. Holly CT	Mt. Holly NT
			lodging, 0-9					
N	Normal†	AIM	7.3	5.3	3.5	0.2	0.5	0.0
		SIM	4.2	1.3	1.3	0.2	0.0	0.0
	High‡	AIM	6.5	7.0	6.3	0.0	0.0	0.0
		SIM	5.0	5.8	1.3	0.5	0.0	0.0
Y	Normal†	AIM	7.2	5.5	4.0	0.2	0.3	0.3
		SIM	5.3	4.0	1.8	0.0	0.0	0.0
	High‡	AIM	7.0	6.3	7.0	0.0	0.0	0.0
		SIM	6.3	4.0	1.5	0.0	0.0	0.0
		LSD = 0.05	0.85	1.3	1.6	ns	ns	ns

†Normal SR = 379 seeds m^{-2} at Blacksburg and Mt Holly CT, 482 seeds m^{-2} at Mt. Holly NT

‡High SR = 482 seeds m^{-2} at Blacksburg and Mt Holly CT, 551 seeds m^{-2} at Mt. Holly NT

Figures

Figure 1. (a) Average daily air temperatures by month in 2008-09 and 2009-2010 and 30-year mean monthly air temperatures and (b) precipitation and 30-year mean precipitation for Blacksburg, Virginia.



