12-1-2010

COMPARING CROPPING SYSTEM PRODUCTIVITY BETWEEN FIXED ROTATIONS AND A FLEXIBLE FALLOW SYSTEM USING MODELING AND HISTORICAL WEATHER DATA IN THE SEMI-ARID CENTRAL GREAT PLAINS

Juan Jose Miceli-Garcia
j.miceli@live.com.mx

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by

Juan J. Miceli-Garcia

A THESIS

Presented to the faculty of

The Graduate College of the University of Nebraska

In Partial Fulfillment of Requirements

For the Degree of Master of Science

Major: Agronomy

Under the Supervision of Professors Drew J. Lyon and Timothy J. Arkebauer

Lincoln, Nebraska

December, 2011

COMPARING CROPPING SYSTEM PRODUCTIVITY BETWEEN FIXED ROTATIONS AND A FLEXIBLE FALLOW SYSTEM USING MODELING AND HISTORICAL WEATHER DATA IN THE SEMI-ARID CENTRAL GREAT PLAINS

Juan J. Miceli-Garcia, M.S.

University of Nebraska, 2011

Advisers: Drew J. Lyon and Timothy J. Arkebauer.

In the Central Great Plains, the predominant crop rotation is winter wheat (*Triticum aestivum* L.)-fallow. Producers are looking to add diversity and intensity to their cropping systems by adding summer crops, however, the elimination of summer fallow may increase crop production risk. The objective of this study was to use crop simulation modeling to compare the productivity of two fixed rotations [winter wheat-corn (*Zea mays* L.)-fallow and winter wheat-corn-spring triticale (X *Triticosecale* Wittmack)] with simulated flexible fallow rotations. The flexible fallow rotations made the decision to plant triticale or use summer fallow prior to winter wheat seeding based on available soil water in spring. Data from three years of field studies at two sites, Sidney, NE and Akron, CO, were used to calibrate and test the model, AquaCrop, for the crop simulation. Twenty-three years of historical weather data from each of the two locations were used to simulate crop production for each rotation. Average income was improved by replacing summer fallow with triticale (from 120 to 160 US \$ ha^{-1} for Akron and from 126 to 199 US \$ ha^{-1} for Sidney), but income variability (standard deviation)

also increased (from 73 to 84 US \$ ha^{-1} for Akron and from 93 to 115 US \$ ha^{-1} for Sidney). Risk-averse growers are likely to always use fallow in their crop rotations prior to planting winter wheat, while non-risk-averse growers will likely eliminate fallow and substitute triticale or a similar early-planted spring forage. Flexible fallow rotations seldom improved profits compared to always using fallow without also increasing income variability. The exception was Sidney using the 400 mm soil water threshold, which lowered income variability compared to always fallowing (from 93 to 91 US \$ ha^{-1}) and increased average income (from 126 to 142 US \$ ha^{-1}). However, the economic benefits of flexible fallow compared to the two fixed cropping systems were minimal.

Acknowledgments

First of all I would like to thank God for all the blessings that He has given to me and to my family. None of this would have been possible without Him.

I would like to acknowledge the advice and guidance of the members of my graduate committee; Drew J. Lyon, David C. Nielsen, and Timothy J. Arkebauer for their guidance, patience, effort and uncountable suggestions. The completion of my masters program and graduation would not be possible without their help. I also want to thank Osval Montesinos for his time as we developed the statistical analysis for this study, and Paul Burgener for his help with the economic analysis.

I thank Vern Florke, Rob Higgins, Jamie Littleton-Sauer, and Albert Figueroa for their help in the field work. I thank Marlene Busse for her patience answering all of my questions regarding paper work. I also want to thank Sam and Mitch for their friendship and advice. I wish to express special gratitude to Steve Mason, John Lindquist and Charles Francis for always having a minute for me.

Thank you to the Anna H. Elliott Fund and the Nebraska Wheat Board for their economic support for this project.

Thanks to my parents, Enrique and Yolanda and my brother and sister, Jose Enrique and Lucia for their support and encouragement. Thanks for being the best family that I possibly could have. Finally, but not least, I would like to thank Chelsea for her love and unconditional support, not only during happy and sad moments, but also during these long hours of work. I could not have done all this work without her love, support and patience.

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INTRODUCTION

In the western portion of the Central Great Plains, the predominant crop rotation is winter wheat (*Triticum aestivum* L.)-fallow using mechanical tillage (Lyon et al., 1993; Dhuyvetter et al., 1996). Summer fallow is an important, and sometimes indispensable, component in the production of winter wheat due to the low amount of highly variable precipitation in this region (450 mm or less annually) (Lyon et al., 1993). The primary objective of summer fallow is the storage of water in the soil for use by the next wheat crop (Nielsen et al., 2011). This is accomplished, in part, by controlling the growth of weeds (Tanaka et al., 2010). However, there are years when precipitation is great enough to allow summer fallow to be replaced by a short-season spring-planted crop (a concept that is referred to as "Flexible Fallow").

In the semiarid portion of the Great Plains, mainly in the western portion, continuous cropping systems are risky due to limited precipitation and high potential evapotranspiration (ET) (Nielsen et al., 2005). The rain shadow caused by the Rocky Mountains, where elevations exceed 4200 m, results in a decline in annual precipitation from east to west in Nebraska (Lyon et al., 2003). Summer fallow is a common practice used in regions where annual precipitation is less than 500 mm per year (Farahani et al., 1998). In the Great Plains, 75% of annual precipitation is received during the warm season (April through September). The amount of water stored in the soil during summer fallow is low, and changes in the amount of water stored over the fallow period can be negative (Farahani et al., 1998). The climatological conditions of the Central Great Plains, where water is the most limiting resource for crop production, makes winter

wheat-fallow the most commonly used production system in order to stabilize the production of winter wheat in this region (McGee et al., 1997; Smika, 1970; Farahani et al., 1998; Lyon et al., 2004).

Unpredictable weather conditions such as variable precipitation, temperature fluctuation, and hail make dryland farming in the Great Plains uncertain (Dhuyvetter et al., 1996). In order to achieve success and sustainability in the dryland agriculture systems of the Great Plains, a more efficient use of the erratic precipitation and stored soil water is necessary (Saseendran et al., 2009; Nielsen et al., 2005).

CHAPTER 1. Literature Review

1.1 Summer Fallow

Fallow attempts to limit the growth of all plants during the non-crop season, thereby increasing the amount of soil moisture stored (Lyon et al., 2004; Dhuyvetter et al., 1996). The control of plant growth is accomplished by either cultivation or herbicide application (Brown et al, 1983).

Summer fallow was first practiced in the Great Plains during the 19th century by farmers as a way to improve yields in small grain production, reduce crop failure, and to reduce labor (Farahani et al., 1998). The lack of crop selection and adverse weather conditions in the Great Plains during 1912 to 1921, led to the wheat-fallow system becoming the dominant agricultural system in this region (Tanaka et al., 2002, Tanaka et al., 2010).

For winter wheat in the Great Plains, the fallow period is approximately 14 months (Farahani et al., 1998). The main objective of a fallow period is to increase the total amount of stored soil water to then be used by the following crop (Moret et al., 2006). Other benefits that can be achieved with fallow are the release of nutrients into the soil through the mineralization of soil organic matter and weed control (Aase et al., 2000; Johnson et al., 1982). Fallow allows for stability in both production and yield, and a better seasonal distribution of work (Johnson et al., 1982).

Even though the objective of fallow is to stabilize production for the next crop by primarily helping to store water in the soil, it has been found that soil water is stored

inefficiently in fallow systems, frequently averaging less than 25% precipitation storage efficiency (Lyon et al., 2004; McGee et al., 1997; Nielsen and Vigil, 2010).

Farahani et al. (1998) divided fallow in the winter wheat-fallow system into three periods: early period (from July after wheat harvest to mid-September), overwinter period (fall to early May), and late period (from spring to mid-September at wheat seeding). Further, they mention that the winter period is the most efficient at storing soil water, having the lowest amount of evaporation and greatest water storage efficiency, even though this period has the lowest precipitation rate. On the other hand, the late period, also known as summer fallow, is the most inefficient at storing soil water, even though it is the period that receives the greatest amount of precipitation (Farahani et al., 1998). In the non-crop periods of the wheat-fallow system, most of the precipitation is lost by evaporation, deep percolation, and runoff (Black et al., 1981).

In Australian dryland wheat production, Angus et al. (2001) reported that little water is stored during the fallow period. Most of the precipitation received during the fallow period is lost due to soil evaporation, weed use, volunteer plants, runoff, deep seepage, and snow blow-off (Farahani et al., 1998). Nielsen et al. (2005) mentions that when tillage is used during summer fallow, the degradation of crop residues make the soil more vulnerable to wind erosion and the reduction in the size of the crop residue particles make them less effective for evaporation reduction. Additionally, the formation of a soil crust by the impact of rain drops on unprotected soil reduces the water infiltration capability of the soil (Nielsen et al., 2005). Crop residues allow for the protection of soil against rain drop impact, the reduction of evaporation, the enhanced retention of

infiltrated water, and the maximum rates of water infiltration are achieved (Peterson et al., 1993).

Under intense tillage, the water storage efficiency of fallow is as low as 10% (Farahani et al., 1998). Moret et al. (2006) comments that in Spain, moldboard and chisel plowing have had an adverse effect on soil water conservation when fallow was applied for the first time during a very wet autumn. Deeper tillage mixed weed seed into deeper soil layers and reduced the effectiveness of herbicides compared to herbicide use with shallow tillage (Black et al., 1981). Research by Black et al. (1981) found that the control of weeds, such as wild oat (*Avena fatua* L.), is better with herbicides when the land has not been tilled to a depth of more than 7.5 cm. Reduction in tillage increases residue cover that allows for a reduction in soil erosion and increase in production. Reduced and no-till farming practices have improved the efficiency of precipitation capture and storage, allowing a reduction in the use of fallow and more intensive cropping systems (Lyon et al., 1995). Nielsen et al. (2010) found that the precipitation storage efficiency in the wheat-fallow system is higher with no-till (35%) than when conventional tillage is used (20%). Precipitation storage efficiency can be increased up to 20 to 30% when farmers use no-till and residue management techniques commonly used today. The increase in water storage efficiency is due to the reduction in the number of times that moisture is brought to the soil surface as tillage is eliminated (Farahani et al., 1998; Nielsen et al., 2005). Note that even with the best technology available today, the water storage efficiency of fallow remains low, i.e., less than 45%.

Soil erosion is an important aspect that needs to be taken into consideration by producers during the evaluation of cropping systems (Dhuyvetter et al., 1996, Young et al., 1986). Wind and water erosion are the two most obvious disadvantages of summer fallow (Burt et al., 1989). The use of tillage during fallow exposes soil to degradative forces such as C removal by erosion, the acceleration of C oxidation, and less C being deposited in the soil surface in comparison with conditions found for native prairie (Peterson et al., 1998). Soil erosion and saline seeps are two sources of pollution of air and water that can result from fallow and affect society (Johnson et al., 1982). Reduced soil productivity and profitability of the farm are other problems related to the use of summer fallow in dryland cropping systems (Lyon et al., 2004).

Fallow may represent an economic disadvantage for growers, in part, because mechanical tillage represents a big cost, and because the area required for an annual cropping system is doubled (Lyon et al., 2007, Tanaka et al., 2010). In addition, anytime the land is not producing there is an opportunity cost, which is higher in years with high crop prices (Johnson et al., 1982). In an extended literature review made by Dhuyvetter et al. (1996), it was found that even with the inclusion of government program payments for wheat, more intensive cropping systems were more profitable than the traditional wheat-fallow cropping system in the Central Great Plains.

Other important effects such as the reduction in soil aggregates, destruction of residues, and N mineralization have been reported as disadvantages of tillage during the fallow period (Peterson et al., 1993). The uses of monoculture systems such as wheat-fallow promote not only soil degradation and the reduction in the profitability of the

system, but also disease, weed, and insect problems (Daugovish et al., 1999; Nielsen et al., 2009).

The decision to fallow land is made by individual farmers, making the total amount of fallowed land greater than the optimal amount for society, consequently, benefiting growers solely in the short term (Johnson et al., 1982). Conditions such as the Dust Bowl in the 1930s were created, in part, by frequent use of tillage operations in the control of weeds in fallow systems (Farahani et al., 1998).

The frequent use of summer fallow in the Central Great Plains can be hazardous for crop production systems, creating ecological, economic, and social problems. Because of this, other alternatives need to be explored that reduce the need for the use of summer fallow.

1.2 Alternatives to Summer Fallow

The agricultural systems of the Central Great Plains are very reliant on summer fallow (McGee et al., 1997). However, because of the environmental and economical implications of the winter wheat-fallow rotation, a different approach that allows for a more efficient use of water is needed.

In order to generate alternatives to the use of summer fallow, the improvement of existing techniques and development of new ones to increase soil water retention and conservation during the non-crop period are necessary (Black et al., 1981). This improvement or new development needs to include crop residue management techniques (such as reduced till and no-till), reduction of the length and/or frequency of the fallow period, and adequate crop selection (Nielsen et al., 2005).

Farmers in the dryland cropping regions are looking for options other than the traditional monoculture systems such as wheat-fallow (Nielsen et al., 2009; Zentner et al., 2009). The use of herbicides for weed control during fallow helps to conserve soil water and allows growers to produce crops more intensively (Lyon et al., 1983). Reduction in tillage due to chemical weed control has increased wheat yields by 37% in wheat-fallow systems compared with systems involving tillage (Nielsen et al., 2002). These enhancements have increased economic returns and improved environmental sustainability (Zentner et al., 2005).

Dhuyvetter et al. (1996) suggested that the use of a more intensive cropping system than wheat-fallow, in combination with less tillage, can be an option for many parts of the Great Plains currently using the wheat-fallow production system. The water stored in the spring of the fallow year by using no-till, can be as much or more than the water stored if fallow is continued until wheat planting in the fall (Peterson et al., 1996). The use of more intense cropping systems with no-till will use the water stored in the soil, and increase productivity per unit of water received and replace summer fallow in many environments (Peterson et al., 1993; Tanaka et al., 2010). The increase in intensity in the system allows a crop to be produced annually on 67 to 100% of the tillable land (Dhuyvetter et al., 1996).

Loss of soil organic C and N is promoted by fallow (Peterson et al., 1993). More intensive cropping systems have higher grain and crop residue production, less soil disturbance that results in increased C content of the soil, and reduced C losses (Peterson et al., 1998). The increase in residue C, in addition to no soil disturbance in a no-till

environment, promotes aggregate stability, which will positively impact the physical and chemical properties of the soil (Tanaka et al., 2010).

Crop intensification in the Great Plains increases precipitation use efficiency on a biomass-produced and price-received basis (Nielsen et al., 2005). Peterson et al. (1993) found that increasing intensification of cropping systems will be an environmentally and economically sustainable practice even in more water stressed environments.

Producers have shown some resistance to changing traditional production systems. Some of the reasons for the slow change are: returns will not cover added costs of machinery, herbicides and fertilizer; the relatively low labor required in wheat-fallow systems; the increase in financial and production risks; and the ability to comply with government programs (Dhuyvetter et al., 1996).

The reduction of summer fallow length and/or frequency will diminish soil erosion, improve the efficiency of water use, and increase the long-term viability of dryland farming in the Great Plains (Lyon et al., 2004; Tanaka et al., 2002). A reduction of summer fallow by crop intensification, e.g., from one crop in 2-yr to two crops in 3-yr, increases precipitation use efficiency (Nielsen et al., 2005). McGee et al. (1997) found that a 3-yr rotation with a fallow period of 11 months was as efficient at storing water as a fallow period of 14 months (McGee et al., 1997). The increase in crop intensification to two crops in three years had little effect on the water available at wheat planting and on wheat yield (Nielsen et al., 2002).

With the implementation of crop intensification, higher production of grain per unit of water is achieved (Peterson et al., 1998). The key point of water use efficiency in

crop intensification is the replacement of water evaporation from the soil surface by crop transpiration (Farahani et al., 1998, Tanaka et al., 2010). The use of perennial grass that resembles the native prairie vegetation provides the highest water use and the least erosive soil condition (Peterson et al., 1993). However, this last option will not allow for the production of a wheat crop. More intensive systems such as wheat-sorghum-fallow showed less financial risk than wheat-fallow (Dhuyvetter et al., 1996). Daugovish et al. (1999) found that 3-yr rotation systems provide at least the same economic return as wheat-fallow production, and in addition, provided excellent control of winter annual grass weeds. The longer a field stays in a 3-yr rotation with a summer crop, the greater the reduction in winter annual grass weeds (Daugovish et al., 1999). No significant differences were found between wheat yields from wheat-fallow (no till), wheat-corn-fallow, and wheat-millet-fallow systems (Nielsen et al., 2002).

The most efficient way to improve cropping system water use is to substitute a summer crop for summer fallow (Farahani et al., 1998), and the frequency of summer fallow can be reduced by reducing or eliminating tillage and increasing precipitation storage efficiency between crops (Peterson et al., 1993). An early harvest, or short duration spring-planted crop, used in transition from a full-season summer crop to winter wheat minimizes the impact of not having summer fallow on the following winter wheat (Lyon et al, 2004). Wheat following an early planted summer crop exhibited greater tiller production, faster germination, and more growth compared to wheat following a late planted summer crop (Lyon et al., 2007). The use of forage crops prior to winter wheat seeding, due to the early date of harvest, allows more time for soil water storage than the

use of grain crops (Lyon et al., 2004). Dhuyvetter et al. (1996) analyzed the economics of eight studies of dryland cropping systems in the Great Plains and found that in seven of these studies the net return was greater in a more intensive crop rotation in combination with practices of reduced-till or no-till following wheat harvest and prior to planting the summer crop, than from the wheat-fallow rotation.

Spring triticale (*X Triticosecale rimpaui* Wittm.), dry pea (*Pisum sativum* L.), foxtail millet (*Setaria italica* L. Beauv.), and proso millet *(Panicum miliaceum* L.) are short-season crops that can be used in crop rotation to replace summer fallow (Saseendran et al., 2009). Lyon et al. (2004) found that rotations that involved oat (*Avena sativa* L.) + pea for forage or proso millet as summer fallow replacement crops were economically competitive with summer fallow.

1.3 Flexible Fallow

Cropping decisions need to be based on the amount of soil water at planting and expected precipitation during the growing season (Black et al., 1981). The practice of having a continuous cropping system (no monoculture), where the selection of the crops depends on the water available in the soil profile is defined as “opportunity cropping” (Nielsen et al., 2005 ; Peterson et al., 1993). Lyon et al. (1995) defined it as a “flexible cropping system”. A flexible cropping system involves planting a crop when the stored soil water and the expected precipitation are considered sufficient for a successful crop. In years where the water is not sufficient, fallow is implemented (Black et al., 1981). Flexible cropping systems avoid the rigidity of fixed cropping. The implementation of a

flexible cropping system along with proper crop and soil management can reduce or eliminate the necessity of summer fallow (Black et al., 1981).

In order to be successful in the development of a flexible cropping system, it is necessary to take into consideration the relationship between initial soil water and subsequent yield of the crop (Lyon et al., 1995, and Young et al., 1986). Zentner et al. (2005) evaluated the use of an annual legume green manure crop as a summer fallow substitute depending on the available soil water reserves. In this experiment, they found that the "flex-crop" rotation had greater earnings than more traditional rotations, such as those that include fallow. Lyon et al. (1995) analyzed the response of five spring-planted crops to three different soil water levels at planting the year following winter wheat harvest. The crops analyzed were corn, grain sorghum, pinto bean (*Phaseolus vulgaris* L.), proso millet and sunflower (*Helianthus annuus* L.). They found that for pinto bean and proso millet, soil water at planting appeared to be a good indicator of the success of these short duration crops. However, for the long duration crops (corn, grain sorghum, and sunflower), soil water at planting did not appear to be a good indicator of grain yield (Lyon et al., 1995). This conclusion was verified by Nielsen et al. (2009) for dryland corn in Colorado. Other points to take into consideration in the success of flexible cropping are crop management and soil factors such as fertility and weed control (Black et al., 1981).

Flexible cropping systems allow farmers a better use of environmental and/or market conditions due to better adaptability from a bigger portfolio of crop options (Hanson et al., 2007). Flexible cropping systems can control the risk of production and

soil loss, being in this way an option to respond to the challenges that agricultural systems will be facing in the future due to uncertain conditions (Hanson et al., 2007, Young et al., 1986).

The concept known as “flexible fallow” consists of the substitution of a short-season, spring-planted crop for summer fallow when the soil water at planting is sufficient, thus reducing soil degradation by summer fallow without significantly compromising the next winter wheat crop (Felter et al., 2006). Flexible rotations that allow the decision to fallow or not based on available soil water in spring represent a more effective option than fixed rotation (Zentner et al., 2005). By fallowing in the driest springs and planting a spring crop when the soil water at planting is sufficient, the farmer has the opportunity to increase the sustainability of the system, obtain a higher income, and reduce the riskiness of a fixed spring cropping system (Young et al., 1989).