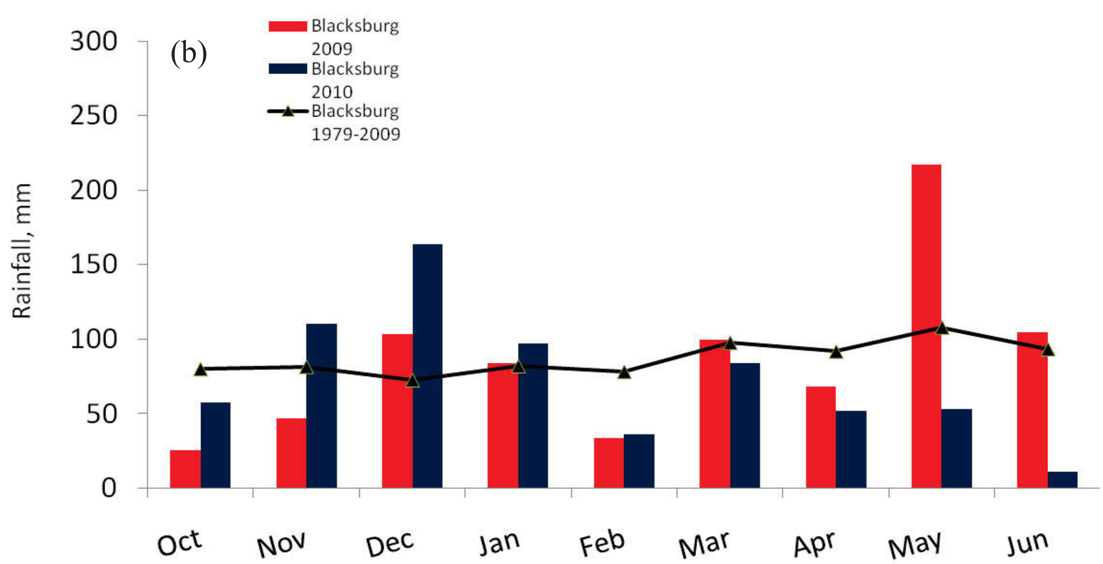
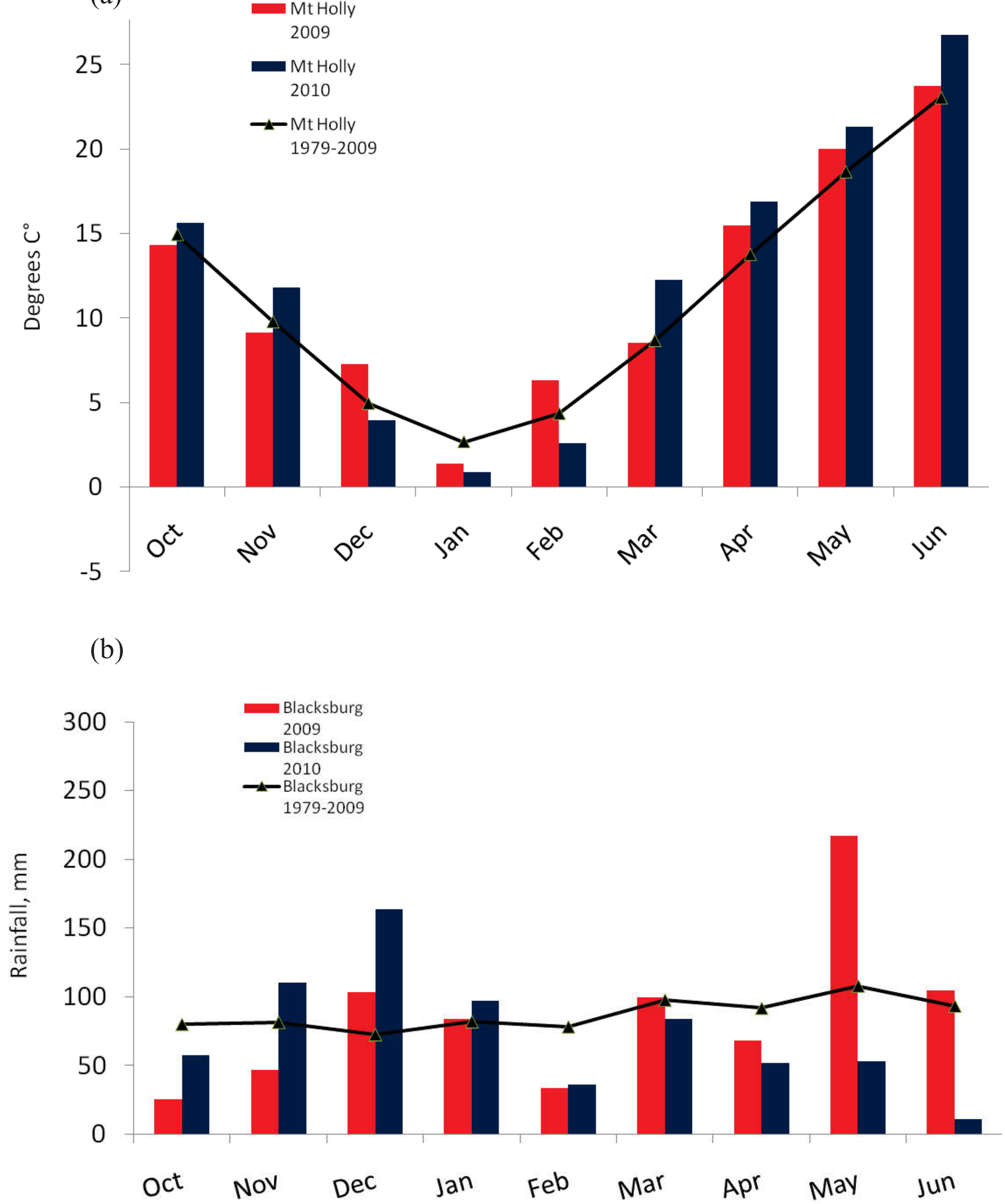


Figure 2. (a) Average daily air temperatures by month in 2008-09 and 2009-2010 and 30-year mean monthly air temperatures and (b) precipitation and 30-year mean precipitation for Mt. Holly, Virginia.