In dryland crop production, the amount of soil moisture at seeding is usually a limiting factor (Young et al., 1989). Nielsen et al. (1999, 2002 and 2009) conducted many experiments to evaluate the relationship between soil water at planting and yield of different crops used to diversify the wheat-fallow system. Wheat and millet yield, planted after sunflower, declined as soil water at planting declined at Akron, CO (Nielsen et al., 1999). In 2002, Nielsen et al. found a linear relationship between wheat grain yield and soil water at planting. In the same study, they found that the intensification of the traditional wheat-fallow system under no-till by the addition of a crop (corn or millet) between wheat and fallow reduced the fallow period and did not significantly affect the yield of the next wheat crop or the soil water available at wheat plating (Nielsen et al.,

2002). Nielsen et al. (2009) mention that corn can be used as a rotation crop in order to diversify the traditional monoculture wheat-fallow system in the Central Great Plains. The study showed that under dryland conditions, there is a positive relationship between the soil water at planting and corn grain yield, with the slope of the relationship increasing dramatically as precipitation during the flowering and grain filling stages increased.

Zentner et al. (2005) compared the economic benefits of substituting an annual legume green manure for summer fallow based on available soil water. The legume was seeded and turned down before it reached full bloom to allow maximum N_2 fixation, but at the same time minimize soil water depletion. The conclusions of this study were that flexible cropping systems usually ranked second in annual net returns, just behind continuous wheat when using conservation tillage practices in order to enhance soil water reserves, and under favorable growing conditions. The least profitable cropping systems were fallow-wheat-wheat and annual legume green manure-wheat-wheat.

Good results were obtained by using annual legume green manure from Indianhead black lentil (*Lens culinaris* Medikus) and chickling vetch *(Lathyrus sativus* L.) cv. AC Greenfix as replacement crops for fallow when the soil water reserve in spring was enough to avoid compromising the following wheat crop (Zentner et al., 2005).

The implementation of flexible fallow seems to have a better response when a short duration summer annual crop is used (Lyon et al., 2007). In the western portion of the Great Plains, forage crops had higher precipitation use efficiency on a biomass-produced basis in comparison to oilseed crops or continuous small-grain production

(Nielsen et al., 2005). Short duration annual forage crops such as triticale and foxtail millet use less water than grain crops because the length of the growing season is reduced by harvesting prior to grain development, which is often the period of greatest water use (Lyon et al., 2004; Lyon et al., 2007).

Saseendran et al. (2009) mentions that spring triticale and foxtail millet as forage crops, and proso millet as a grain or forage crop, have the potential to substitute for summer fallow in the winter wheat-fallow system.

Felter et al. (2006) used spring planted crops to evaluate substitutes for summer fallow when soil water was sufficient at planting. They used four crops: spring triticale for forage, dry pea for grain, proso millet for grain, and foxtail millet for forage. They concluded that triticale, foxtail millet, and proso millet can be used as substitutes for summer fallow in a flexible fallow cropping system based on available soil water at planting. They found a linear relationship between dry matter accumulation and soil water availability at planting time for triticale and foxtail millet. The two forage crops in this study, spring triticale and foxtail millet, had an increase in harvested biomass for each centimeter of water available at planting of 229 kg ha^{-1} and 339 kg ha^{-1} respectively (Felter et al., 2006). They found that soil water at planting has a stronger relationship with yield in years where seasonal precipitation is limited. The early harvest date of triticale allows for more time to accumulate water in the soil prior to winter wheat seeding compared to foxtail millet, which is planted and harvested later than spring triticale (Lyon et al., 2007).

Producers and agricultural lenders need ways to assess the level of risk that the increase in intensity of the traditional wheat-fallow rotation creates (Nielsen et al., 2002). The study by Felter et al. (2006) suggests that soil water at planting can be used as an indicator of yield potential for a short-season spring-planted crop used as a substitute for summer fallow, particularly for crops grown for forage.

A short-season spring-planted forage crop such as triticale can be used as a substitute for summer fallow in years where the amount of stored soil water at planting is enough to produce sufficient triticale biomass without significantly reducing grain yield of the following winter wheat crop (Felter et al., 2006; Lyon et al., 2007). Lyon et al. (2007) found that the decision to plant or not plant a short-season crop as a summer fallow replacement is more critical than the selection of what crop is planted. Since the water available at planting for the short-season summer fallow replacement crop is critical not only for the summer crop, but also for the following wheat crop, the determination of the threshold soil water at which to plant the crop is a key point for the success of the flexible fallow system (Lyon et al., 2007).

The use of summer fallow needs to be a judicious decision and not a habitual practice (Black et al., 1981).The flexible fallow system can help growers increase crop production during wetter years and minimize the risk of crop loss in dry years (Lyon et al., 1995). In regions such as western Nebraska, where crop production is limited by lack of precipitation, soil water at planting might be a good predictor for potential yield. The development of a tool that helps growers to decide when to substitute a short-season spring-planted crop for summer fallow might be useful (Felter et al., 2006).

1.4 Crop Simulation Modeling

In regions where the environmental conditions make production decisions uncertain, models have been successfully used to analyze agronomic practices (Lyon et al., 2003). In the Central Great Plains, long-term experiments to evaluate crop rotation effects on water use and yield have been done since the 1990s (Saseendran et al., 2010). However, there are not many long-term experiments that can be used to evaluate the impact of no-till and altered crop rotations on the wheat-fallow system (Peterson et al., 1993). Dryland cropping systems research in the Great Plains has to confront the difficulty of conducting experiments over a long time period, with the demand of high investment in many resources such as land and labor (Staggenborg et al., 2005). The ability of conventional statistical techniques to extrapolate location-specific findings to other regions and climates with heterogenic land conditions, such as the one presented in the semiarid regions, is questionable (Saseendran et al., 2010).

The effect of summer fallow is well known in specific locations, but limited information is available about extrapolating this information to locations with different soil and climatic conditions (Peterson et al., 1993). With modeling, it is possible to see the way that an agricultural crop will behave in other locations, climates, seasons, and soils (Saseendran et al., 2009). The combination of long-term simulation with field research data may give a good prediction of performance for new crops included in the system, after only a couple of seasons of field data, avoiding the necessity of long-term experiments (Staggenborg et al., 2005). This saves time and money in agricultural research and accelerates the delivery of technologies to producers.

Field research results can be limited to the period of time in which they were conducted, however, with crop modeling and long-term climate data, it is possible to make an analysis that will allow for an adjustment of recommendations, avoiding the time limitation of field research (Lyon et al., 2003; Staggenborg et al., 2005). Models are needed to sensitize results obtained from long-term experiments in order to make adequate management decisions in the Central Great Plains (Saseendran et al., 2010). The combination of historical weather data and simulation modeling can be used to predict system stability and the potential effect of future climatic changes (Peterson et al., 1993). Modeling is a tool that can be used by producers to avoid the risks implied in the adoption of new crops and practices (Staggenborg et al., 2005). In order to offer this tool to producers, the development of the model for the crop selected is necessary, along with its conscious calibration and testing of its performance under the climate of the region (Saseendran et al., 2009).

Moret et al. (2006) mentions that even though there are many different crop models, only a few of them have been applied to the study of soil water changes during the fallow period.

Stochastic dynamic programming (DP) has been used to select dryland cropping systems with high average annual returns, low variability, and reduced risk for water percolation below the root zone (Burt et al., 1989). Young et al. (1986) used DP and target prices for barley (*Hordeum vulgare* L.) to evaluate flexible cropping systems in traditional wheat-fallow rotations. In this study, the authors were able to identify the critical level of available soil moisture at planting for a flexible cropping strategy in a

wheat-fallow system using barley. They found that reduced soil erosion, improved profitability, and reduced risk associated with continuous cropping were possible with the use of DP and a flexible cropping approach in the traditional wheat-fallow system of the region.

Stochastic dynamic programming can help to improve the economics of dryland cropping systems, although the lack of data for different locations represents a problem for this approach (Burt et al., 1989). The use of well calibrated and tested crop simulation models can help to overcome this lack of information.

Another tool is the Crop Sequence Calculator, which is a relatively simple program that gives information to the user about crop production, economics, diseases, weeds, water use and soil properties, in order to evaluate different crop sequences (USDA, 2011). However, the Crop Sequence Calculator does not predict crop yield response to variable environmental conditions. Farmer interest in this relatively simple program demonstrates the potential and necessity of more robust decision support tools in order to increase the sustainability of the wheat-fallow cropping system (Tanaka et al., 2010).

Root Zone Water Quality Model (RZWQM), Decision Support System for Agrotechology Transfer (DSSAT), Cropping System Model (CSM), and Agricultural Production System Simulator (APSIM) are some of the modeling programs reported in the literature as being used to simulate the effects on yield and soil water use from changes to the traditional cropping systems of the Central Great Plains.

RZWQM was developed by the Agricultural Research Service of the United States Department of Agriculture. The model simulates the impact that alternative management strategies have on plant growth, movement of water, nutrients, and agro-chemicals within, over, and below the root zone (USDA, 2009).

DSSAT is a simulation package developed by the International Benchmark Sites Network for Agrotechnology Transfer. DSSAT has been in use for over 15 years. DSSAT allows the integration of soil, crop, phenotype, weather, and management in a multi-spatial and multi-temporal simulation. DSSAT v4.0 includes 27 different crops and the ability to analyze the environmental impact and economic risk of climate change, soil carbon sequestration, climate variability, and nutrient and irrigation management (ICASA, 2011).

RZWQM with DSSAT v4.0 crop growth modules (RZWQM2) was used by Saseendran et al. (2009), who used data from two different Great Plains locations with different plant available water levels and planted in different years, to successfully simulate the response of summer crops used as a substitute for summer fallow in the semiarid climate of the High Plains. The crops investigated were: spring triticale, proso millet, and foxtail millet. For this experiment, the Cropping System Model (CSM)-CERES-Wheat v4.0 module was adapted for the simulation of spring triticale growth while the CSM-CERES-Sorghum module was adapted for proso millet and foxtail millet. Modeling was used as an accurate tool to simulate the crop growth and development of the three short-season crops as possible substitutes for summer fallow through multiple years and different locations (Saseendran et al., 2009).

In 2010, Saseendran et al. evaluated the cropping system model RZWQM2 with the DSSAT v4.0 in two traditional rotations in the Central Great Plains: wheat-fallow and wheat-corn-fallow. The simulations were done from 1992 to 2008 and the calibration of the model was made with data from the wheat-corn-millet rotation at Akron, CO from 1995 to 2008. The model was able to successfully simulate long-term sequential yield, biomass production, and water and precipitation use efficiencies in crop rotations involving wheat, millet, corn, and fallow in the Central Great Plains. Cropping systems successfully simulated were: wheat-fallow, wheat-corn-fallow, and wheat-corn-millet. In addition to these rotations, without further calibration, the model predicted accurately enough the average yield of corn, millet, and wheat in the wheat-millet-fallow and wheat-corn-millet-fallow rotations (Saseendran et al., 2010).

Staggenborg et al. (2005) used CERES-Wheat and CERES-Sorghum to simulate wheat-fallow and wheat-sorghum-fallow systems in western Kansas. Wheat was better simulated than sorghum. The error contained in the simulation of wheat, overestimated by 10%, was higher than the one reported by other authors, suggesting that CERES-Wheat does not perform as well under dryland conditions such as that of the Great Plains. The authors mention that the error reported in the simulation may be due to overestimation in the leaf area index and the prediction of winter temperature damage more frequently than actually observed. Sorghum yield was also overestimated; in this case the error was 25%. The authors mention that this error might be due to the yield overestimation of the previous wheat in the rotation and because CERES-Sorghum

estimates water stress more severely than under actual conditions (Staggenborg et al., 2005).

APSIM simulates agricultural systems that integrate plant, animal, soil, and management interactions. APSIM can simulate over 20 crops. APSIM is able to simulate a wide range of farming systems. These options include dryland and irrigated cropping. Moeller et al. (2007) used APSIM to successfully simulate the productivity, and water and N use from 0-0.45 m soil depth in a wheat-chickpea system in Syria under different levels of N and water. The authors reported that the model was not able to simulate soil dynamics when the soil water content was set to “air-dry” and when each growing season finalized (Moeller et al., 2007).

Mupangwa et al. (2011) used APSIM to simulate the seasonal and mulching effects on corn using 69 years of climatic records. The program simulated yield reasonably well for most of the seasons. Other parameters simulated in this experiment were biomass and soil water balance until the crop was mature (Mupangwa et al., 2011).

CropSyst, a mathematical model that uses daily steps to simulate crop growth, biomass production, and N and water balance (Stockle et al., 1994), was used by Sadras et al. (2004) to evaluate more intensive cropping approaches than wheat-fallow in the Australian wheat-belt. The experiment included wheat, canola (*Brassica napus* L.), and grain legumes. In this experiment, the authors were not only able to successfully simulate crop yield at different N levels, but they also found that a more intense flexible approach could bring economic benefits superior to fixed rotations.

AquaCrop is a computer model developed by the Land and Water Division of the Food and Agriculture Organization of the United Nations (FAO). FAO developed AquaCrop in an effort to increase the water use efficiency in food production (Araya et al., 2010). The webpage (http://www.fao.org/nr/water/aquacrop.html) of AquaCrop mentions that the program was designed to simulate the response that different crops have to water, especially in conditions where water is the liming factor. AquaCrop is focused on the simulation of biomass and yield using water available for the crop (Steduto et al., 2009).

Features of AquaCrop include the comparison between possible and actual yields, the development of irrigation schedules, crop sequencing simulations, future climatic scenarios, and the interaction of low water and fertility on yields, among others (FAO, 2011). In AquaCrop transpiration is calculated, and with the use of crop-specific parameters, biomass is calculated (Steduto et al., 2009). The model can be used to generate yield predictions and improve water use efficiency of crops interacting with projected climatic changes (Araya et al., 2010).

AquaCrop uses a relatively small number of parameters that can be separated into four categories: climate, crop, management, and soil (Raes et al., 2009). Steduto et al. (2009) should be consulted for more details regarding the specifics of the concepts, rationale and procedures taken in AquaCrop in each category. Due to the robustness of the model and user friendliness use, AquaCrop is a program that can be used to fill in the gap between researchers and growers in aspects related to irrigation (Steduto et al., 2009;

Geerts et al., 2010). This model differs from others in that it is really simple to understand (Araya et al., 2010).

Steduto et al. (2009) mentions that after calculating biomass production from transpiration, AquaCrop normalizes the biomass for atmospheric evaporative demand and air CO_2, making it, in that way, applicable for different locations and seasons. The characteristics mentioned before, along with the fact that AquaCrop focuses on canopy cover instead of leaf area index, are the main attributes that distinguish AquaCrop from other crop models. Yield is calculated as a product of biomass and harvest index (HI) (Steduto et al., 2009). For further information about the calculations and algorithms used in AquaCrop, as well as the software description, a good explanation is presented by Raes et al. (2009). The robustness of the model, the simplicity of the inputs required, and its ability to simulate biomass and yield production based on water and water stress in crops make AquaCrop an efficient tool to evaluate the effects of irrigation and field management strategies, sowing dates, water use efficiency, and water-limited production under irrigated and dryland production (Steduto et al., 2009 and Raes et al., 2009, Heng et al., 2009)

Because AquaCrop has only recently been developed and released, there are not many publications that describe its use and validity. Geerts et al. (2010) presented charts for deficit irrigation developed using AquaCrop and historical climate data. The charts were to be used by farmers as a decision tool to determine when to irrigate in order to supplement erratic precipitation. A Central Bolivian Altiplano location and quinoa (*Chenopodium quinoa* Willd.) were selected to exemplify the strategy described.

Araya et al. (2010) used AquaCrop version 3.0 to model barley yield response and biomass under different water inputs and different planting dates, and soil water in the root zone. The experiment conducted to calibrate and validate the model was done in northern Ethiopia. The authors mention that AquaCrop not only successfully simulated the biomass, yield production, and water in the root zone, but that this model can be used for the evaluation of irrigation strategies, making AquaCrop an option in the evaluation of planting dates and irrigation strategies in barley.

Other authors had evaluated AquaCrop in other crops. Farahani et al. (2009) and Garcia-Vila et al. (2009) evaluated the performance of AquaCrop modeling cotton (*Gossypium hirsutum* L.) for northern Syria and Spain, respectively. Farahani et al. (2009) reported that considering the simplicity of AquaCrop and the advantage of requiring fewer parameters than other models, the results obtained in the modeling of ET, biomass, yield and soil water across four levels of irrigation are promising. Garcia-Villa et al. (2009) found that AquaCrop in combination with economic analysis can be used for decision makers to grow irrigated cotton under water supply restrictions.

Hsiao et al. (2009) used AquaCrop to simulate corn in different locations and seasons.

AquaCrop contains two types of parameters. The first one is a conservative parameter that considers no change within different types of climates, time, management practices, cultivar, and geographic location. The second one is cultivar specific and it changes with climate, management, or soil type (Raes et al., 2010). The work presented by Hsiao et al. (2009) shows that after parameterizing AquaCrop with data collected in

six field experiments with different irrigation treatments and in different years at Davis, California, the model was able to simulate corn biomass and yield for the California location (with the largest deviation of 22% for biomass and 23% for yield). They were also able to simulate corn production in other locations, including Gainsville, Florida and Bushland, Texas. It is important to mention that the set of conservative parameters was held constant for the three locations and for different irrigation treatments, although, the authors mention that adjustment to these parameters would be expected when the model is tested against more diverse climatic and soil conditions (Hsiao et al., 2009).

Salemi et al. (2011) used AquaCrop to successfully simulate winter wheat (sowing date at the beginning of November, harvesting mid June of the following year) in Iran under three levels of irrigation: 60, 80 and 100% of water requirement. The model was successful in the simulation of canopy cover, grain yield, and water productivity. The three-yr set of values modeled in comparison with the observed data showed a deviation percent from -0.7 to 12%, and *d statistic* from 0.97 to 1.00. The work done by Salemi et al. (2011) showed that AquaCrop can be used to model winter wheat. The limitations for the program found in this study were for drought stress and other stresses such as salinity.

Models capable of simulating the effect of water deficits on yield and productivity are important tools (Heng et al., 2009). AquaCrop is a crop modeling program that can be used in the simulation of dryland cropping systems where the main limiting factor is water. The use of AquaCrop for the simulation of dryland cropping systems in the Central Great Plains can be a way to study options that allow for the increase in intensity of the cropping system, such as winter wheat-fallow, in years where water storage in the

soil and the precipitation are enough to grow another crop without comprising the following wheat crop.

The objective of this study was to compare two fixed no-till cropping systems, WW-C-F (winter wheat-corn-fallow) and WW-C-T (winter wheat-corn-triticale) to a flexible fallow cropping system using three different soil water thresholds to determine when to plant spring triticale or summer fallow prior to winter wheat seeding using AquaCrop 3.1+ and at least 20 yr of historic climatic data to create a probability distribution for yields. In the flexible fallow system, the model will grow a spring triticale crop only in years when a threshold value of soil water at triticale planting (April 1) is exceeded; otherwise summer fallow will be used.

CHAPTER 2. Materials and Methods

Field studies were conducted in 2009, 2010 and 2011 at the High Plains Agricultural Laboratory of the University of Nebraska (41°12’ N, 130°0’ W, 1315 m elevation above sea level) located near Sidney, NE and at the USDA-ARS Central Great Plains Research Station (40°09’ N, 103°09’ W, 1383 m elevation above sea level) located near Akron, CO. Soil at both locations were silt loams (Aridic Argiustolls). Additional soil characteristics for both locations are described in Felter et al. (2006). The cropping systems treatments described below were initially established in 2007 allowing the plots to go through two growing seasons with the treatments in place before data were collected.

At each location, two fixed no-till crop rotations where established: WW-C-F and WW-C-T. Each phase of the rotations was present each year in a randomized complete block experimental design with eight replications per location. Plot size at Sidney was 18.3 by 9.1 m and 24.4 by 12.2 m at Akron. At each location, the study area was divided in two, with four replications of each treatment receiving no supplemental irrigation, and four replications of each treatment receiving supplemental irrigation (applied at the beginning and mid-point of each month) from March through October whenever the previous 2-wk period had less precipitation than the 30-yr normal precipitation for that period of time. Only enough water was applied to bring the total precipitation plus irrigation up to the 30-yr normal. The supplemental irrigation was applied with a lateral-move drop-nozzle irrigation system.

Planting and harvesting dates for both locations are presented in Tables 1 and 2. For corn ('DK 5259 RR') a seeding rate of 34,600 seeds ha^{-1} and row spacing of 76 cm were used at both locations. For spring triticale ('Tritical 2700') a seeding rate of 100 kg ha^{-1} was used, except at Sidney in 2010, where a seeding rate of 112 kg ha^{-1} was used. Winter wheat ('Pronghorn') was seeded at a rate of 67 kg ha^{-1}, except in 2009 and 2011 at Sidney, where a seeding rate of 56 kg ha^{-1} was used.

In order to successfully calibrate and validate AquaCrop 3.1+ for the three crops involved in the simulations (wheat, corn, and triticale), measurement of soil water content, phenological development, leaf area index (LAI), and aboveground plant biomass were taken at several phenological stages through the growing season. Grain yield was also collected for wheat and corn at harvest, and a harvest index calculated. Table 3 shows the timing of each measurement for each crop. Additional measurements were made at Akron as time and labor permitted.

Nutrient needs were based on state recommendations. At Akron, 16.8 kg P_2O_5 ha^{-1} was applied in the seeded row and 67.2 kg N ha^{-1} was applied on the soil surface beside each row at corn planting, except for 2009 when no additional phosphorus was applied. Triticale was seeded at a row spacing of 19 cm with 16.8 kg P_2O_5 ha^{-1} applied in the seeded row and 67.2 kg N ha^{-1} applied to the soil surface beside each row at planting, except for 2009, when 22.4 kg P_2O_5 ha^{-1} was applied. In 2009, winter wheat was seeded at a row spacing of 19 cm, with 16.8 kg P_2O_5 ha^{-1} applied in the seeded row and 44.8 kg N ha^{-1} applied to the soil surface beside each row. In 2010, no additional phosphorus was

applied, and in 2011, 16.8 kg P_2O_5 ha^{-1} was applied in the seeded row and 67.2 kg N ha^{-1} was applied to the soil surface beside each row at corn planting.