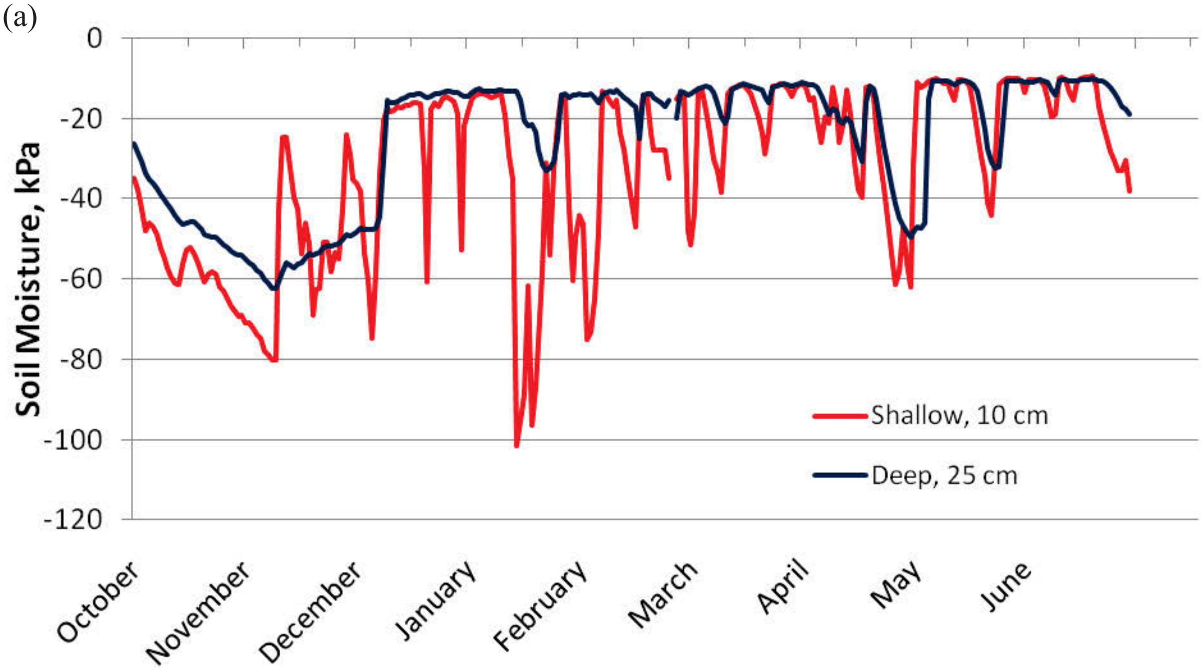
(a)



(b)

Figure 3. (a) Soil moisture measurements by month from 10 and 25 cm in 2008-2009 and (b) 2009-2010 for Blacksburg, Virginia

(a)



(b)