At Sidney, corn was seeded at a row spacing of 76.2 cm. Winter wheat and triticale were seeded at a row spacing of 25.4 cm. No supplemental fertilization was required at Sidney in any year.

At Akron, corn was harvested by hand and threshed by a stationary plot machine. Harvest index was calculated by hand harvesting 6.1 m of the two center rows. Triticale harvest samples were cut at ground level from 3.05 m of the two center rows near the neutron probe access tube. Wheat was mechanically harvested with a plot combine from 8 rows with variable length (averaging 12.6 m). The reason for variable harvest length was that on occasion the area harvested included areas where biomass had been previously taken, or where plants had been knocked down when access tubes were removed, so length needed to be adjusted. In each case, HI was adjusted for the area harvested.

At Sidney, corn was harvested by hand and threshed by a stationary machine. Harvest index was calculated by hand harvesting 2 m of row. Triticale harvest samples were mechanically harvested using a flail chopper, with the area harvested being 0.91 by 9.1 m and located in the center of the plots, near the neutron probe access tubes. Wheat was mechanically harvested with a plot combine. The HI was determined from 2 m of row. Moisture and test weight of grain crops were determinate using a Dickey-John Grain Analyzer (GAC-2000, Dickey-John, Auburn, IL).

Triticale at both locations was harvested when approximately 50% of the plants had spikes fully emerged from the culm. Harvest samples were weighed in the field at harvest moisture. Subsamples were taken to determine moisture content by drying in an oven at 50°C until the weight remained constant. Field weights were then adjusted to a dry weight basis using the moisture content of the subsample to make the adjustment.

Glyphosate [*N*-(phosphonomethyl)glycine] was used for weed control during the non-crop periods. During the cropping season, weeds were controlled by hand-weeding.

Crop water use was calculated using the water balance method. At Sidney, a neutron probe (Campbell Pacific 503 DR, Campbell Pacific, Pacheco, CA) was used to determine soil water content at 30 cm depth increments down to 150 cm. When the volumetric water content reported by neutron probe in the 0-to 30-cm layer was less than 0.12 cm cm^{-1}, soil samples were collected from this soil layer, gravimetric soil water content determined and multiplied by soil bulk density to determine volumetric water content. At Akron, soil water measurements with the neutron probe were taken at 30 cm depth increments down to 180 cm. In the 0- to 30-cm layer, time-domain reflectometry was used. The neutron probes were calibrated using gravimetric soil water samples from the plot areas at both locations. Measurement sites were located near to the center of each plot.

Total available water in the soil profiles at planting for each crop and location were estimated and from this amount ending water in the soil profiles was subtracted to determine soil water extraction. In-season precipitation and irrigation were added to the

soil water extraction to calculate crop water use (evapotranspiration, ET). Runoff and deep percolation were assumed to be negligible.

LAI measurements at both locations were obtained using an LAI-2000 Plant Canopy Analyzer (LIA-2000; Li-Cor, Inc., Lincoln, NE, USA). Four sets of readings were taken at two locations in each plot at each sampling date. The instrument operator stood with the sun to his/her back and used a 90° view cap to block his/her body from the sensor. Observations of corn LAI were adjusted by recomputing while ignoring the fifth ring sensor reading as recommended by the manufacturer and using the manufacturer's FV2000 data processing software.

Phenological growth stages were observed and recorded weekly. Biomass samples were taken several times during the growing season from two meters of row by hand clipping approximately 1 cm above the soil surface. Samples were oven-dried at 50 ^{o}C until the weight remained constant.

FAO has calibrated non-location-specific parameters for the major agricultural crops, providing default values that can be found in the AquaCrop database (Raes et al., 2009). The calibration for winter wheat and triticale were not in this database, so calibrations for these crops were necessary.

Data from Akron, CO were used for the AquaCrop calibration of winter wheat, corn, and triticale. The calibration for corn was done using the non-location-specific parameters predetermined in AquaCrop, but with modifications to better fit the Akron, CO region. Tables 4, 5 and 6 provide the calibrated parameter values used in AquaCrop to simulate the three crops used in this study. For the calibration of winter wheat, the data

collected in the current study in crop years 2008-2009 and 2009-2010 provided four data sets (irrigated and dryland treatments for both WW-C-F and WW-C-T) in each year, to which were added twelve sets of data collected from a single year (2005-2006 crop year) of a study conducted by Felter et al. (2006). For the calibration of spring triticale, six sets of data collected from 2 yr of a study conducted by Felter et al. (2006) were used along with the 2009 triticale data collected from the dryland treatment in this current study. Additionally, one set of triticale data (D.C. Nielsen, unpublished data) was used from the 2008 setup year for the current study (irrigated and dryland treatments averaged together since no irrigation was applied in 2008). For the corn calibration, the data collected in the current study in 2009 and 2010 (irrigated and dryland treatments for both WW-C-F and WW-C-T) were used, to which were added four sets of data collected from the 2007 setup year for the current study (D.C. Nielsen, unpublished data). The additional data sets were used for the calibration of AquaCrop to provide greater diversity to the data collected from this study in 2009 through 2011.

One of the characteristics of AquaCrop is that it simulates the development of a crop in terms of canopy cover (CC) instead of LAI (Steduto et al., 2009). For this study, CC was calculated from LAI measurements.

At the beginning, the equation presented by Hsiao et al. (2009) was used to estimate the corn CC from measured LAI:

$$CC=1.005 \times [1 - \exp(-.06\ LAI)]^{1.2} \qquad (1)$$

However, the CC obtained did not represent the observed values. Therefore, an estimation of CC development from Akron data was calculated. The method used to

estimate the CC consisted of the use of digital photos of canopy development when the LAI measurements were taken during the seasons of 2009 and 2010. Visual estimates of CC from digital photos has been used by previous authors, e.g. Farahani et al. (2009). The digital photos were taken above the canopy at three different representative points per plot. In order to calculate the CC per plot, each picture was analyzed by laying them under a grid that contained 45 random points. A CC percentage was estimated by the fraction of points that contacted green crop canopy. From the percentage of CC and the LAI measurements, an empirical relationship was obtained by regression. The equation is:

$$CC=83.7 \times [1- \exp (0.7811\ LAI)] \quad (2)$$

With an $R^2 = 0.983$.

The same approach used in the generation of the equation that represents the correlation between CC and LAI in corn was used to generate the equations for winter wheat and spring triticale. For winter wheat the equation is:

$$CC=17.806 \ln (LAI) + 64.47 \quad (3)$$

With an $R^2 = 0.948$

For spring triticale the equation is:

$$CC= 11.77 + 54.08 \times LAI – 10.91 * LAI^2; \text{ for } LAI < 2.3 \quad (4)$$

$$CC = 80; \text{ for } LAI > 2.3 \quad (5)$$

With an $R^2= 0.91$

At the end of the calibration generated for winter wheat, it was used to adapt the calibration for spring triticale. This means that the equation generated for spring triticale was discarded and the one generated for winter wheat was used instead.

During the AquaCrop calibration for the three crops simulated, the first section parameterized was the crop development calendar. The data required in the calendar section was obtained from the CC equations previously described. After the parameterization of the calendar section was completed, the water stress section was calibrated and parameterized. In the water stress section, canopy expansion, stomatal closure, and early canopy senescence were adapted to field data observed at Akron. No aeration stress was considered. The final calibration step was the parameterization of the crop water productivity value (WP*). After these three sections were calibrated, minimal changes were made to the development and ET sections. No fertility stress was considered during the calibration process since water is the main limiting factor for crop production in the Great Plain, and field plots were fertilized with adequate amounts of N fertilizer.

A sensitivity analysis of the different changes made in each parameter was performed. In this analysis, variation of only one of the parameters was conducted for each model run. The effect that the incremental changes in individual calibration parameters had on grain yield for winter wheat and the effect on ET and biomass for winter wheat, corn and triticale were recorded. The values modeled for grain yield, biomass and ET were compared with the actual values obtained in the field for each crop under at least three different levels of soil water content at planting (low, medium and

high). The modeled values were divided by the observed values in order to generate a coefficient. The coefficient was then used to see how close the predicted value was to the observed value. This coefficient varies between 0 (poor model) and 1 (perfect model).

In order to validate the ratio previously explained, further statistics were performed to evaluate the simulated results obtained in the validation: (i) Root Mean Square Error (RMSE), Eq. (6) which shows the average deviation between simulated and observed values; (ii) Mean Relative Error (MRE), Eq. (7), which gives the bias of the simulated value relative to the observed value; and (iii) the index of agreement (d-statistic), Eq. (8) between measured and simulated parameters (Willmott, 1981), which varies between 0 (poor model) and 1 (perfect model):

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(P_i - O_i)^2} \tag{6}$$

$$MRE = \frac{1}{n}\sum_{i=1}^{n} Abs\left[\frac{P_i - O_i}{O_i}\right] \times 100 \tag{7}$$

$$d = 1.0 - \frac{\sum_{i=1}^{n}(P_i - O_i)^2}{\sum_{i=1}^{n}(|P_i - \bar{O}_i| + |O_i - \bar{O}_i|)^2} \tag{8}$$

where,

= the ith simulated value

= the ith observed value

$\bar{O}_i$ = the mean observed value

n = the number of data pairs

Data from Sidney, NE was used to validate the AquaCrop calibrations. For the validation of winter wheat and spring triticale, twelve and six sets of data were used

respectively. For the corn validation, eight sets of data were used. The same statistical analysis described for the Akron calibration was performed for the simulated values obtained in the Sidney validation.

The ET_o Calculator, version 3.1 generated by FAO, was used to compute reference evapotranspiration by the FAO Penman-Monteith equation. The ET_o Calculator creates the ET_o, temperature and CO_2 files used by AquaCrop for the long-term modeling runs. Historical weather data from 1988 through 2010 were obtained from the High Plains Regional Climate Center (http://hprcc1.unl.edu/cgi-hpcc/home.cgi) in Lincoln, NE. The values used were daily values of temperature maximum (^oC), temperature minimum (^oC), average vapor pressure (kPa), wind run (km day^{-1}), and solar radiation (MJ m^{-2} day^{-1}) and were recorded by automated weather stations within a few hundred meters of the plot areas at both locations. The rainfall values were entered into AquaCrop from records of manually read rain gauges at both locations.

In order to model crop development and production with AquaCrop it is necessary to specify the sowing date for each crop. For triticale, not only the sowing date was necessary, but also the harvest date. Since spring triticale was grown for forage, an earlier termination date than physiological maturity was necessary. For Akron, the following sowing dates were determined using the average date from the data sets used for calibration of the model; 25 Sept. for winter wheat, 13 May for corn, and 8 April for spring triticale. The average harvest date for spring triticale was 23 June. For Sidney, the following dates were determined; 10 Sept. for winter wheat, 12 May for corn, and 4 April for spring triticale. The average harvest date for spring triticale was 25 June.

AquaCrop predicted the soil water content at the end of the season or when the crop was terminated. The ending soil water content predicted by AquaCrop was added to the precipitation observed during the non-crop period between crops for each location to generate the beginning soil water content for the next crop. Before adding the amount of precipitation observed, the 10-yr average precipitation storage efficiency reported by Nielsen et al. (2010) was applied. Those storage efficiencies were 35% between wheat harvest and September 30, 81% between October 1 and corn plating, 64% between corn harvest and triticale planting, 10% between triticale harvest and wheat plating, and 29% between corn harvest and wheat plating. This last value was from the same experiment as reported in Nielsen et al. (2010) but is unpublished data from corn residue. The calculated amount of soil water at plating was distributed in the simulated soil profile by filling each 30-cm layer to field capacity from top to bottom until the calculated amount of beginning water was used up.

In order to implement the flexible fallow approach, three soil water content thresholds at triticale planting were established. These were 350, 375, and 400mm. Simulations using weather data from 1988 through 2010 were performed for each location using the three thresholds. If the beginning soil water content at triticale planting met the threshold, triticale was planted; if not, fallow was implemented. When fallow was implemented, the precipitation received during this period was carried forward to the next wheat crop after applying the precipitation storage efficiency reported by Nielsen et al. (2010). In addition to the three flexible fallow rotations mentioned before using the three water threshold conditions, two fixed rotations were modeled, these were winter wheat-

corn- fallow (WW-C-F) and winter wheat- corn- triticale (WW-C-T). Each phase of each rotation was simulated every year, beginning with the 1988 starting soil water conditions. Grain yield for winter wheat and corn and biomass yield for triticale modeled for each year were simulated and recorded for both locations. Since winter wheat and corn are measured in kg of grain produced per ha, and spring triticale in kg of total biomass per ha, economic analysis was performed in order to compare the highest economic yield as risk associated with the five different cropping systems.

Net return was calculated as the return to land and management, where the land and management will be residual claimants on the cash return generated in the system. Crop production budgets were generated for each crop and fallow period using the 2010 University of Nebraska Crop Budget Generator (http://cropwatch.unl.edu/web/cropwatch/archive?articleID=4529324). Once the 2010 crop production costs were determined, the United States Department of Agriculture – National Agricultural Statistics Service prices paid index for agriculture was used to index the production costs back to the appropriate values for the 1988 to 2009 crop production seasons (http://www.nass.usda.gov/Publications/Ag_Statistics/2010/Chapter09.pdf). By this the production cost was matched with the production year and historical price data (Tables 7 and 8).

The three price series used for this study were national weighted average annual prices from the United States Department of Agriculture – Economic Research Service (http://www.ers.usda.gov/Data/FeedGrains/). Corn and wheat prices were the reported

prices for the year based on actual farm gate sales. The triticale forage price was based on two thirds of the national average alfalfa price. The price of other hay crops such as triticale, sorghum, millets, and oats is traditionally discounted from the alfalfa hay price by at least 30 percent, and as much as 50 percent. There is a limited market for these forages, so pricing for this type of study must be based on the alfalfa market.

To determine the per hectare profitability for each of the systems, an average across the three crops in each year was developed for those years where all three crops are grown in the system, Eq. (4).

$$\text{Return} = \{[(Y_w * P_w) - C_w] + [(Y_c * P_c) - C_c] + [(Y_t * P_t) - C_t]\} / 3 \qquad (9)$$

where,

Y_w = wheat grain yield, (kg ha^{-1})

Y_c = corn grain yield, (kg ha^{-1})

Y_t = triticale dry biomass yield, (kg ha^{-1})

P_w = grain wheat price, (US $ kg ha^{-1})

P_c = grain corn price (US $ kg ha^{-1})

P_t = biomass triticale price (US $ kg ha^{-1})

C_w = wheat cost of production (US $ ha^{-1})

C_c = corn cost of production (US $ ha^{-1})

C_t = triticale of cost production (US $ ha^{-1})

In the years where fallow is inserted into the system instead of the triticale forage, Eq. (5) was used.

$$\text{Return} = \{[(Y_w * P_w) - C_w] + [(Y_c * P_c) - C_c] - C_f\} / 3 \qquad (10)$$

where,

Y_w = wheat grain yield, (kg ha^{-1})

Y_c = corn grain yield, (kg ha^{-1})

P_w = grain wheat price, (US $ kg ha^{-1})

P_c = grain corn price (US $ kg ha^{-1})

C_w = wheat cost of production (US $ ha^{-1})

C_c = corn cost of production (US $ ha^{-1})

C_f = fallow cost (US $ ha^{-1})

Medians of winter wheat and corn grain yield and spring triticale biomass modeled for the three flexible rotations and the two fixed rotations, and medians of the economic return for each cropping system, were analyzed and compared using PROC GLIMMIX in SAS (SAS Institute, 1985) in order to identify differences.

CHAPTER 3. Results and Discussion

3.1. AquaCrop Calibration and Validation

AquaCrop 3.1+ can be used to simulate growth in winter wheat, corn and triticale in the Central Great Plains. During the calibration with Akron data, good agreement was found between the observed and predicted values for all three crops (Table 9 and Figures 1-8). The best simulation was grain yield for corn with a d-statistic value of 0.961. A larger difference was found between the observed and predicted values for spring triticale ET and corn biomass (d-statistic values of 0.713 and 0.764, respectively). The poor prediction of spring triticale ET might be explained by the water contents of the surface 60 cm of soil at planting, which was the lowest of all crops evaluated in this study. Previous studies reported that AquaCrop was very sensitive to initial soil water content (Garcia-Villa et al., 2009). The prediction of winter wheat and corn grain yield, and triticale biomass was acceptable, with d-statistic values of 0.921, 0.961, and 0.861, respectively.

Winter wheat performance was well predicted by the model, which is important to note since AquaCrop 3.1+ does not account for winter dormancy, which made the calibration more challenging. In general, AquaCrop was able to simulate, with acceptable precision, the observed values for all three crops at Akron.

Validation of AquaCrop using data from Sidney indicated that the model was not accurate in simulating any of the three crops used (Table 10 and Figures 9-16), with d-values ranging from 0.242 for corn yield to 0.481 for wheat yield and biomass. It is not clearly understood why AquaCrop did such a poor job modeling the crops at Sidney. The

calibration done at Akron was expected to produce similar simulation results at Sidney without recalibration since the weather and soil environment at Sidney were not greatly different from Akron. The lower d-values obtained for Sidney could be attributed to the sensitivity of the program to soil water content. Even though the crops were poorly predicted at Sidney, we decided to do the multi-year predictions at both locations using the calibration parameters determined at Akron since they were developed under a fairly broad range of environmental conditions. Further analysis will likely need to be performed to determine if there are errors in the field data collected at Sidney, or if adjustments to some calibration parameters could be made to make the model more responsive to Sidney conditions. Such an analysis may be helpful in delineating potential areas of improvement for AquaCrop.

3.2. Multi-year Simulations

Tables 11 and 12 show the different values for winter wheat and corn grain yield and triticale forage yield predicted by AquaCrop for Akron and Sidney, respectively. In Tables 13 and 14 it is possible to see that average winter wheat yields were greatest in WW-C-F and lowest in WW-C-T. For Akron (Table 13), the average values for winter wheat yield in WW-C-F and WW-C-T were 2670 and 2240 kg ha^{-1}, respectively. For Sidney (Table 14), the values were 2450 kg ha^{-1} for WW-C-F and 2290 kg ha^{-1} for WW-C-T. The higher winter wheat grain yield average obtained in WW-C-F was likely the result of increased soil water after fallow compared to after triticale, 430 and 394 mm, respectively. The average winter wheat yield tended to decline as the frequency of summer fallow declined, which agrees with the main objective of summer fallow, which

is to increase the total amount of stored soil water to then be used by the following crop (Moret et al., 2007). This may also explain the increase in yield variability with the intensification of the cropping system.

Even though winter wheat yield tended to decline as the frequency of summer fallow declined, and grain yield statistically significant difference was found between the 400 mm flexible fallow system and WW-C-F at Akron (p-value 0.007, Table 15), no statistical difference was found between these two cropping systems at Sidney (p-value 0.093, Table 16).

Table 17 shows that at Akron, average corn yields were generally not affected by cropping system, except between WW-C-T and WW-C-F (p-value of 0.001), where WW-C-F had a greater average corn grain yield. Other statistically significant differences for corn grain yield were too small to be of any practical significance. A similar situation at Sidney was found (Table 18).

Average triticale forage yields were not affected by cropping system at either location (Tables 19 and 20). This might be explained by the fact that winter wheat and corn crops planted before triticale, likely eliminated any effect that the previous spring triticale or fallow treatments might have had on soil water storage prior to triticale planting.

Tables 21 and 22 show the different economic returns for each system at Akron and Sidney, respectively. At both locations, average income was improved by replacing summer fallow with spring triticale, but income variability also increased (Tables 23 and 24). Aakre (1991, unpublished data) cited by Dhuyvetter et al. (1996) reported higher

income variability in winter wheat-sunflower than in winter wheat-fallow. The increase in variability in income was attributed to yield variability of the cropping system.

Flexible fallow did not seem to provide much benefit over fixed rotations, i.e., flexible fallow did not result in increased yield with little or no increase in income variability. The exception was Sidney, where the 400 mm threshold had a slightly greater average return and slightly reduced income variability compared to WW-C-F (Table 24).

From Tables 23 and 24 we can infer that risk-averse growers are likely to prefer WW-C-F over WW-C-T, but non-risk-averse growers will likely prefer WW-C-T. Performance of the flexible fallow system using a 400 mm soil water threshold exhibited a slightly higher average return and slightly smaller income variability than WW-C-F at Sidney, which may suggest that some risk-averse farmers may prefer flexible fallow with a high soil water threshold, e.g. 400 mm, over WW-C-F if the cost of obtaining soil water content information is not prohibitive. However, in general, the economic benefits of flexible fallow compared to the two fixed cropping systems were minimal.

Tables 25 and 26 show the statistical analysis of the economic returns for the different systems at both locations. In Figures 17 and 18, it is possible to see the distribution of the economic returns for each cropping system at Akron and Sidney, respectively. We can see that at both locations, the economic returns from WW-C-T were statistically superior to the returns from WW-C-F (p-value of 0.001) for both locations. Dhuyvetter et al. (1996) reported that the combination of reduced tillage and no-till with wheat rotations involving sunflower, corn and sorghum had a higher net return than the traditional winter wheat-fallow rotation in the Great Plains. Nielsen et al. (2005) reported

that the increase in precipitation use efficiency on a mass-produced and economic-return basis was higher in more intense cropping systems involving annual forages.

Even further, WW-C-F was only economically competitive with the flexible fallow system using a 400 mm soil water threshold. The use of more intense cropping system than the traditional winter wheat-fallow can reduce the negative impact that fallow has on the environment. A more intense cropping system not only provides marketing advantages, but also improves weed control, increases residue retention, and minimizes insects and diseases associated with monoculture (Nielsen et al., 2008; Peterson et al., 1993).

CHAPTER 4. Conclusions

AquaCrop can be used to simulate ET, which can be used to estimate soil water content following winter wheat, corn and triticale in the Central Great Plains. AquaCrop was also effective at simulating grain yield in corn and winter wheat.

The multi-year simulations of flexible fallow using three different soil water thresholds and two fixed rotations showed that average winter wheat yields were greatest in WW-C-F and lowest in WW-C-T. However, average annual income was greater without summer fallow. This suggests that although summer fallow may reduce income variability, it also likely reduces income potential. Lyon et al. (2004) found that replacing summer fallow with oat + pea for forage or proso millet reduced subsequent winter wheat yield, but economic returns were similar to systems with summer fallow.

Even though flexible fallow did not seem to provide much economic benefit over the two fixed rotations, the adoption of flexible fallow might help to reduce some of the negative consequences of summer fallow, e.g., soil erosion or the necessity of herbicide application for weed control by reducing the frequency of summer fallow. Lyon et al. (2004) mentioned that the elimination or significant reduction of summer fallow use will not only protect the soil from degradation, but also bring a higher efficiency in water use and improve the viability of the dryland cropping system in the long-run.

Risk-averse growers are likely to prefer WW-C-F over WW-C-T because of the reduction in year-to year income variability that summer fallow provides. However, non-risk-averse growers will likely prefer WW-C-T because of the increase in the average and total income. For farmers that have animal production incorporated into their farm

operations, a cropping system that includes a spring-planted annual forage such as spring triticale may have greater value than indicated here, where we have included cutting, baling, and transportation costs for spring triticale in the economic analysis. Grazing forages can reduce these costs (Clampham et al., 2008) by allowing animals to do some of the work related to harvesting the forages (Munson et al., 1990).

Our simulations using AquaCrop and 23 yr of historical weather data from Akron, CO and Sidney, NE suggest that a flexible fallow system, (i.e., a system that uses soil water in the spring to determine whether to summer fallow prior to planting winter wheat or plant an annual forage such as triticale as suggested by Felter et al. (2006), provides little benefit compared to fixed cropping systems with or without summer fallow. Seldom in this study did flexible fallow provide increased income with little or no increase in income variability compared to WW-C-F, which is the goal of the flexible fallow system. This suggests that knowing soil water content in the spring does not insulate growers sufficiently from the vagaries of seasonal precipitation to significantly reduce crop production risk in the Central Great Plains. This suggests that growers need to decide if they are willing to accept greater income variability for the potential of greater income. If they are, then annual forages can substitute for summer fallow. If not, summer fallow will lower annual income variability but it will also lower overall income.

The major influence that climate variability has on agriculture is increased economic risk (Jones et al., 2000). We hypothesized that flexible fallow systems based on the quantity of soil water in the spring could reduce the production and economic risk associated with climate variability. However, our crop simulation results provide little

support for this hypothesis. Short-term (3 to 4 months) climate forecast combined with information on stored soil water at planting have been used to help make crop management decisions in northeast Australia (Stone et al., 1992), which is strongly influenced by the El Nino southern oscillation. With accurate data input (soil physical properties, genetic material and weather conditions) modeling can be used as a cropping system tool (Staggenborg et al., 2005). Perhaps flexible fallow systems will need to await better climate forecasting skill than is currently available for the Central Great Plains. Until that time, growers need to make their decisions on the use of summer fallow based on their level of aversion to risk, i.e. variability, or their level of concern about the negative soil and environmental consequences of summer fallow.

Tables

Table 1. Planting and harvesting dates at Akron, CO for corn, winter wheat and triticale.

Year of harvest	Maize		Spring triticale		Winter wheat	
	Planting date	Harvest date	Planting date	Harvest date	Planting date	Harvest date
2009	12-May-09	6-Oct-09 (dryland) 26-Oct-10 (irrigated)	3-Apr-09	7-May-09	20-Sep-08	20-Jul-09
2010	10-May-10	6-Oct-10 (dryland) 13-Oct-10 (irrigated)	20-Apr-10	*	28-Sep-09	14-Jul-10
2011	17-May-11	13-Oct-11 (dryland) 24-Oct-11 (irrigated)	1-Apr-11	22-Jun-11	22-Sep-10	18-Jul-11

*Not harvested because winter triticale was seeded in error and it failed to vernalize and produce spikes.

Table 2. Planting and harvesting dates at Sidney, NE for corn, winter wheat and triticale.

Year of harvest	Maize		Spring triticale		Winter wheat	
	Planting date	Harvest date	Planting date	Harvest date	Planting date	Harvest date
2009	13-May-09	7-Oct-09	13-Apr-09	30-Jun-09	10-Sep-08	15-Jul-09
2010	10-May-10	7-Oct-10	30-Mar-10	22-Jun-10	10-Sep-09	13-Jul-10
2011	*	*	1-Apr-11	22-Jun-11	9-Sep-10	19-Jul-11

*No corn was planted at Sidney in 2011.

Table 3. Phenological stages at which various soil and crop measurements were taken for each crop.

Spring Triticale			Wheat			Corn		
Soil water	*LAI	Biomass	Soil water	LAI	Biomass	Soil water	LAI	Biomass
Planting	Jointing	Jointing	Emergence	Jointing	Jointing	Planting	V8	V8
Emergence	Heading	Harvest	Mid November	Mid way to flowering	Flowering	V8	Flowering	Flowering
Jointing			Mid March	Flowering	Harvest	Flowering	Late milk	Late milk
Harvest			Jointing	Dough		Late milk		
			Flowering			Maturity		
			Maturity					

*LAI= leaf area index .

Table 4. Crop parameters used in AquaCrop to simulate winter wheat.

Parameter	Value	Units
Initial canopy cover	3.75	%
Canopy growth coefficient (CGC)	2.4	%/day
Maximum canopy cover (CCx)	90	%
Canopy decline coefficient (CDC)	3.1	%/day
Senescence	253	Calendar days
Maturity	296	Calendar days
Duration of flowering	14	Calendar days
From day 1 after sowing to flowering	246	Calendar days
Maximum effective rooting depth	1.8	Meter
Minimum effective rooting depth	0.3	Meter
Soil evaporation coefficient (Ke)	50	%
Crop transpiration coefficient (Kcb)	0.6	
Crop water productivity (WP*)	21	g/m2
Reference harvest index (HIo)	27	%
Canopy expansion p-upper	0.3	
Canopy expansion p-lower	0.65	
Canopy expansion shape factor	3.5	
Stomatal closure p-upper	0.45	
Stomatal closure shape factor	3.5	
Early canopy senescence p-upper	0.75	
Early canopy senescence shape factor	3.5	
Aeration stress	None	
Fertility stress	None	

Table 5. Crop parameters used in AquaCrop to simulate triticale.

Parameter	Value	Units
Initial canopy cover	4.95	%
Canopy growth coefficient (CGC)	8.7	%/day
Maximum canopy cover (CCx)	80	%
Canopy decline coefficient (CDC)	13.5	%/day
Senescence	125	Calendar days
Maturity	125	Calendar days
Duration of flowering	8	Calendar days
From day 1 after sowing to flowering	90	Calendar days
Maximum effective rooting depth	1.8	Meter
Minimum effective rooting depth	0.3	Meter
Soil evaporation coefficient (Ke)	50	%
Crop transpiration coefficient (Kcb)	0.65	
Crop water productivity (WP*)	23	g/m2
Reference harvest index (HIo)	27	%
Canopy expansion p-upper	0.3	
Canopy expansion p-lower	0.65	
Canopy expansion shape factor	3.5	
Stomatal closure p-upper	0.45	
Stomatal closure shape factor	3.5	
Early canopy senescence p-upper	0.75	
Early canopy senescence shape factor	0.35	
Aeration stress	None	
Fertility stress	None	

Table 6. Crop parameters used in AquaCrop to simulate corn.

Parameters	Value	Units
Initial canopy cover	0.24	%
Canopy growth coefficient (CGC)	12.2	%/day
Maximum canopy cover (CCx)	75	%
Canopy decline coefficient (CDC)	7.4	%/day
Senescence	109	Calendar days
Maturity	141	Calendar days
Duration of flowering	12	Calendar days
From day 1 after sowing to flowering	80	Calendar days
Maximum effective rooting depth	1.8	Meter
Minimum effective rooting depth	0.3	Meter
Soil evaporation coefficient (Ke)	50	%
Crop transpiration coefficient (Kcb)	1.05	
Crop water productivity (WP*)	30.7	g/m2
Reference harvest index (HIo)	49	%
Canopy expansion p-upper	0.1	
Canopy expansion p-lower	0.45	
Canopy expansion shape factor	2.6	
Stomatal closure p-upper	0.45	
Stomatal closure shape factor	6	
Early canopy senescence p-upper	0.45	
Early canopy senescence shape factor	2.7	
Aeration stress	None	
Fertility stress	None	

Table 7. Historical prices for winter wheat, corn, and spring triticale.

	Winter wheat	Corn	Spring triticale
Year	----------US $ kg^{-1}----------		
1988	0.138	0.100	0.079
1989	0.136	0.093	0.077
1990	0.093	0.090	0.071
1991	0.120	0.093	0.061
1992	0.119	0.081	0.064
1993	0.115	0.098	0.073
1994	0.128	0.089	0.075
1995	0.176	0.128	0.071
1996	0.157	0.107	0.083
1997	0.118	0.096	0.087
1998	0.095	0.076	0.072
1999	0.095	0.074	0.065
2000	0.100	0.074	0.073
2001	0.100	0.078	0.085
2002	0.135	0.091	0.082
2003	0.119	0.095	0.074
2004	0.121	0.081	0.080
2005	0.124	0.079	0.085
2006	0.166	0.120	0.092
2007	0.226	0.165	0.112
2008	0.253	0.160	0.135
2009	0.178	0.140	0.092
2010	0.238	0.204	0.100

Table 8. Production cost for winter wheat, corn, spring triticale and fallow.

	Price index	Winter wheat	Corn	Spring triticale	Fallow
Year	----------US $ ha^{-1}----------				
1988	92	166	200	170	26
1989	97	175	211	179	27
1990	99	179	216	183	28
1991	100	180	218	185	28
1992	101	182	220	186	29
1993	103	186	224	190	29
1994	106	191	231	196	30
1995	108	195	235	199	31
1996	115	207	250	212	33
1997	118	213	257	218	33
1998	114	206	248	210	32
1999	113	204	246	209	32
2000	115	207	250	212	33
2001	120	217	261	221	34
2002	119	215	259	220	34
2003	124	224	270	229	35
2004	132	238	287	244	37
2005	140	253	305	258	40
2006	150	271	327	277	42
2007	162	292	353	299	46
2008	188	339	409	347	53
2009	183	330	398	338	52
2010	186	336	405	343	53

Table 9. Statistics for the comparison between observed and simulated values for seed yield, final biomass, and crop evapotranspiration (ET) for winter wheat and corn, and final biomass and crop ET for triticale, for the calibration of AquaCrop for Akron, CO.

		Mean				
Variable name	**n**	**Observed**	**Simulated**	**MRE**	**RMSE**	**d statistic**
Winter wheat						
Yield (kg ha $^{-1}$)	20	2180	2010	13	399	0.921
Biomass (kg ha $^{-1}$)	20	7340	7820	12	1050	0.938
ET (mm)	20	380	395	9	35.1	0.890
Spring triticale						
Biomass (kg ha $^{-1}$)	8	4370	4490	28	1140	0.861
ET (mm)	8	160	186	20	36.6	0.713
Corn						
Yield (kg ha $^{-1}$)	12	3970	4010	20	754	0.961
Biomass (kg ha $^{-1}$)	8	11000	12500	24	2460	0.764
ET (mm)	12	430	435	9	41.9	0.886

Table 10. Statistics for the comparison between observed and simulated values for seed yield, final biomass, and crop evapotranspiration (ET) for winter wheat and corn, and final biomass and crop ET for triticale, for the validation of AquaCrop for Sidney, NE.

		Mean				
Variable name	**n**	**Observed**	**Simulated**	**MRE**	**RMSE**	**d statistic**
Winter wheat						
Yield (kg ha $^{-1}$)	12	3390	2530	24	1330	0.481
Biomass (kg ha $^{-1}$)	12	11400	9490	17	2880	0.481
ET (mm)	12	534	410	23	135	0.389
Spring triticale						
Biomass (kg ha $^{-1}$)	6	4480	5500	39	1620	0.420
ET (mm)	6	186	318	38	153	0.461
Corn						
Yield (kg ha $^{-1}$)	8	6990	7370	4	500	0.242
Biomass (kg ha $^{-1}$)	8	16800	15800	13	2910	0.457
ET (mm)	8	472	499	4	30.2	0.398

Table 11. Simulated grain yields for winter wheat and corn, and forage yields for triticale, in two fixed rotations [winter wheat-corn-triticale (WW-C-T) and winter wheat-corn-fallow (WW-C-F)] and flexible fallow using three different soil water thresholds at planting (350, 375, and 400 mm) to determine when to plant triticale or use fallow at Akron, CO. using historical weather data from 1988 through 2010. Winter wheat yields are reported at 12.5% moistures; corn yields are reported at 12.5% moisture; triticale yields are reported at 0% moisture.

	WW-C-T			350 mm			375 mm			400 mm			WW-C-F	
Year	**WW**	**C**	**T**	**WW**	**C**	**T**	**WW**	**C**	**T**	**WW**	**C**	**T**	**WW**	**C**
	---kg ha^{-1}---													
1988	2140	3840	4800	2140	3840	4800	2140	3840	4800	2140	3840	4800	2700	3840
1989	1720	3270	4510	1720	3270	****	1720	3270	****	1720	3270	****	2230	4310
1990	1990	7010	4800	2660	7010	4210	2660	7010	****	2660	7010	****	2920	7100
1991	2320	4550	4960	2320	4760	4960	2920	4760	****	2920	4760	****	2920	4550
1992	2880	6720	4740	2880	6720	4770	3000	7000	****	3000	7000	****	3060	6990
1993	2080	6390	4770	2100	6390	4770	2450	6460	****	2450	6460	****	2450	6470
1994	1830	4400	4620	1830	4600	4620	2450	4400	4640	2450	4400	****	2450	4400
1995	3000	2960	4370	3000	2960	4370	3000	2960	****	3020	2960	****	3020	2960
1996	3040	7240	4770	3060	7240	****	2860	7310	****	2860	7310	****	2870	7310
1997	2140	6260	4990	2390	6360	4990	2390	6260	5000	2390	6260	****	2390	6260
1998	1970	5800	4550	1970	6220	4570	2030	6220	4550	2450	6220	****	2450	6220
1999	1760	7250	4990	1810	7250	****	1760	7270	****	2570	7580	****	2570	7580
2000	2110	4130	4600	2530	4200	4600	2530	4130	4610	2530	4150	4710	2530	4150
2001	2440	6360	5040	2440	6540	5040	2450	6540	4950	2580	6540	****	2930	6540
2002	1540	70	3760	1580	70	****	1010	71	****	1760	75	****	1750	590
2003	2590	2900	5080	3350	2900	5080	3350	2900	5080	3350	2900	5080	3350	2900
2004	2980	5820	4590	2980	6500	****	3030	6490	****	3030	6490	****	3030	6490
2005	2000	5840	4950	2730	5840	****	2730	5850	****	2730	5850	****	2730	5850
2006	1780	4870	4580	2170	4870	4580	2170	4870	****	2170	4870	****	2770	4870
2007	1940	2140	4970	1940	3040	5270	2940	3040	5270	2940	3040	****	2940	3040
2008	1770	5060	5060	2420	5060	5060	2420	5300	****	2600	5300	****	2650	5300
2009	2650	6900	5180	2570	6900	5180	3290	6900	5180	3290	6900	5180	3290	6900
2010	2860	3570	5020	2860	3570	5020	2860	3570	5020	2860	3570	****	1350	3570

**** Years where fallow was implemented since the water threshold to grow spring triticale was not reached.

Table 12. Simulated grain yields for winter wheat and corn, and forage yields for triticale, in two fixed rotations [winter wheat-corn-triticale (WW-C-T) and winter wheat-corn-fallow (WW-C-F)] and flexible fallow using three different soil water thresholds at planting (350, 375, and 400 mm) to determine when to plant triticale or use fallow at Sidney, NE using historical weather data from 1988 through 2010. Winter wheat yields are reported at 12.5% moistures; corn yields are reported at 12.5% moisture; triticale yields are reported at 0% moisture.

	WW-C-T			350 mm			375 mm			400 mm			WW-C-F	
Year	**WW**	**C**	**T**	**WW**	**C**	**T**	**WW**	**C**	**T**	**WW**	**C**	**T**	**WW**	**C**
	---kg ha^{-1}---													
1988	1780	2720	5370	1780	2720	5370	1780	2720	5370	1780	2720	5370	1780	2720
1989	2310	3930	4990	2310	3930	****	2310	3930	****	2310	3930	****	2200	3930
1990	1280	5300	5310	2040	5300	5310	2040	5300	5310	2040	5300	****	2040	5130
1991	2400	4190	5600	2400	5030	5600	2400	5030	****	2710	5030	****	2710	5030
1992	2750	7140	5300	2750	7140	****	2680	7140	****	2680	7140	****	2680	7140
1993	1960	6870	5610	2300	6870	5610	2300	6870	****	2300	6870	****	2300	6870
1994	2140	6910	5720	2140	6910	5720	2330	6910	5720	2330	6910	5720	2330	6910
1995	2490	3350	4975	2490	3350	****	2490	3350	****	2490	3350	****	2500	3350
1996	2510	6170	5310	2400	6170	****	2400	6170	****	2400	6170	****	2400	6170
1997	2250	5380	5600	2450	5380	5600	2450	5380	5600	2450	5380	5600	2450	5380
1998	2440	7420	5510	2440	7420	5510	2440	7420	****	2440	7420	****	2440	7420
1999	2660	7350	5620	2660	7350	****	2710	7350	****	2500	7350	****	2710	7350
2000	2330	1650	5650	2630	1650	5650	2630	1650	5650	2630	1650	****	2630	1650
2001	2420	7180	5630	2420	7180	5630	2420	7180	5630	2470	7180	****	2470	7180
2002	1820	795	4690	1820	795	4690	1820	795	****	1820	3070	****	1820	3070
2003	1870	1510	5650	1870	1510	5650	2840	1510	5650	2840	1510	5650	2840	1510
2004	2410	4910	5520	2410	4740	****	2410	6140	****	2420	6140	****	2550	6130
2005	2380	7180	5520	2530	7180	****	2530	7180	****	2530	7180	****	2530	7180
2006	2210	4790	5180	2320	4790	5180	2360	4790	5180	2360	4790	****	2360	4800
2007	2810	5000	5950	2810	5000	5950	2810	5000	5950	2940	5000	****	2940	5000
2008	2340	6170	5610	2340	6170	****	2340	6170	****	2380	6200	****	2380	6200
2009	2680	7330	5830	2850	7330	5830	2850	7330	****	2850	7330	****	2850	7330
2010	2480	6240	5630	2480	6240	5630	2480	6240	5630	2480	6240	****	2400	6240

**** Years where fallow was implemented since the water threshold to grow spring triticale was not reach.

Table 13. Summary of simulated grain yield for winter wheat and corn and forage yield for triticale for Akron, CO. Winter wheat yields are reported at 12.5% moistures; corn yields are reported at 12.5% moisture; triticale yields are reported at 0% moisture.

	WW-C-T			350mm			375 mm			400mm			WW-C-F		
	WW	**C**	**T**	**WW**	**C**	**T**	**WW**	**C**	**T**	**WW**	**C**	**T**	**WW**	**C**	**T**
	---kg ha^{-1}---														
Average	2240	4930	4770	2410	5050	4820	2530	5060	4910	2630	5080	4940	2670	5140	--
Total	51500	113000	111000	55500	116000	81900	58200	116000	49100	60500	117000	19800	61400	118000	--
SD	469	1870	310	482	1850	294	551	1870	249	422	1890	221	458	1800	--
Minimum	1543	1543	1543	1543	1543	1543	1543	1543	1543	1543	1543	1543	1543	1543	--
Maximum	3042	3042	3042	3042	3042	3042	3042	3042	3042	3042	3042	3042	3042	3042	--
Range	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	--

Table 14. Summary of simulated grain yield for winter wheat and corn and forage yield for triticale for Sidney, NE. Winter wheat yields are reported at 12.5% moistures; corn yields are reported at 12.5% moisture; triticale yields are reported at 0% moisture.