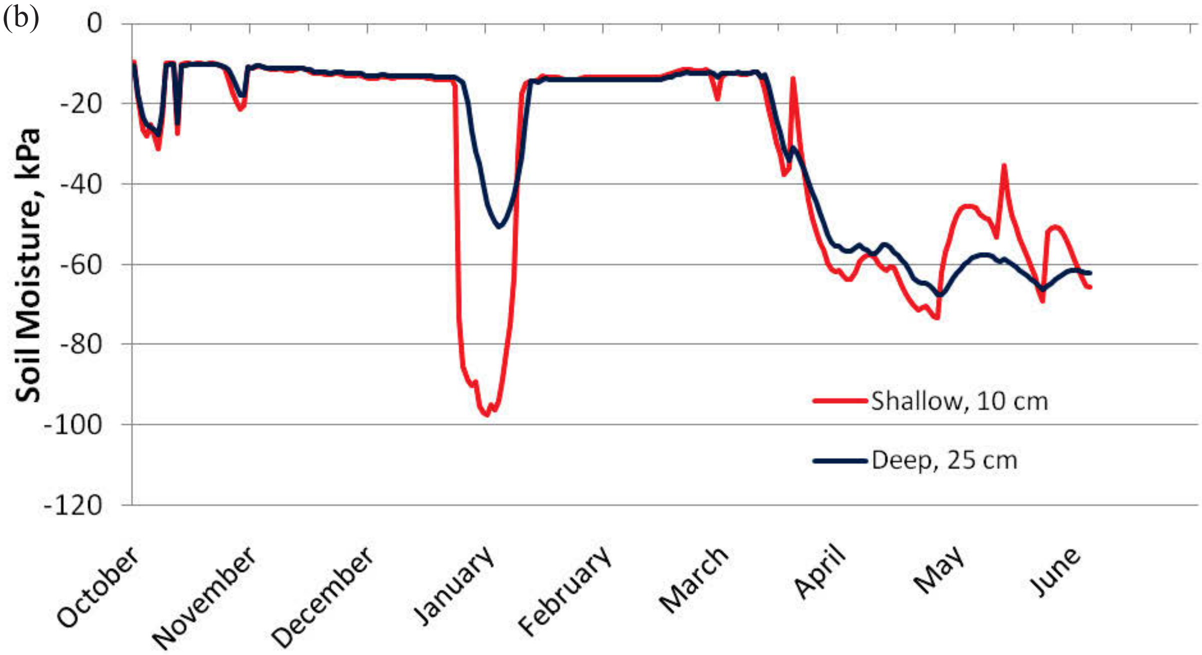
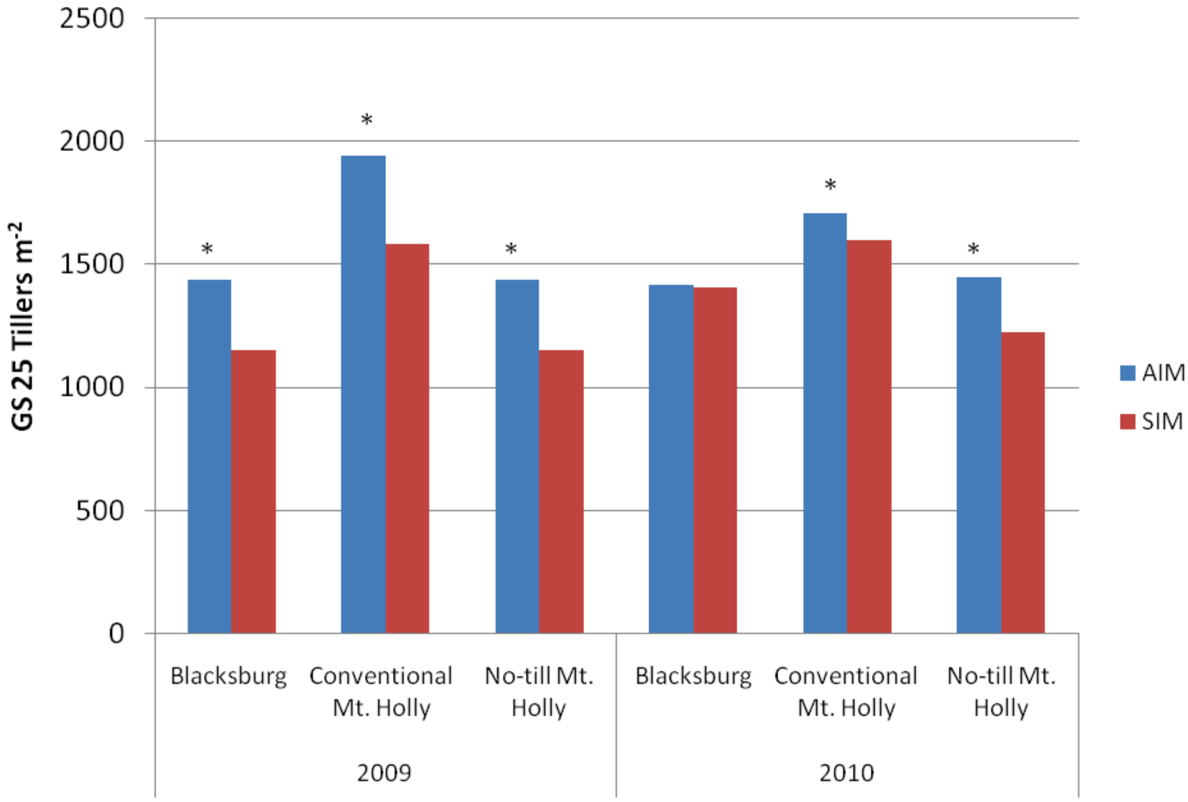
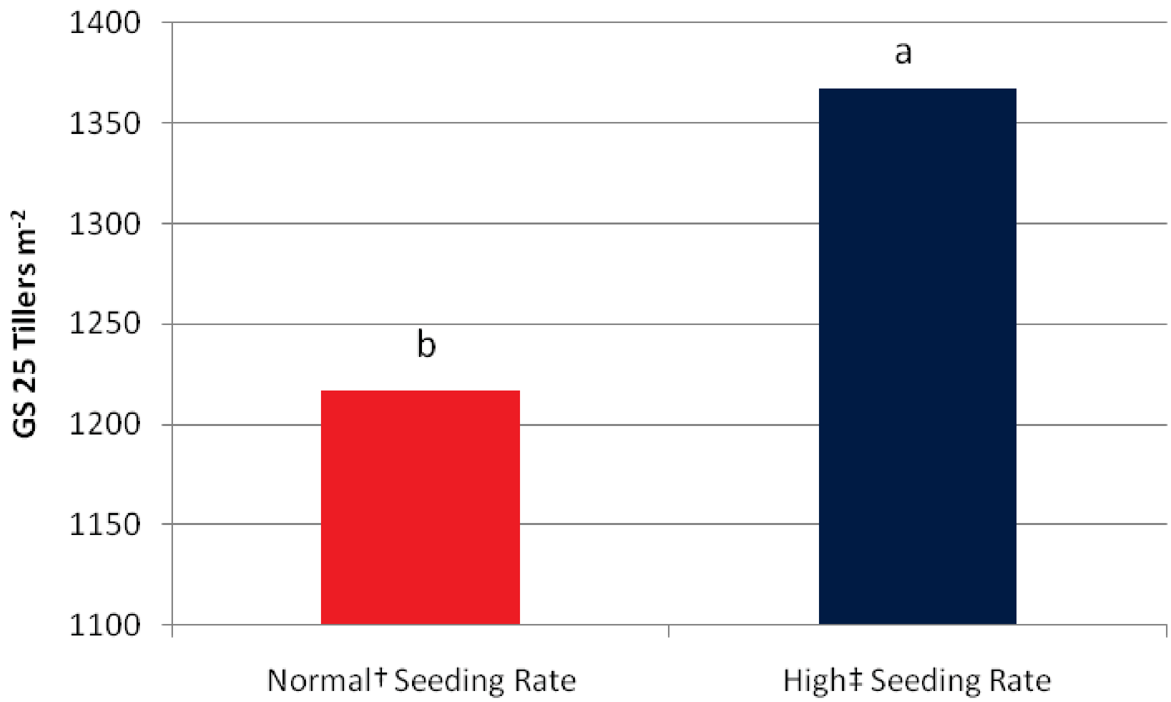