	WW-C-T			350mm			375 mm			400mm			WW-C-F		
	WW	**C**	**T**	**WW**	**C**	**T**	**WW**	**C**	**T**	**WW**	**C**	**T**	**WW**	**C**	**T**
	---kg ha^{-1}---														
Average	2290	5200	5470	2370	5220	5530	2430	5290	5570	2240	5390	5580	2450	5380	--
Total	52700	119000	126000	54600	120000	82900	55800	122000	55700	56100	124000	22300	56300	124000	--
SD	356	2050	293	291	2040	301	278	2050	224	286	1870	1870	296	1870	--
Minimum	1283	1283	1283	1283	1283	1283	1283	1283	1283	1283	1283	1283	1283	1283	--
Maximum	2813	2813	2813	2813	2813	2813	2813	2813	2813	2813	2813	2813	2813	2813	--
Range	1530	1530	1530	1530	1530	1530	1530	1530	1530	1530	1530	1530	1530	1530	--

Table 15. Statistical comparison of average winter wheat grain yield predicted for each cropping system at Akron, CO.

Water threshold			Estimate	Std. error	DF	t-value	Pf > |t|
WW-C-T	vs.	350 mm	-80	62.3	52	-1.24	0.222
WW-C-T	vs.	375 mm	-150	68.6	52	-2.19	0.033
WW-C-T	vs.	400 mm	-313	70.4	52	-4.44	<.0001
WW-C-T	vs.	WW-C-F	-545	74.9	52	-7.27	<.0001
350 mm	vs.	375 mm	-73	70.8	52	-1.03	0.307
350 mm	vs.	400 mm	-236	73.5	52	-3.21	0.002
350 mm	vs.	WW-C-F	-468	79.3	52	-5.90	<.0001
375 mm	vs.	400 mm	-163	75.3	52	-2.16	0.035
375 mm	vs.	WW-C-F	-395	83.1	52	-4.75	<.0001
400 mm	vs.	WW-C-F	-232	82.9	52	-2.79	0.007

Table 16. Statistical comparison of average winter wheat grain yield predicted for each cropping system at Sidney, NE.

Water threshold			Estimate	Std Error	DF	t-value	Pf > |t|
WW-C-T	vs.	350 mm	-37	40	52	-0.94	0.353
WW-C-T	vs.	375 mm	-75	41	52	-1.83	0.073
WW-C-T	vs.	400 mm	-150	44	52	2.42	0.019
WW-C-T	vs.	W-C-F	-197	46	52	-4.25	<.0001
350 mm	vs.	375 mm	-39	43	52	-0.89	0.337
350 mm	vs.	400 mm	-68	46	52	-1.50	0.14
350 mm	vs.	W-C-F	-160	50	52	-3.23	0.002
375 mm	vs.	400 mm	-30	45	52	-0.66	0.514
375 mm	vs.	W-C-F	-121	51	52	-2.37	0.021
400 mm	vs.	W-C-F	-92	54	52	-1.71	0.093

Table 17. Statistical comparison of average corn grain yield predicted for each cropping system at Akron, CO.

Water threshold			Estimate	Std Error	DF	t-value	Pf > |t|
WW-C-T	vs.	350 mm	-121.0	58.9	52	-2.05	0.045
WW-C-T	vs.	375 mm	-129.4	64.9	52	-1.99	0.051
WW-C-T	vs.	400 mm	-149.6	66.7	52	-2.24	0.029
WW-C-T	vs.	WW-C-F	-243.2	71.0	52	-3.43	0.001
350 mm	vs.	375 mm	-8.5	66.9	52	-0.13	0.900
350 mm	vs.	400 mm	-28.6	69.5	52	-0.41	0.682
350 mm	vs.	WW-C-F	-122.3	75.1	52	-1.63	0.110
375 mm	vs.	400 mm	-20.2	71.0	52	-0.28	0.778
375 mm	vs.	WW-C-F	-113.8	78.7	52	-1.45	0.154
400 mm	vs.	WW-C-F	-93.6	78.4	52	-1.19	0.238

Table 18. Statistical comparison of average corn grain yield predicted for each cropping system at Sidney, NE.

Water threshold			Estimate	Std Error	DF	t-value	Pf > |t|
WW-C-T	vs.	350 mm	-14.5	160.9	52	-0.14	0.893
WW-C-T	vs.	375 mm	-118.2	112.5	52	-1.05	0.298
WW-C-T	vs.	400 mm	-304.1	118.6	52	-2.57	0.013
WW-C-T	vs.	W-C-F	-94.9	126.1	52	-0.75	0.455
350 mm	vs.	375 mm	-103.7	118.0	52	-0.88	0.383
350 mm	vs.	400 mm	-289.7	124.0	52	-2.34	0.023
350 mm	vs.	W-C-F	-80.4	134.7	52	-0.6	0.553
375 mm	vs.	400 mm	-185.9	122.9	52	-1.51	0.136
375 mm	vs.	W-C-F	23.3	139.1	52	0.17	0.867
400 mm	vs.	W-C-F	209.3	145.8	52	1.43	0.157

Table 19. Statistical comparison of average triticale biomass yield predicted for each cropping system at Akron, CO.

Water threshold			Estimate	Std Error	DF	t-value	Pf > |t|
WW-C-T	vs.	350 mm	8.6	32.3	26	0.27	0.792
WW-C-T	vs.	375 mm	-9.0	39.9	26	-0.23	0.823
WW-C-T	vs.	400 mm	-31.4	58.1	26	-0.54	0.593
350 mm	vs.	375 mm	-17.6	40.0	26	-0.44	0.664
350 mm	vs.	400 mm	-40.0	58.2	26	-0.69	0.497
375 mm	vs.	400 mm	-22.4	59.8	26	-0.38	0.710

Table 20. Statistical comparison of average spring triticale biomass yield predicted for each cropping system at Sidney, NE.

Water threshold			Estimate	Std Error	DF	t-value	Pf > |t|
WW-C-T	vs.	350 mm	-2E-05	0.042	26	0	1
WW-C-T	vs.	375 mm	-3E-05	0.049	26	0	1
WW-C-T	vs.	400 mm	-3E-05	0.071	26	0	1
350 mm	vs.	375 mm	-7E-06	0.049	26	0	1
350 mm	vs.	400 mm	-8E-06	0.071	26	0	1
375 mm	vs.	400 mm	-2E-06	0.072	26	0	1

Table 21. Economic returns for simulated grain yields for winter wheat and corn, and forage yields for triticale, in two fixed rotations [winter wheat-corn-triticale (WW-C-T) and winter wheat-corn-fallow (WW-C-F)] and flexible fallow using three different soil water thresholds at planting (350, 375, 400 mm) to determine when to plant triticale or use fallow at Akron, CO. using historical weather data from 1988 through 2010.

									375 mm				400 mm				WW-C-F			
Year	**WW**	**C**	**T**	**System**	**WW**	**C**	**T**	**System**	**WW**	**C**	**T**	**System**	**WW**	**C**	**T**	**System**	**WW**	**C**	**T**	**System**
	---US $ ha^{-1}---																			
1988	129	184	209	174	129	184	209	174	129	184	209	174	129	184	209	174	206	184	-26	121
1989	58	92	166	106	58	92	-27	41	58	92	-27	41	58	92	-27	41	127	189	-27	96
1990	6	414	157	192	68	414	115	199	68	414	-28	151	68	414	-28	151	92	422	-28	162
1991	97	207	117	140	97	226	117	147	169	226	-28	122	169	226	-28	122	169	207	-28	116
1992	160	328	116	201	160	328	118	202	174	350	-29	165	174	350	-29	165	180	349	-29	167
1993	53	404	158	205	55	404	158	206	96	411	-29	159	96	411	-29	159	96	413	-29	160
1994	43	160	152	118	43	178	152	124	121	160	152	145	121	160	-30	84	122	160	-30	84
1995	334	142	112	196	334	142	112	196	333	142	-31	148	338	142	-31	150	338	142	-31	150
1996	271	522	184	325	273	522	-33	254	243	529	-33	246	243	529	-33	246	243	529	-33	247
1997	39	341	218	200	68	351	218	213	68	341	218	209	68	341	-33	126	68	341	-33	125
1998	-19	195	117	97	-19	227	118	109	-13	227	118	111	26	227	-32	74	26	227	-32	74
1999	-37	293	118	125	-32	293	-32	76	-37	295	-32	75	40	317	-32	108	40	317	-32	108
2000	4	57	122	61	46	62	122	77	46	57	122	75	46	58	122	75	46	58	-33	24
2001	27	232	207	155	27	245	207	160	27	245	207	160	40	245	-34	84	76	245	-34	96
2002	-6	-253	87	-57	-1	-253	-34	-96	-78	-253	-34	-121	23	-252	-34	-88	22	-206	-34	-72
2003	84	6	147	79	174	6	147	109	174	6	147	109	174	6	147	109	174	6	-35	48
2004	122	184	125	144	122	239	-37	108	128	239	-37	110	128	239	-37	110	128	239	-37	110
2005	-5	155	162	104	86	155	-40	67	86	155	-40	67	86	155	-40	67	86	155	-40	67
2006	25	256	146	142	90	256	146	164	90	256	-42	101	90	256	-42	101	190	256	-42	135
2007	147	1	257	135	147	149	290	195	372	149	290	271	372	149	-46	158	372	149	-46	158
2008	109	399	335	281	274	399	334	336	274	438	-53	219	319	438	-53	235	333	438	-53	239
2009	140	566	140	282	127	566	140	278	255	566	140	320	255	566	140	320	255	566	-52	256
2010	346	323	160	277	346	323	160	277	346	323	160	277	346	323	-53	206	-14	323	-53	86

Table 22. Economic return for simulated grain yields for winter wheat and corn, and forage yields for triticale, in two fixed rotations [winter wheat-corn-triticale (WW-C-T) and winter wheat-corn-fallow (WW-C-F)] and flexible fallow using three different soil water thresholds at planting (350, 375, 400 mm) to determine when to plant triticale or use fallow at Sidney, NE using historical weather data from 1988 through 2010.

	WW-C-T				350 mm				375 mm				400 mm				WW-C-F			
Year	WW	C	T	System	WW	C	T	System	WW	C	T	System	WW	C	T	System	WW	C	T	System
	----US $ ha^{-1}----																			
1988	79	71	253	134	79	71	253	134	79	71	253	134	79	71	253	134	79	71	-26	42
1989	138	154	203	165	138	154	-27	88	138	154	-27	88	138	154	-27	88	123	154	-27	83
1990	-60	260	193	131	10	260	193	154	10	260	193	154	10	260	-28	81	10	244	-28	75
1991	106	173	156	145	106	252	156	172	106	252	-28	110	144	252	-28	122	144	252	-28	122
1992	144	362	152	219	144	362	-29	159	136	362	-29	156	136	362	-29	156	135	362	-29	156
1993	40	451	219	237	78	451	219	249	78	451	-29	167	78	451	-29	167	78	451	-29	167
1994	82	384	234	233	82	384	234	233	107	384	234	242	107	384	234	242	107	384	-30	154
1995	245	192	155	197	245	192	-31	135	245	192	-31	135	245	192	-31	135	245	192	-31	135
1996	187	407	229	274	169	407	-33	181	169	407	-33	181	169	407	-33	181	169	407	-33	181
1997	52	258	271	194	75	258	271	201	75	258	271	201	75	258	271	201	75	258	-33	100
1998	25	318	186	176	25	318	186	176	25	318	-32	104	25	318	-32	104	25	318	-32	104
1999	48	301	159	169	48	301	-32	106	53	301	-32	107	33	301	-32	101	53	301	-32	107
2000	26	-127	197	32	56	-127	197	42	56	-127	197	42	56	-127	-33	-35	56	-127	-33	-35
2001	25	295	256	192	25	295	256	192	25	295	256	192	29	295	-34	97	29	295	-34	97
2002	31	-187	163	3	31	-187	163	3	31	-187	-34	-63	31	21	-34	6	31	21	-34	6
2003	-2	-126	190	21	-2	-126	190	21	114	-126	190	59	114	-126	190	59	113	-126	-35	-16
2004	53	111	200	121	53	97	-37	38	53	210	-37	75	54	210	-37	76	70	210	-37	81
2005	43	260	210	171	61	260	-40	94	61	260	-40	94	61	260	-40	94	61	260	-40	94
2006	97	247	201	181	115	247	201	187	122	247	201	190	122	247	-42	109	122	247	-42	109
2007	343	473	367	394	343	473	367	394	343	473	367	394	371	473	-46	266	371	473	-46	266
2008	253	577	408	413	253	577	-53	259	253	577	-53	259	265	581	-53	264	265	581	-53	264
2009	146	625	200	324	176	625	200	334	176	625	-52	250	176	625	-52	250	176	625	-52	250
2010	257	868	221	449	257	868	221	449	257	868	221	449	257	868	-53	357	238	868	-53	351

Table 23. Summary of economic returns for Akron, CO.

	WW-C-T	350mm	375 mm	400mm	WW-C-F
	----------US $ ha^{-1}----------				
Average	160	157	145	129	120
Standard Deviation	84	93	93	81	73
Minimum	-57	-96	-121	-88	-72
Maximum	325	336	320	320	256
Range	383	432	442	408	329

Table 24. Summary of economic returns for Sidney, NE.

	WW-C-T	350mm	375 mm	400mm	WW-C-F
	----------US $ ha^{-1}----------				
Average	199	174	162	142	126
Standard Deviation	115	112	110	91	93
Minimum	3	3	-63	-35	-35
Maximum	449	449	449	357	351
Range	446	446	512	392	386

Table 25. Statistical comparisons of average differences in economic returns between cropping systems at Akron, CO.

Water threshold			US $ ha $^{-1}$	Std Error	DF	t-value	Pf > |t|
WW-C-T	vs.	350 mm	2.9	8.68	88	0.34	0.733
WW-C-T	vs.	375 mm	15.1	8.68	88	1.74	0.085
WW-C-T	vs.	400 mm	30.6	8.68	88	3.53	<0.001
WW-C-T	vs.	W-C-F	40.3	8.68	88	4.63	<0.001
350 mm	vs.	375 mm	12.1	8.68	88	1.4	0.165
350 mm	vs.	400 mm	27.7	8.68	88	3.18	0.002
350 mm	vs.	W-C-F	37.3	8.68	88	4.29	<0.001
375 mm	vs.	400 mm	15.5	8.68	88	1.79	0.008
375 mm	vs.	W-C-F	25.1	8.68	88	2.89	0.005
400 mm	vs.	W-C-F	9.6	8.68	88	1.11	0.271

Table 26. Statistical comparisons of average differences in economic returns between cropping systems at Sidney, NE.

Water threshold			US $ ha^{-1}	Std Error	DF	t-value	Pf > |t|
WW-C-T	vs.	350 mm	25.0	9.24	88	2.71	0.008
WW-C-T	vs.	375 mm	37.2	9.24	88	4.03	<0.001
WW-C-T	vs.	400 mm	57.5	9.24	88	6.22	<0.001
WW-C-T	vs.	W-C-F	73.2	9.24	88	7.93	<0.001
350 mm	vs.	375 mm	12.2	9.24	88	1.32	0.189
350 mm	vs.	400 mm	32.5	9.24	88	3.51	<0.001
350 mm	vs.	W-C-F	48.2	9.24	88	5.22	<0.001
375 mm	vs.	400 mm	20.2	9.24	88	2.19	0.031
375 mm	vs.	W-C-F	36.0	9.24	88	3.9	<0.001
400 mm	vs.	W-C-F	15.8	9.24	88	1.71	0.091

Figures

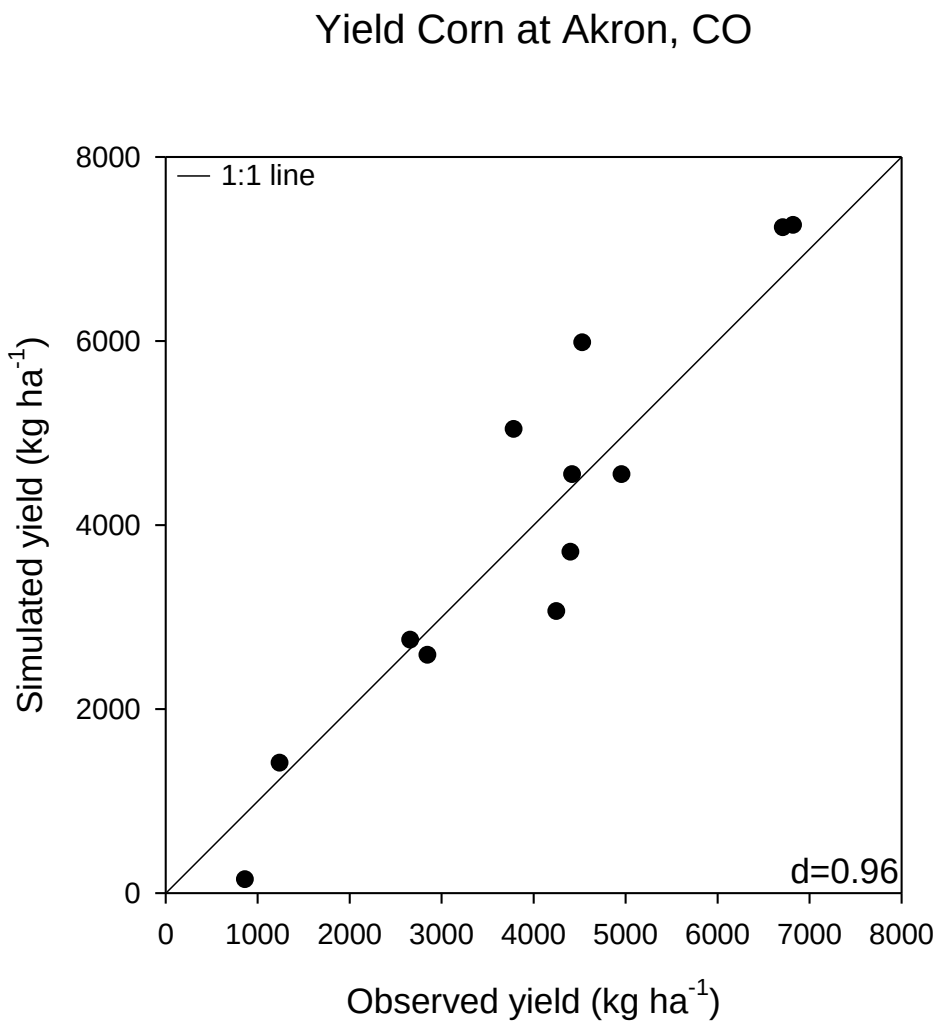

Figure 1. Simulated vs. observed yield values for corn at Akron, CO.

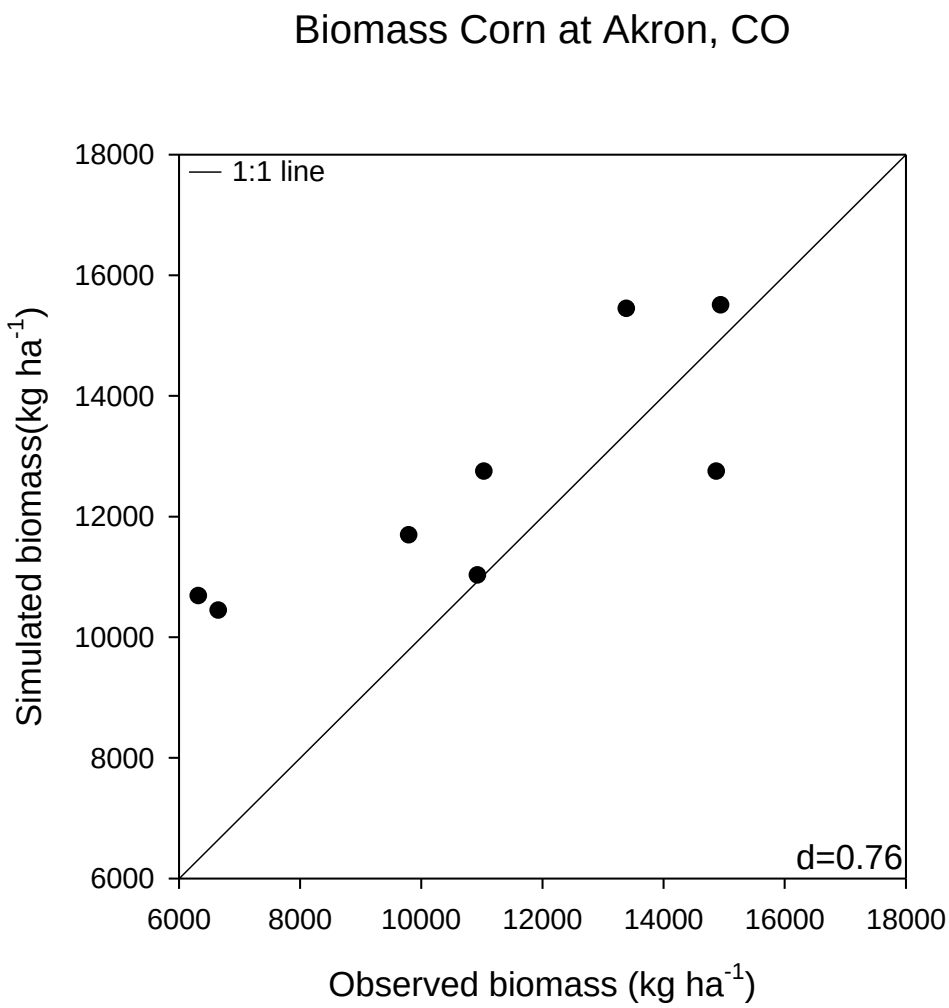

Figure 2. Simulated vs. observed biomass values for corn at Akron, CO.