Figure 4. Tiller density at GS 25 as influenced by advanced intensive management (AIM) or standard intensive management (SIM), Mt. Holly conventional and no-tillage, and Blacksburg, 2009-2010.



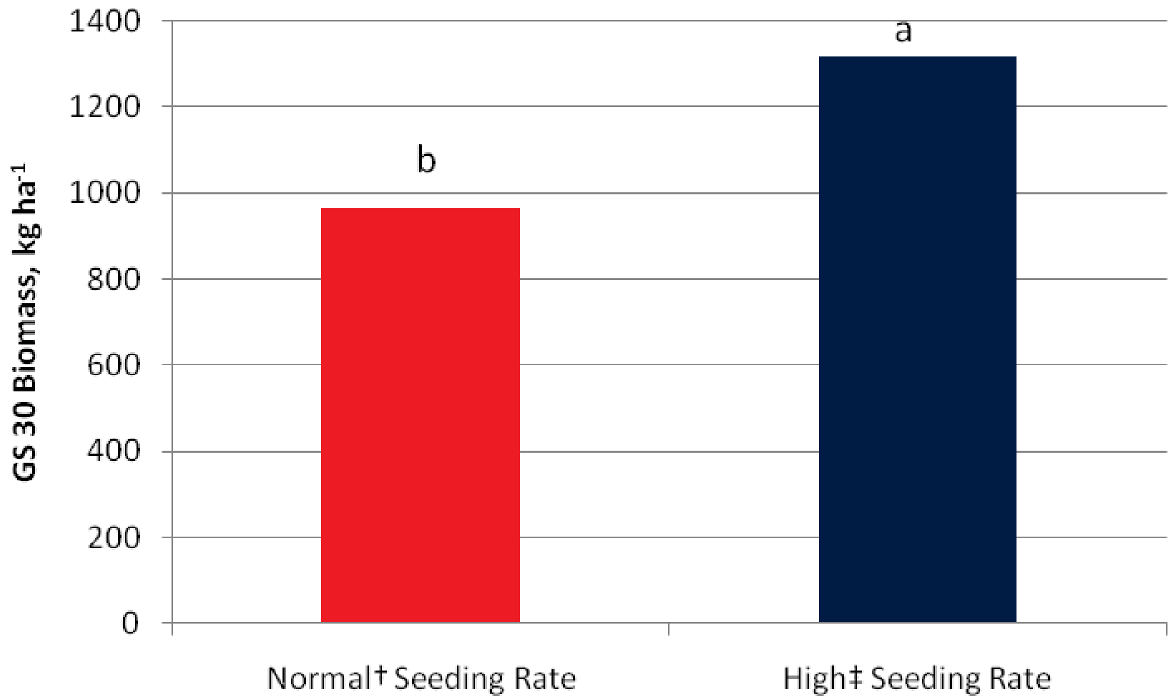
* Indicates means between management treatments are significantly different at the 0.05 level

Figure 5. Tiller density at GS 25 as influenced by seeding rate, Blacksburg, 2009.



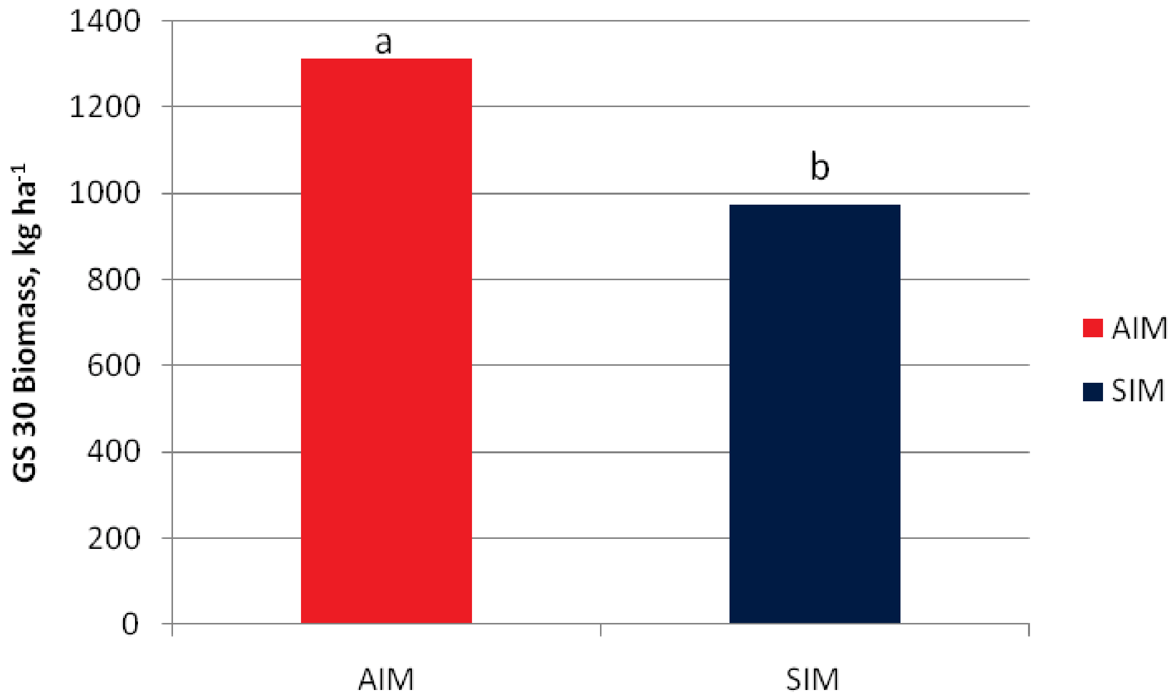
†Normal SR = 379 seeds m^{-2} at Blacksburg and Mt. Holly CT, 482 seeds m^{-2} at Mt. Holly NT
‡ High SR = 482 seeds m^{-2} at Blacksburg and Mt. Holly CT, 551 seeds m^{-2} at Mt. Holly NT
Columns labeled with different letters are significantly different at the 0.05 level

Figure 6. Aboveground biomass at GS 30 as influenced by seeding rate at the Mt. Holly conventional tillage site, 2010.