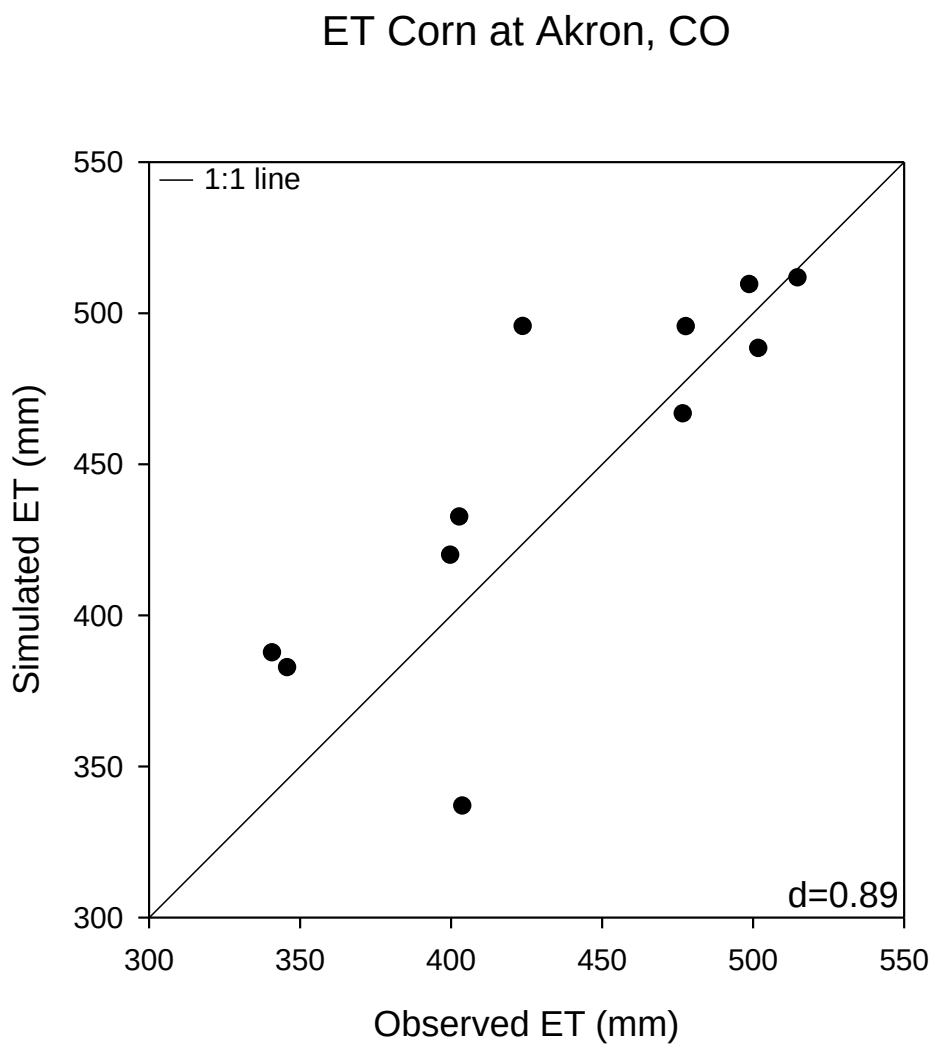

Figure 3. Simulated vs. observed ET values for corn at Akron, CO.

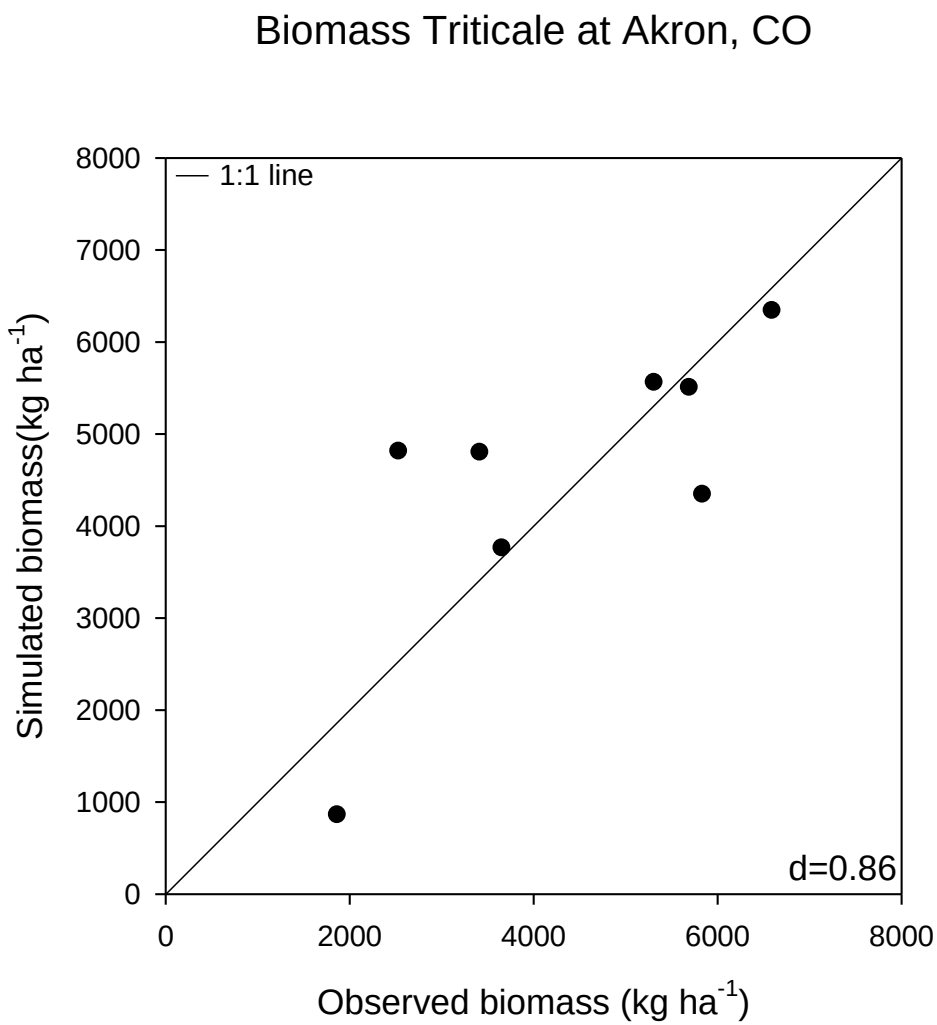

Figure 4. Simulated vs. observed biomass values for triticale at Akron, CO.

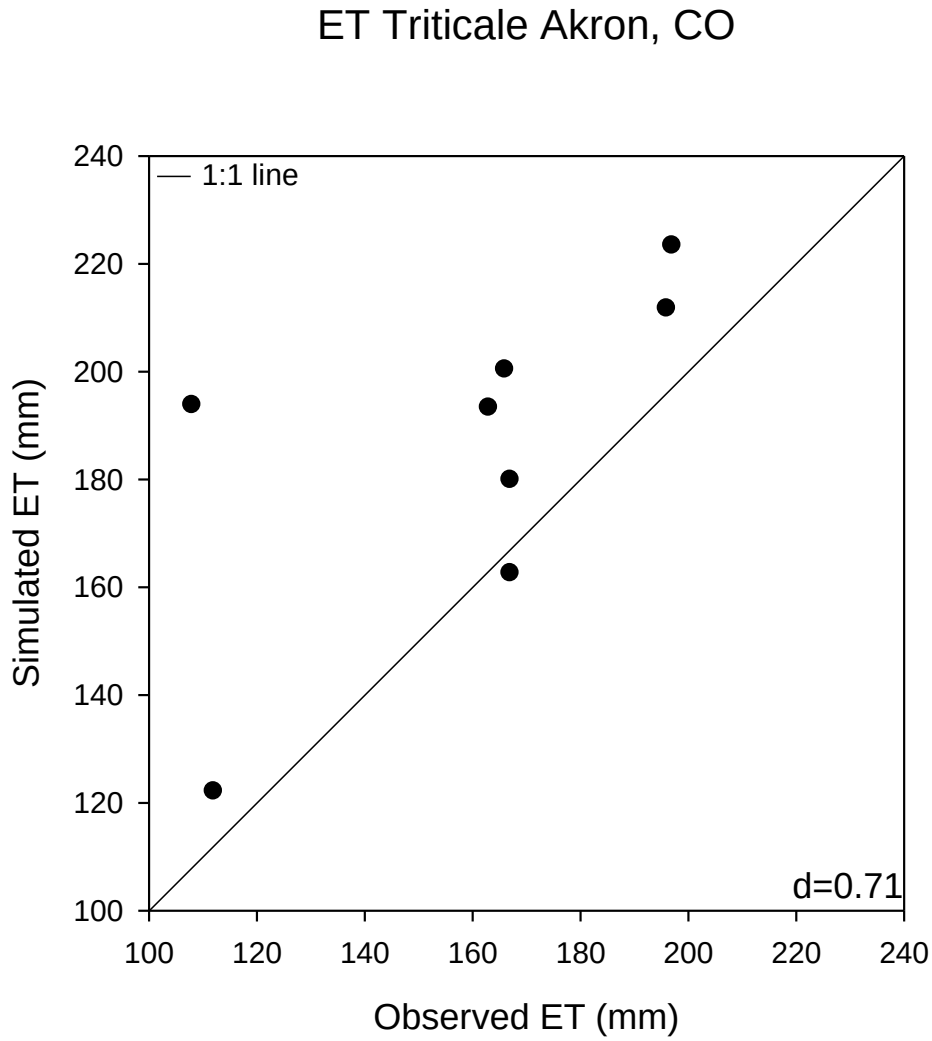

Figure 5. Simulated vs. observed ET values for triticale at Akron, CO.

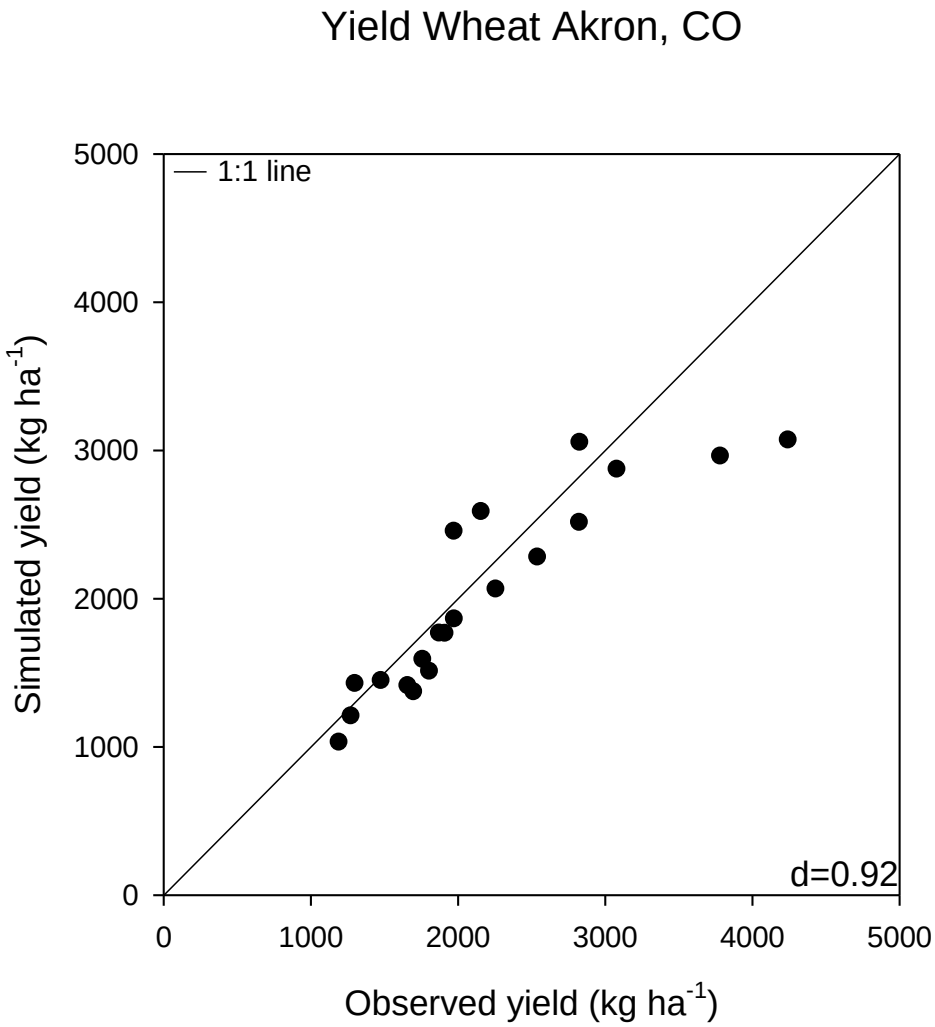

Figure 6. Simulated vs. observed yield values for winter wheat at Akron, CO.

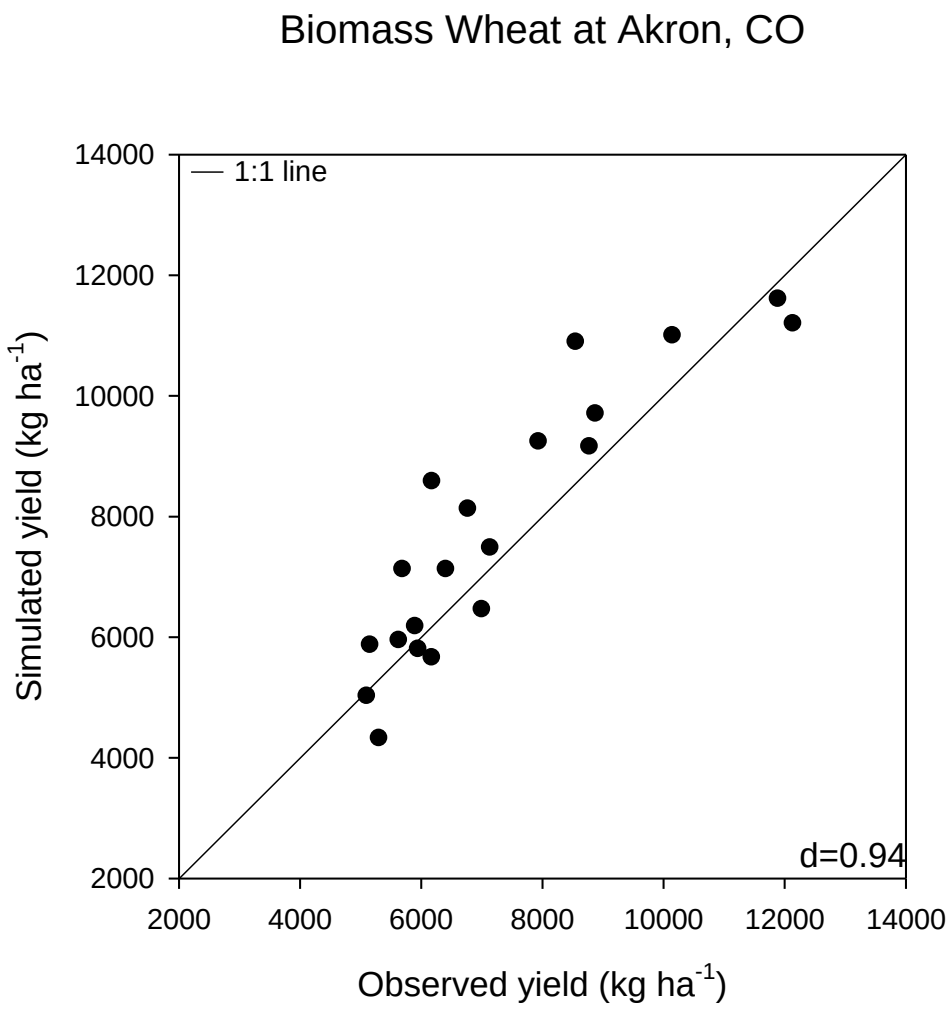

Figure 7. Simulated vs. observed biomass values for winter wheat at Akron, CO.

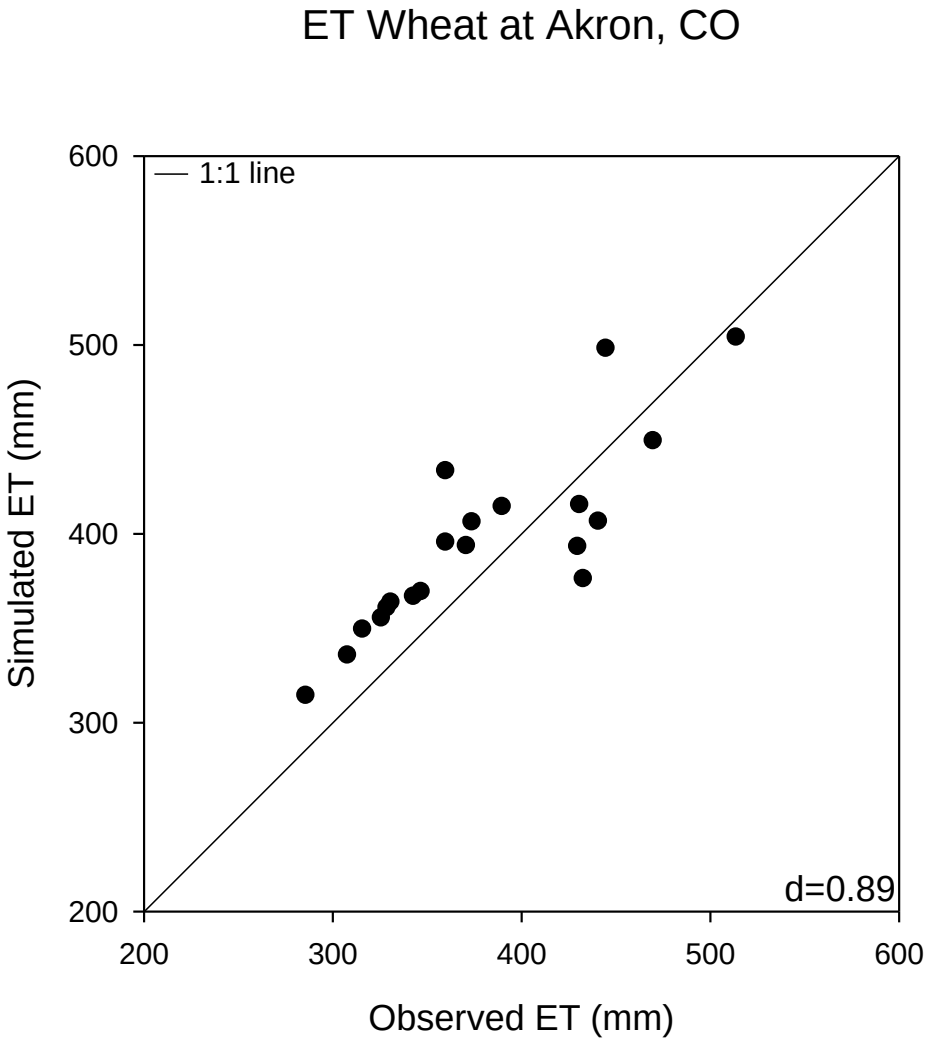

Figure 8. Simulated vs. observed ET values for winter wheat at Akron, CO.

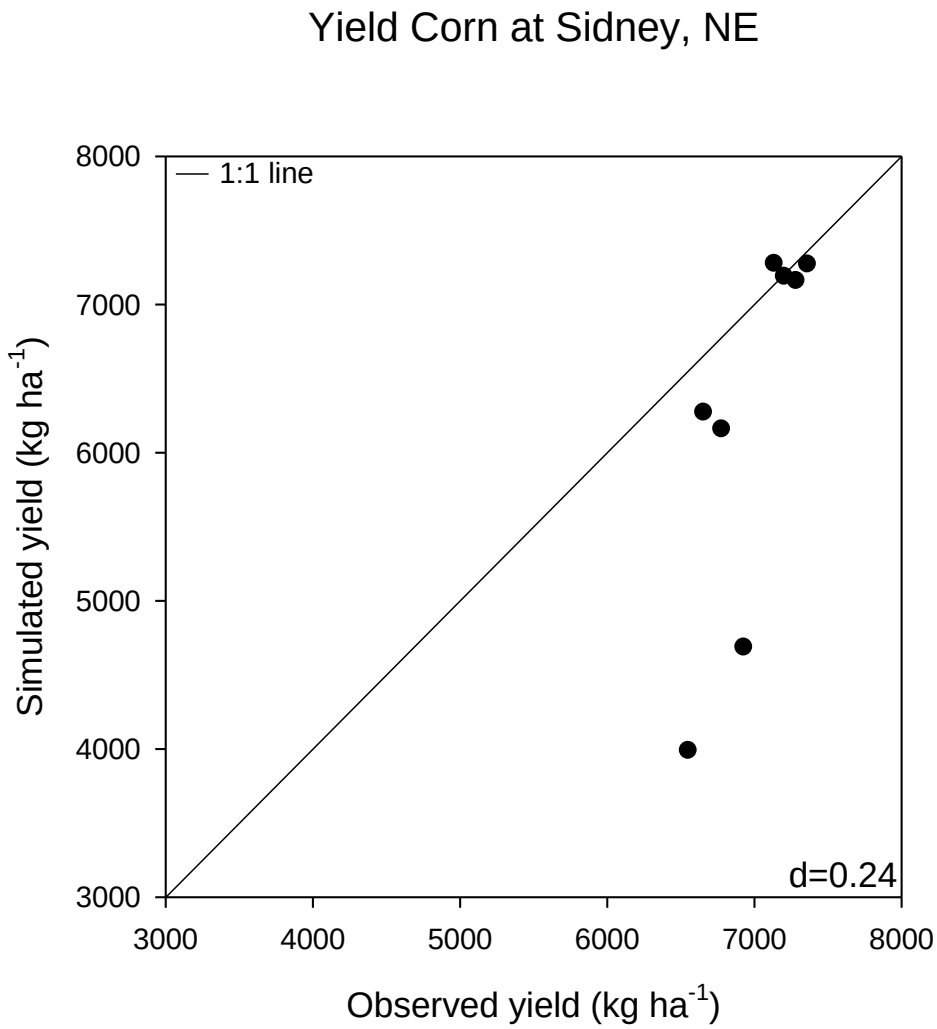

Figure 9. Simulated vs. observed yield values for corn at Sidney, NE.

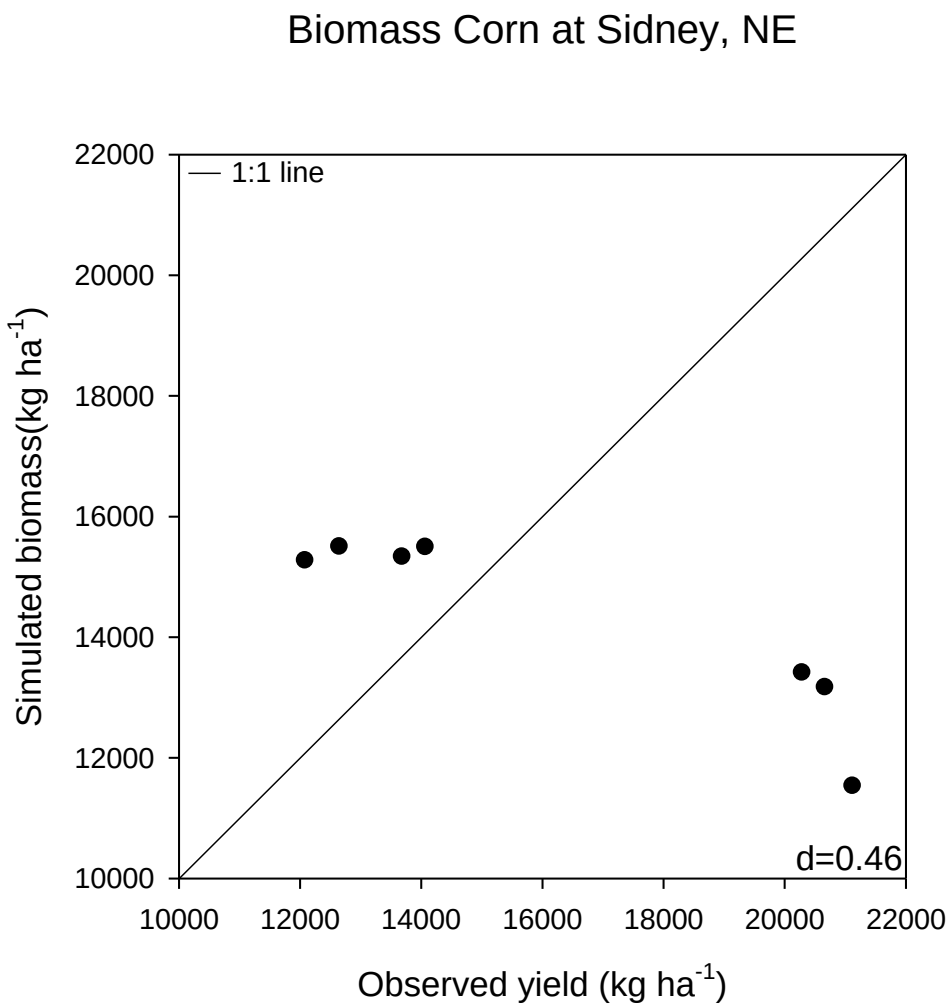

Figure 10. Simulated vs. observed biomass values for corn at Sidney, NE.

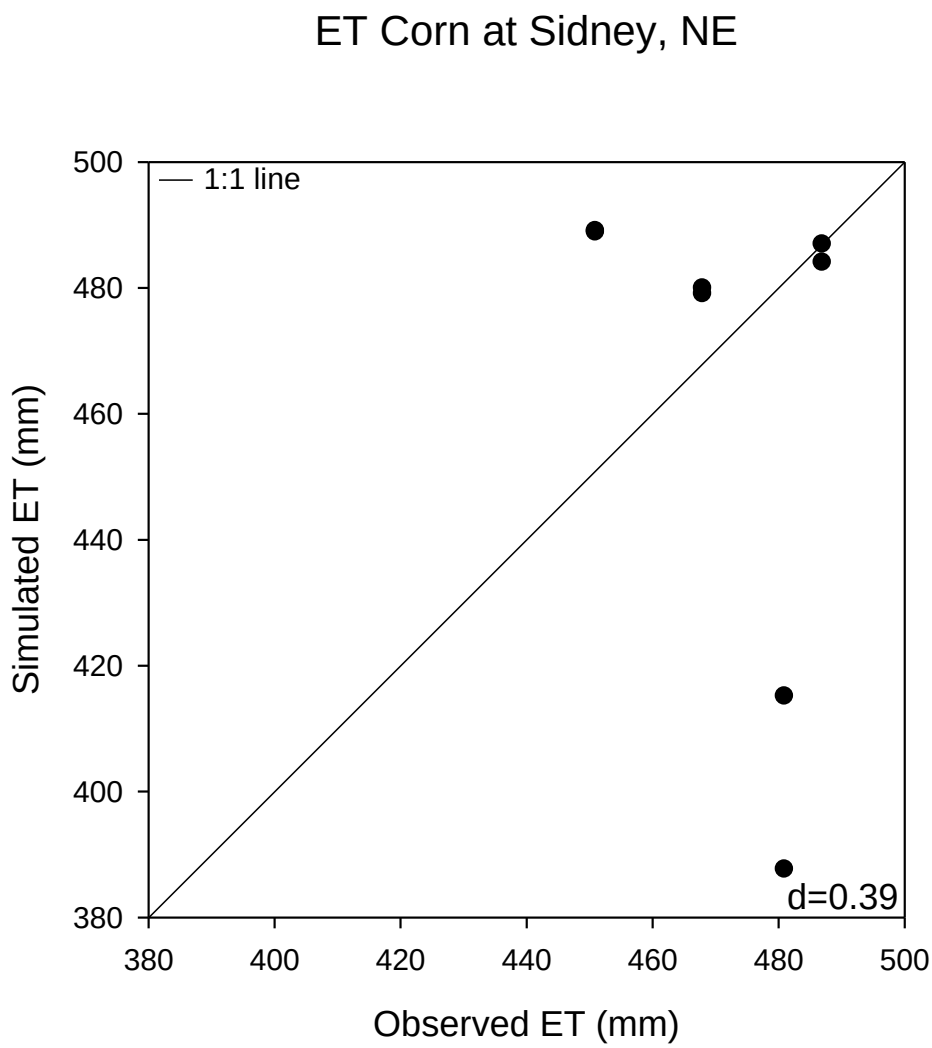

Figure 11. Simulated vs. observed ET values for corn at Sidney, NE.

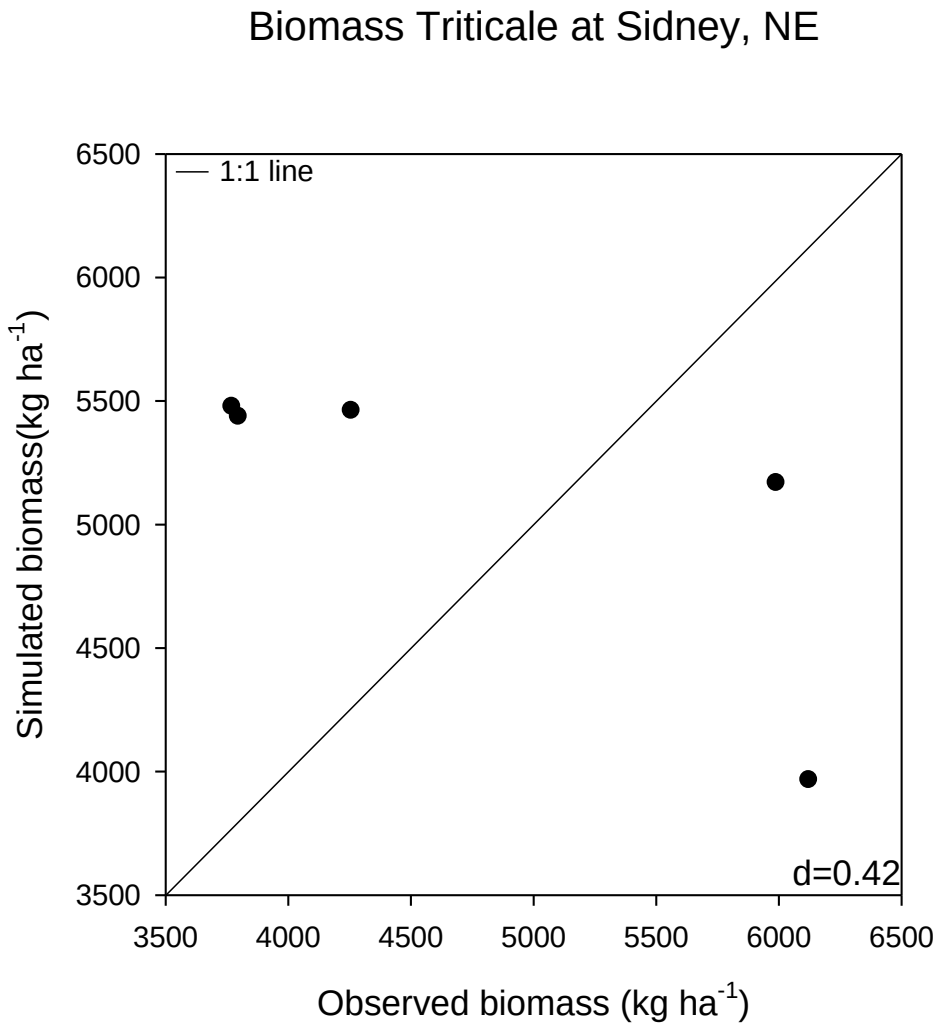

Figure 12. Simulated vs. observed biomass values for triticale at Sidney, NE.

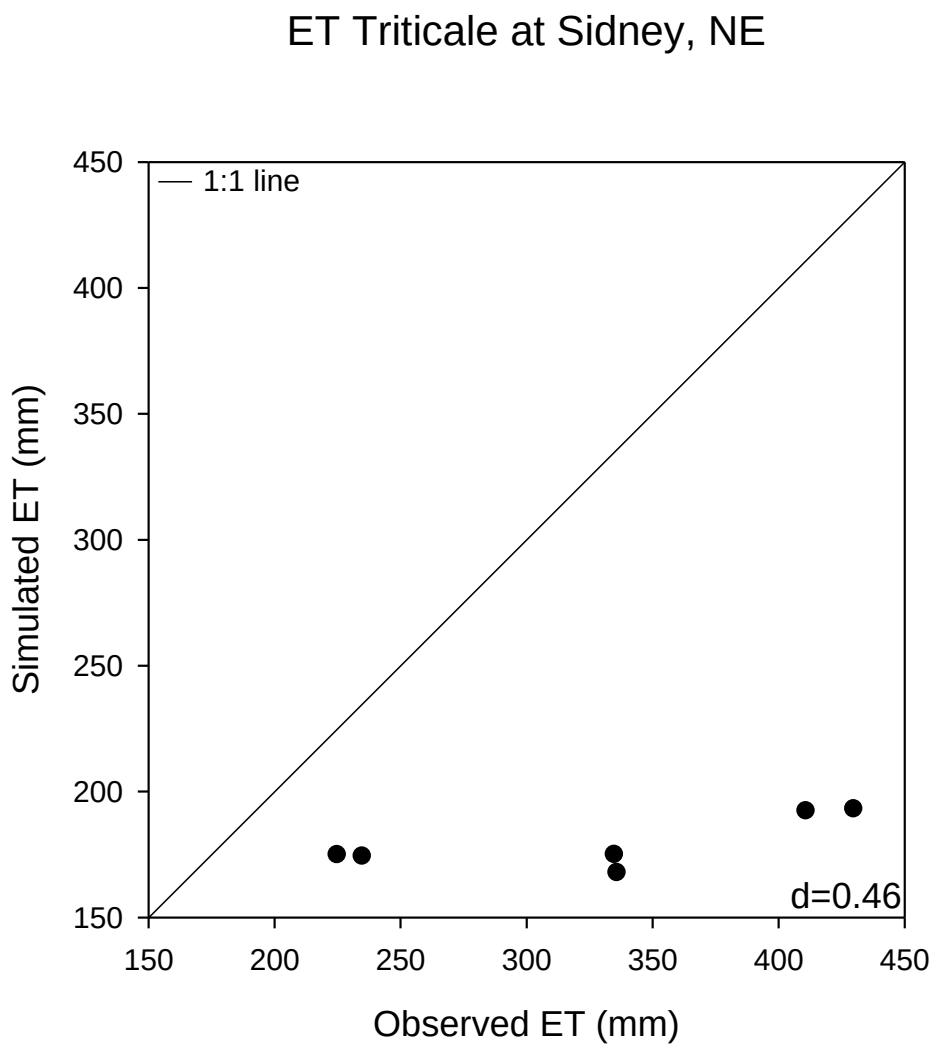

Figure 13. Simulated vs. observed ET values for triticale at Sidney, NE.

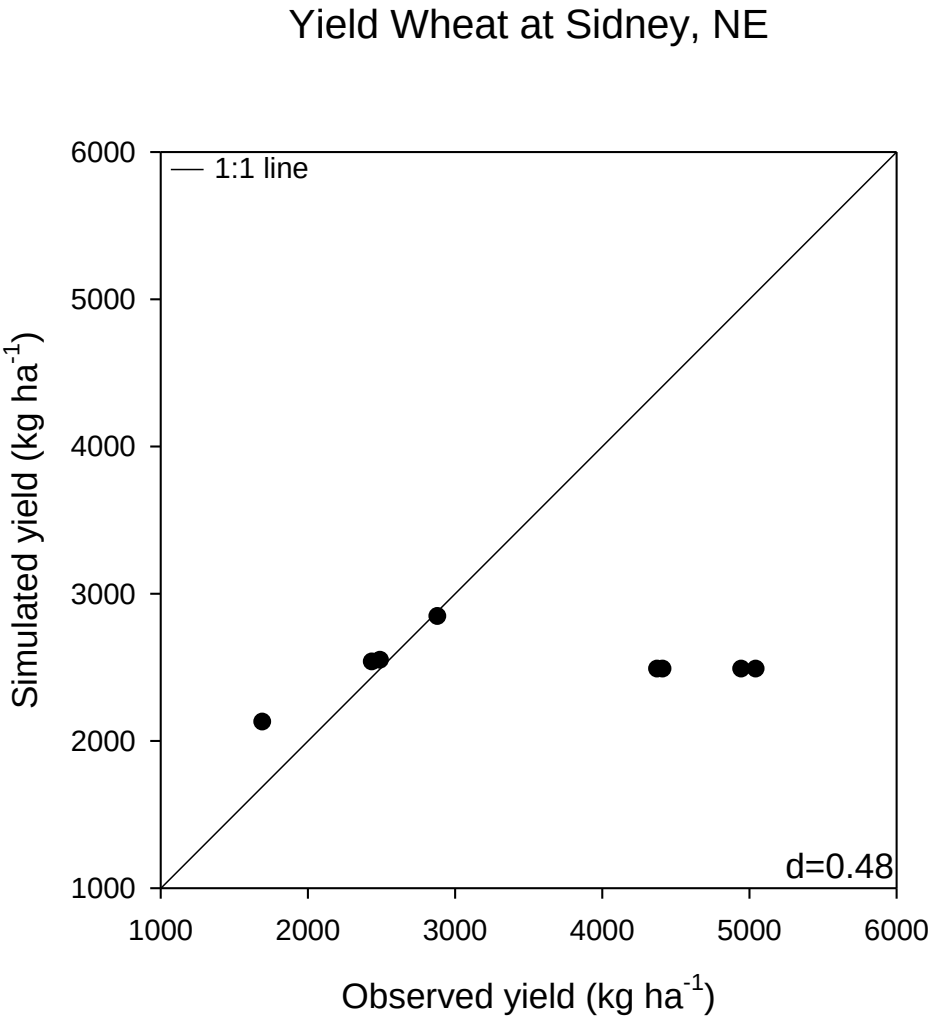

Figure 14. Simulated vs. observed yield values for winter wheat at Sidney, NE.

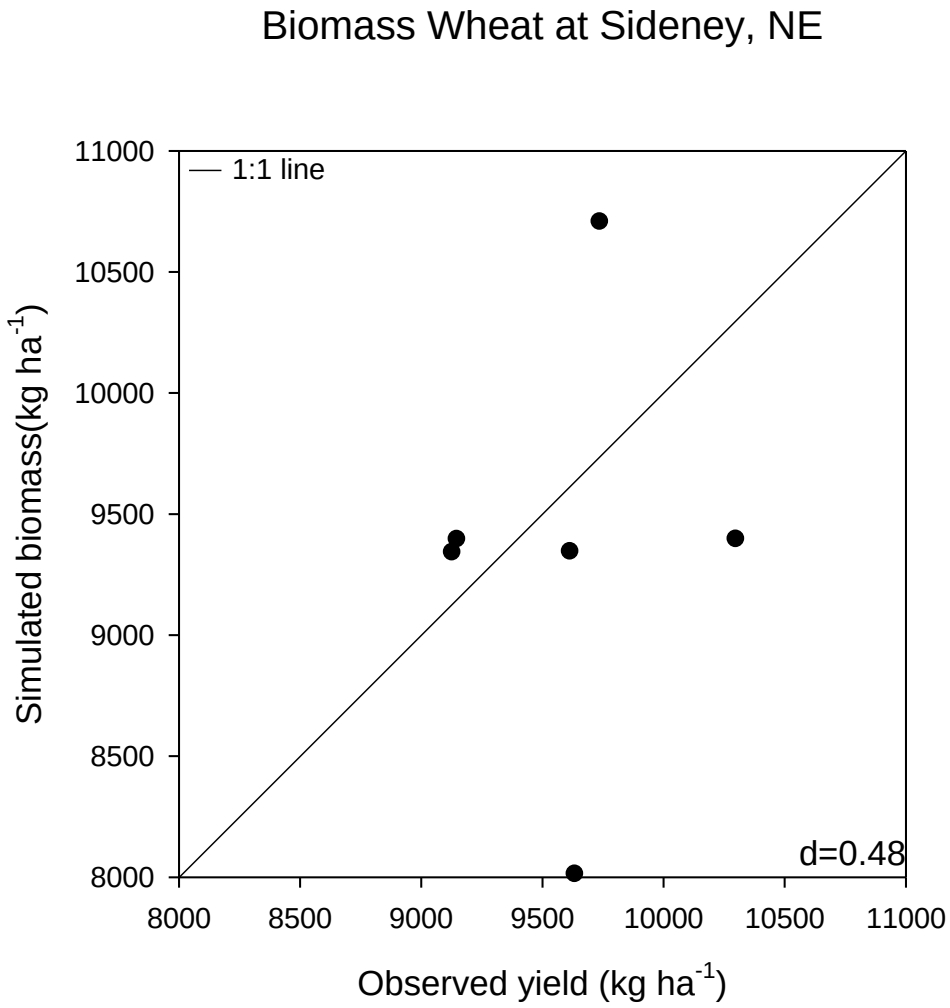

Figure 15. Simulated vs. observed biomass values for winter wheat at Sidney, NE.

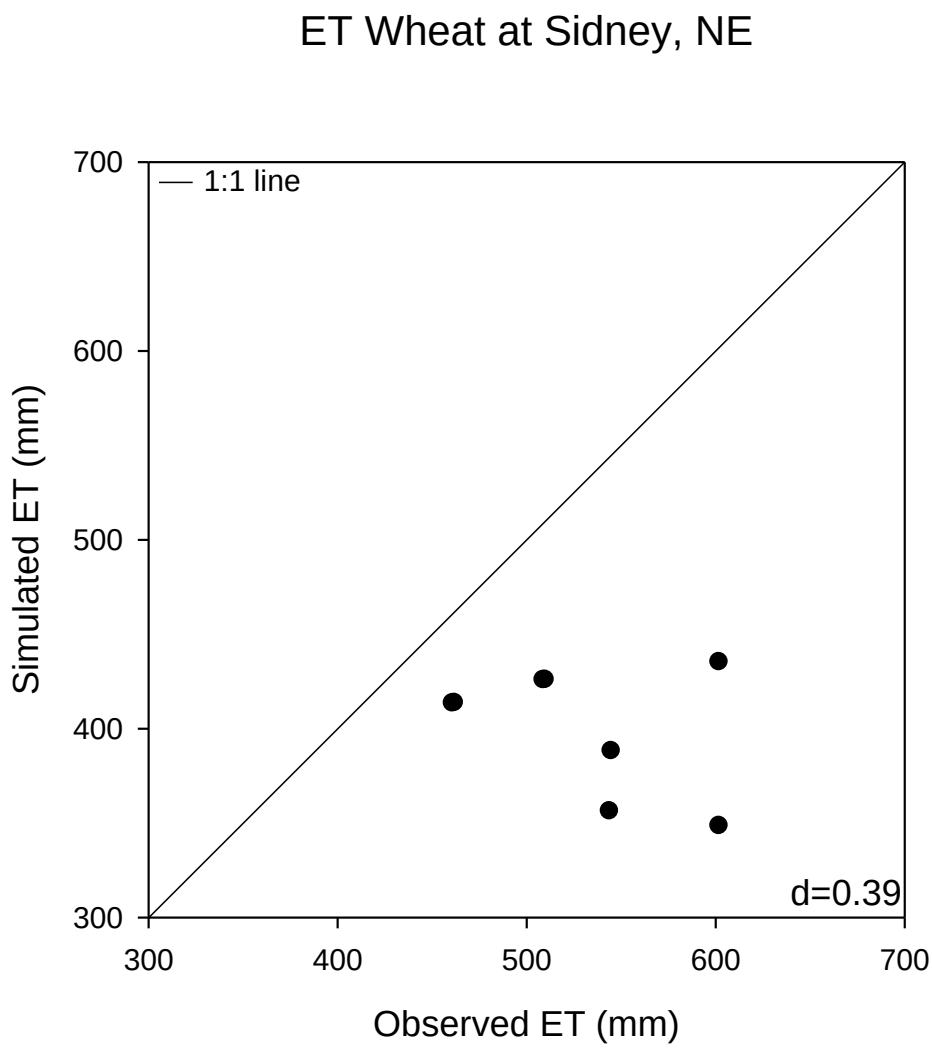

Figure 16. Simulated vs. observed ET values for winter wheat at Sidney, NE.