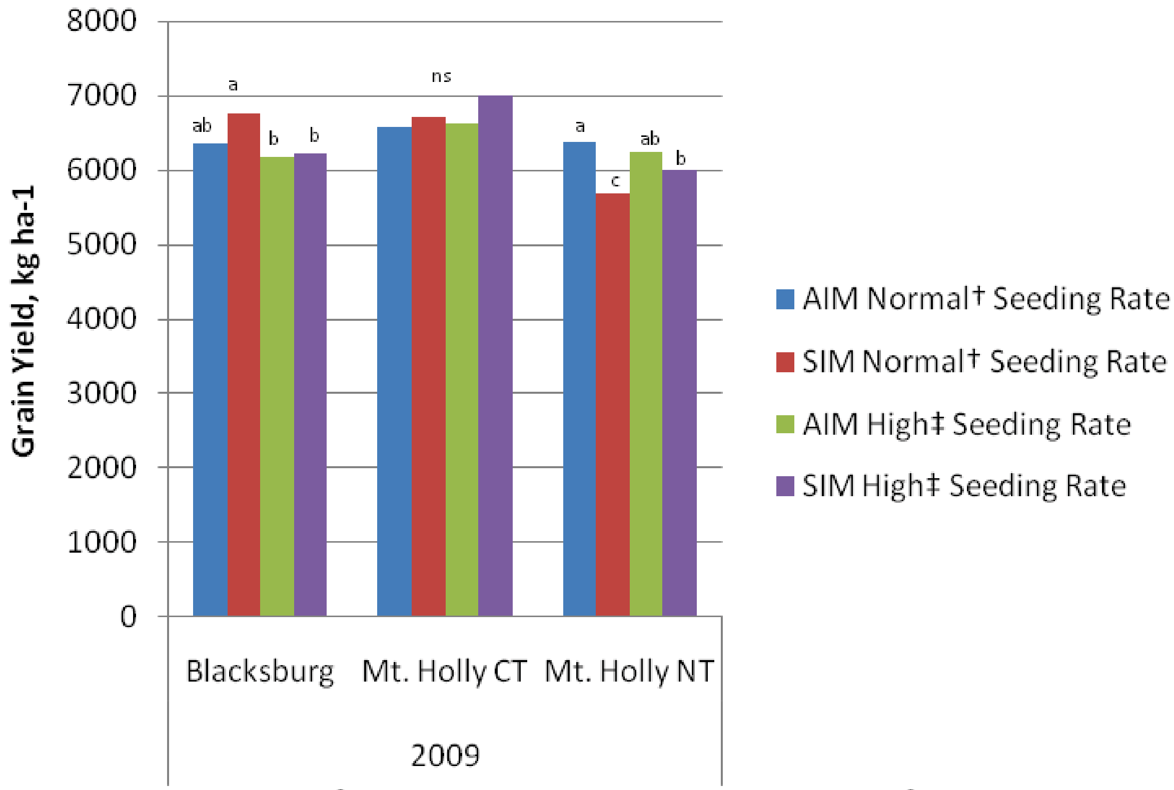
† Normal SR = 379 seeds m^{-2} at Blacksburg and Mt. Holly CT, 482 seeds m^{-2} at Mt. Holly NT
‡ High SR = 482 seeds m^{-2} at Blacksburg and Mt. Holly CT, 551 seeds m^{-2} at Mt. Holly NT
Columns labeled with different letters are significantly different at the 0.05 level

Figure 7. Aboveground biomass at GS 30 as influenced by advanced intensive management (AIM) or standard intensive management (SIM), Mt. Holly conventional tillage site, 2010.



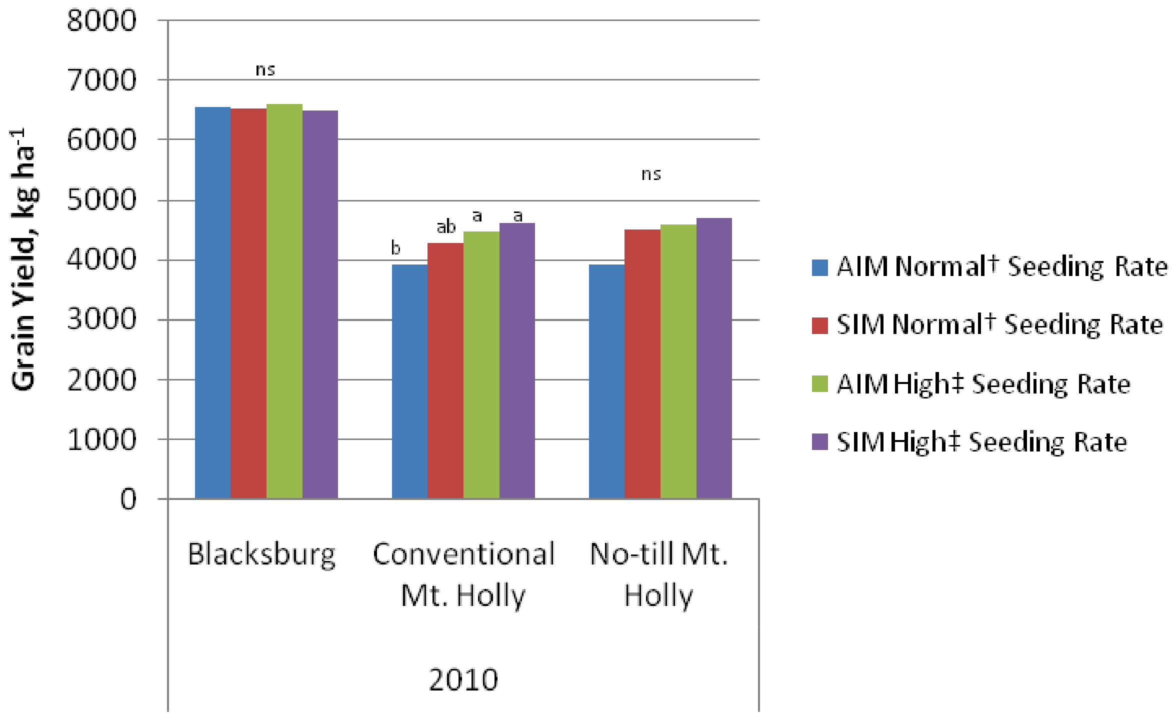
† Normal SR = 379 seeds m^{-2} at Blacksburg and Mt. Holly CT, 482 seeds m^{-2} at Mt. Holly NT
‡ High SR = 482 seeds m^{-2} at Blacksburg and Mt. Holly CT, 551 seeds m^{-2} at Mt. Holly NT
Columns labeled with different letters are significantly different at the 0.05 level

Figure 8. Wheat grain yield as influenced by seeding rate and management type, Blacksburg, and Mt. Holly conventional and no-tillage, 2009.



† Normal SR = 379 seeds m^{-2} at Blacksburg and Mt. Holly CT, 482 seeds m^{-2} at Mt. Holly NT
‡ High SR = 482 seeds m^{-2} at Blacksburg and Mt. Holly CT, 551 seeds m^{-2} at Mt. Holly NT
Columns labeled with different letters are significantly different at the 0.05 level

Figure 9. Wheat grain yield as influenced by seeding rate and management type, Blacksburg, and Mt. Holly conventional and no-tillage, 2010.



† Normal SR = 379 seeds m^{-2} at Blacksburg and Mt. Holly CT, 482 seeds m^{-2} at Mt. Holly NT
‡ High SR = 482 seeds m^{-2} at Blacksburg and Mt. Holly CT, 551 seeds m^{-2} at Mt. Holly NT
Columns labeled with different letters are significantly different at the 0.05 level