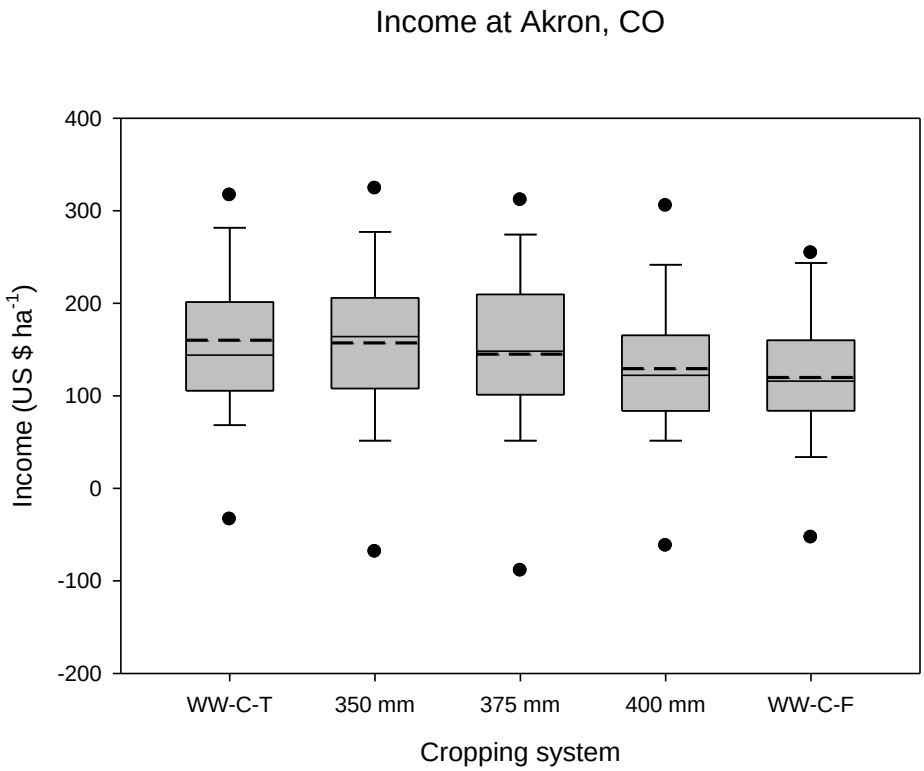

Figure 17. Box plots of income using different cropping systems at Akron, CO.

Note: Black circles represent 5th and 95th percentiles. Box contains the 25th and 75th percentile. Dash line represents median value. Solid line represents median. The ends of the bars represent the 10th and the 90th percentiles.

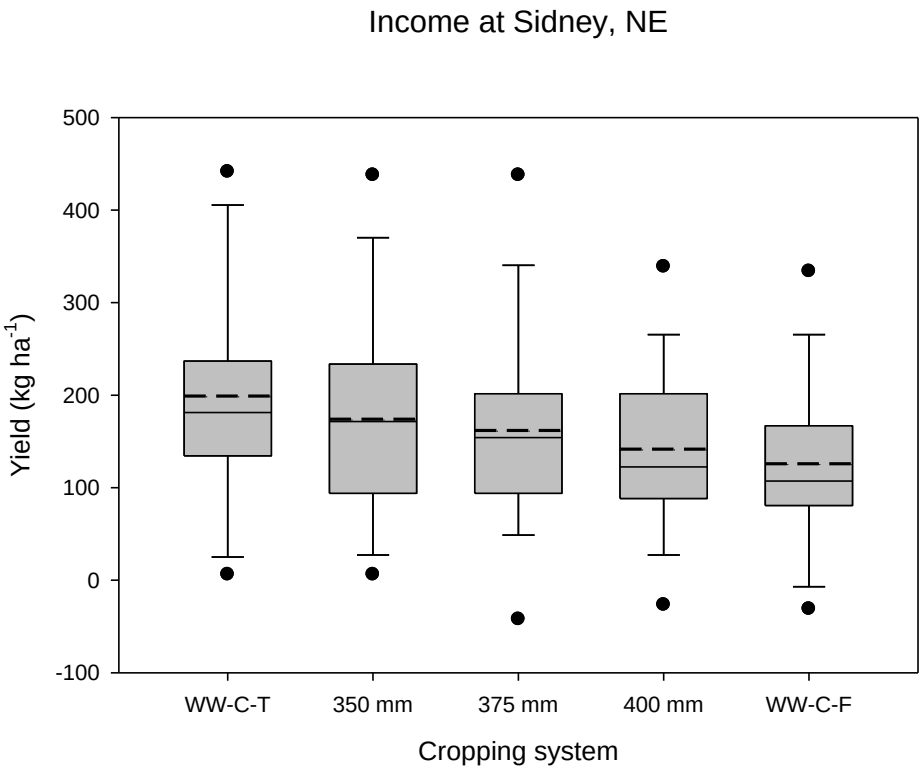

Figure 18. Box plots of income using different cropping systems at Sidney, NE.
Note: Black circles represent 5th and 95th percentiles. Box contains the 25th and 75th percentile. Dash line represents median value. Solid line represents median. The ends of the bars represent the 10th and the 90th percentiles.

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Appendix A. Box plot for winter wheat and corn grain yield, and triticale biomass yield at different cropping system for Akron, CO. and Sidney NE.

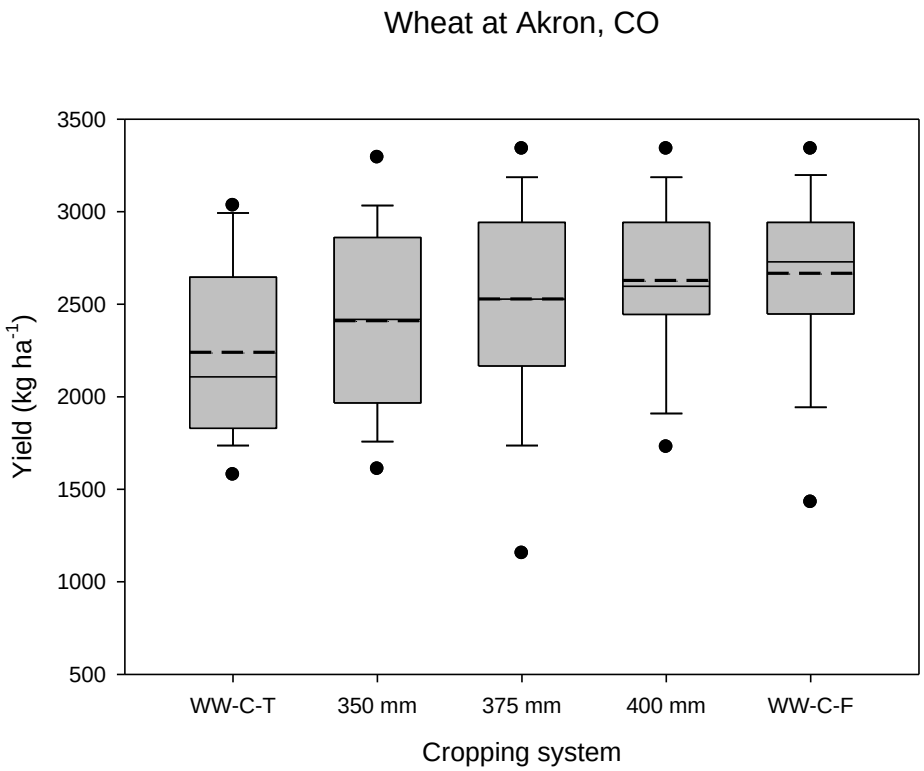

Figure 1. Box plot for winter wheat grain yield at different cropping system at Akron, CO.
Note: Black circles represent 5th and 95th percentiles. Box contains the 25th and 75th percentile. Dash line represents median value. Solid line represents median. The ends of the bars represent the 10th and the 90th percentiles.

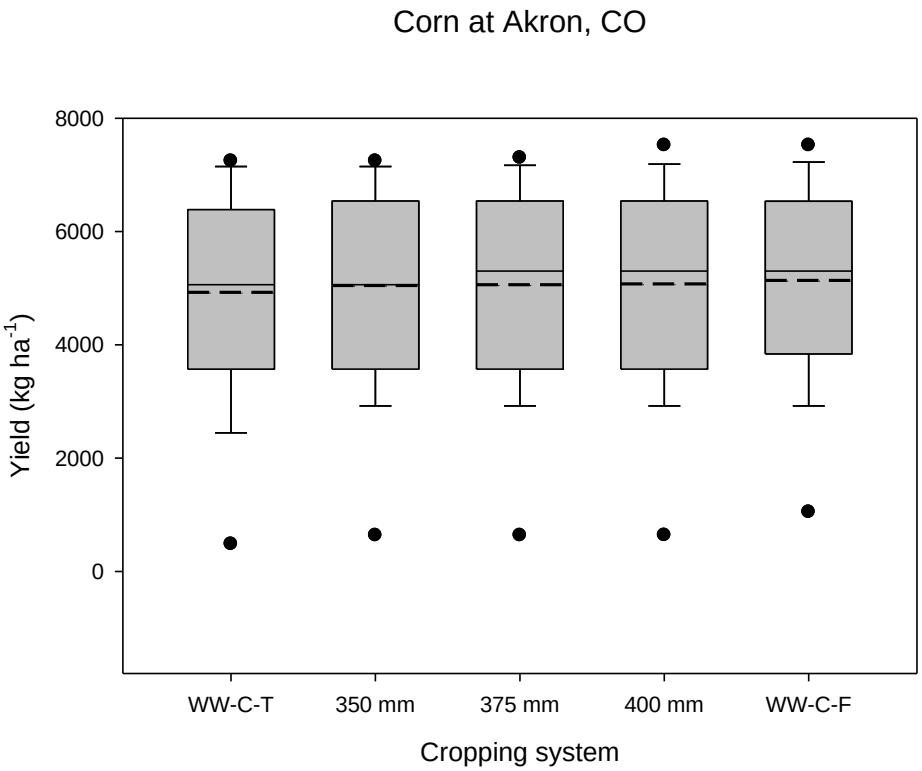

Figure 2. Box plot for corn grain yield at different cropping system at Akron, CO.

Note: Black circles represent 5th and 95th percentiles. Box contains the 25th and 75th percentile. Dash line represents median value. Solid line represents median. The ends of the bars represent the 10th and the 90th percentiles.

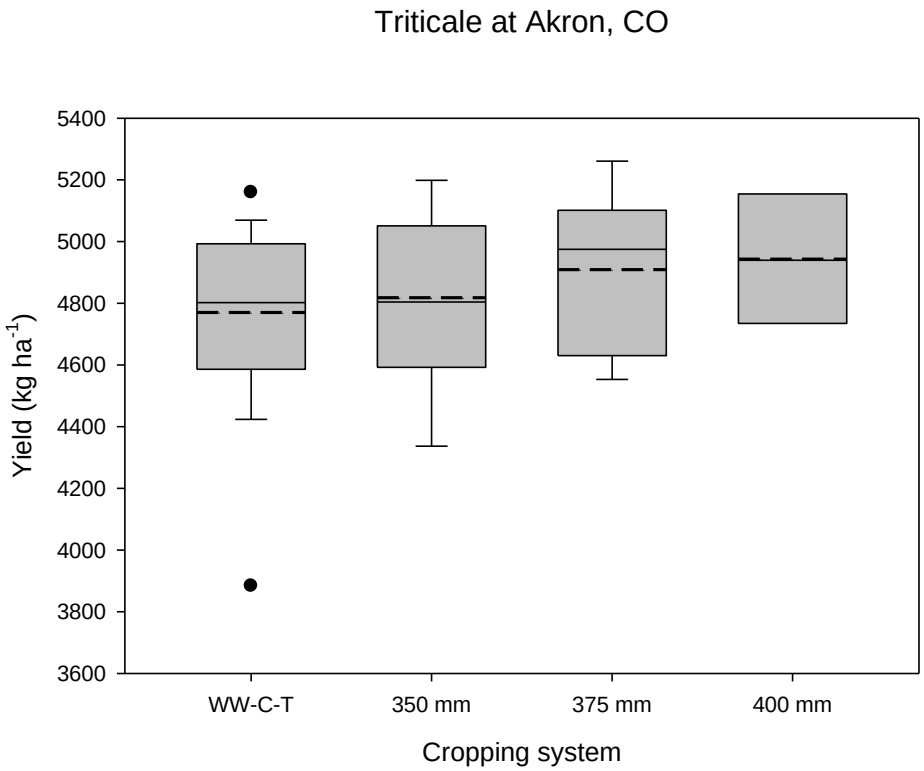

Figure 3. Box plot for triticale biomass yield at different cropping system at Akron, CO.
Note: Black circles represent 5th and 95th percentiles. Box contains the 25th and 75th percentile. Dash line represents median value. Solid line represents median. The ends of the bars represent the 10th and the 90th percentiles.

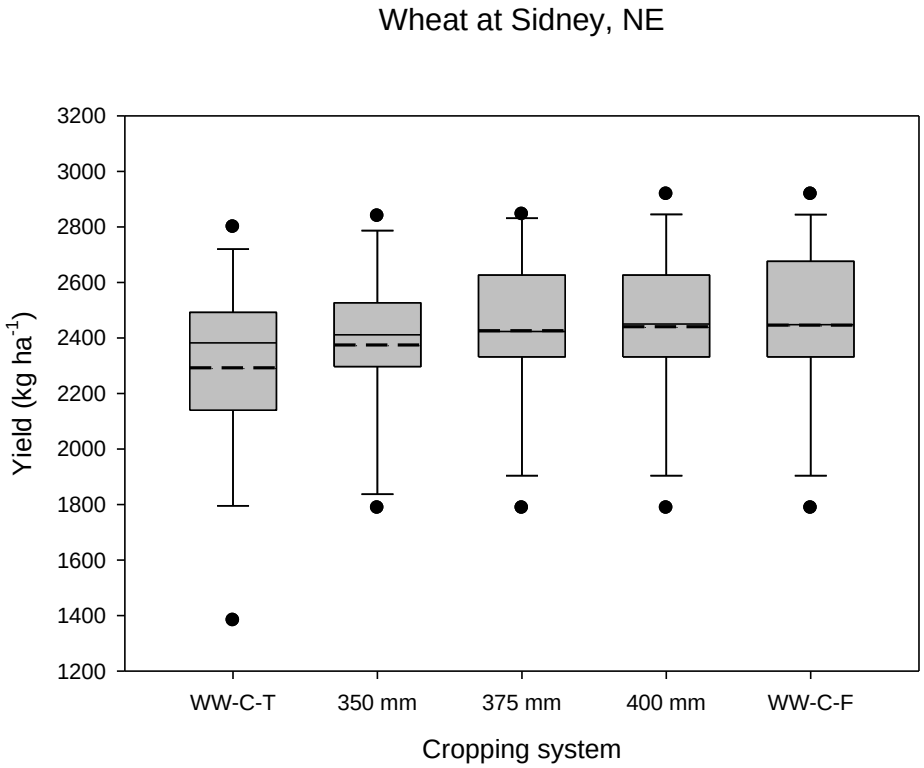

Figure 4. Box plot for winter wheat grain yield at different cropping system at Sidney, NE.
Note: Black circles represent 5th and 95th percentiles. Box contains the 25th and 75th percentile. Dash line represents median value. Solid line represents median. The ends of the bars represent the 10th and the 90th percentiles.

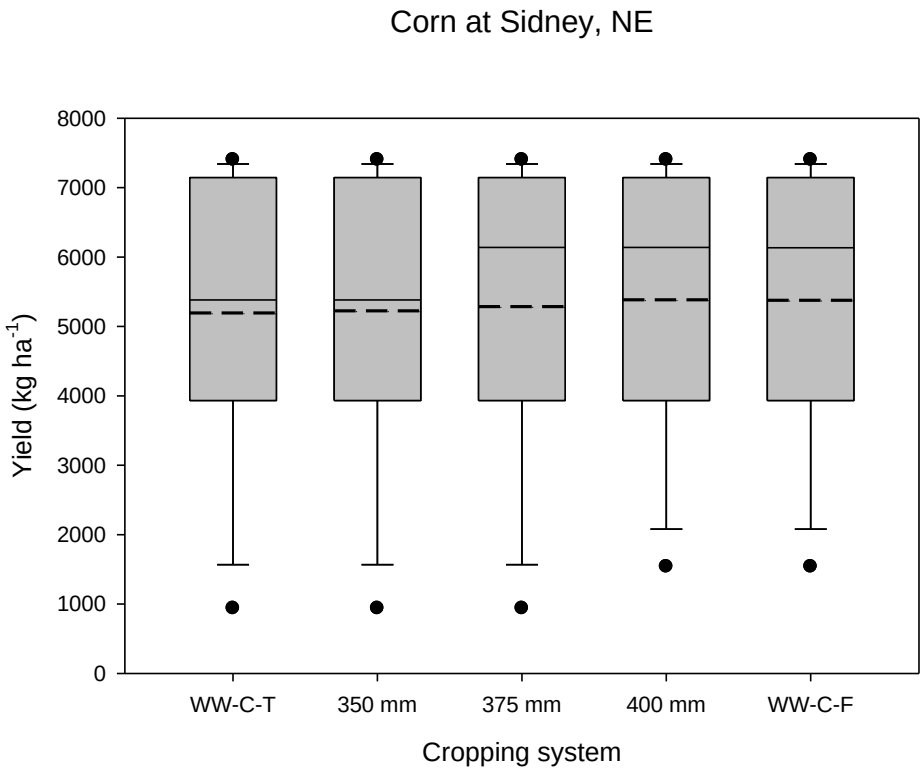

Figure 5. Box plot for corn grain yield at different cropping system at Sidney, NE.

Note: Black circles represent 5th and 95th percentiles. Box contains the 25th and 75th percentile. Dash line represents median value. Solid line represents median. The ends of the bars represent the 10th and the 90th percentiles.

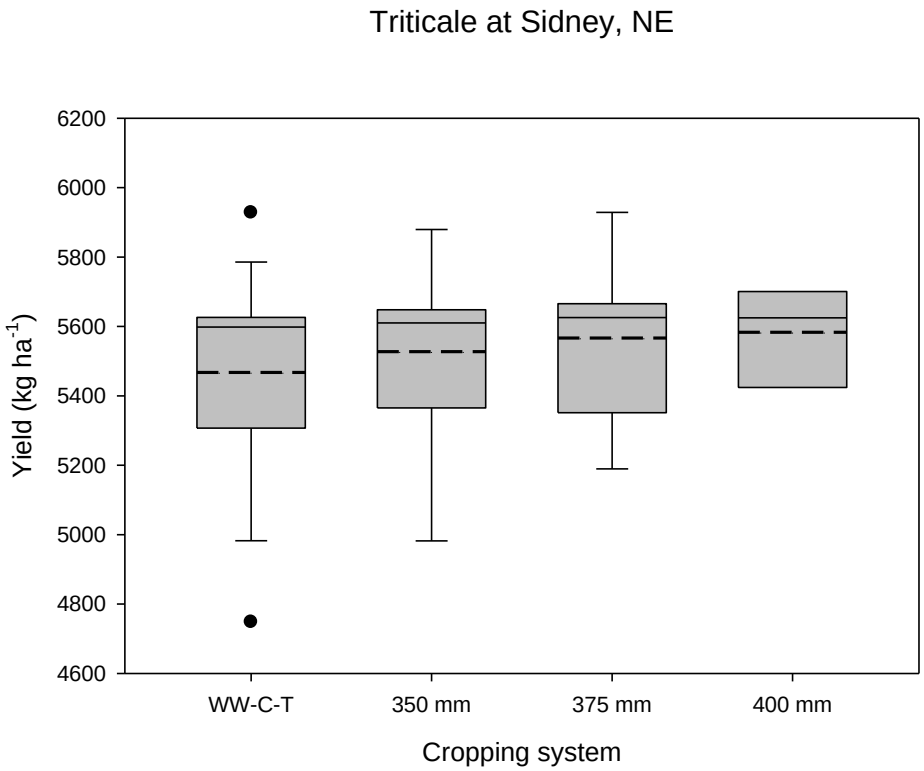

Figure 6. Box plot for triticale biomass yield at different cropping system at Sidney, NE.
Note: Black circles represent 5th and 95th percentiles. Box contains the 25th and 75th percentile. Dash line represents median value. Solid line represents median. The ends of the bars represent the 10th and the 90th percentiles.