MANAGING THE CONTINUOUS CORN YIELD PENALTY WITH CROP AND RESIDUE MANAGEMENT

BY

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DISSERTATION

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ABSTRACT

Corn (*Zea mays* L.) grown in rotation with soybean [*Glycine max* (L.) Merr.] generally yields more than corn grown continuously, with the latter designated the continuous corn yield penalty (CCYP). Due to global food security concerns and corn's versatility in food products, animal feed, and biofuel/bioenergy feedstocks, production of corn must increase with the projected increasing world population. As a result, yield per area or the area in corn production must increase, which could result in more corn following corn acres. Primary causative factors contributing to the CCYP are soil nitrogen availability, residue accumulation, and the weather. Therefore, the objective of this research was to evaluate and determine management practices that could help relieve the yield penalty associated with production of continuous corn compared to when rotated with soybean. This research encompasses two research areas:

What are the effects of hybrid selection, enhanced fertility, and population on corn yield and can these factors reduce the CCYP?

Enhanced fertility improved grain yield across rotations and there was a 40 to 60% greater yield response to intensive management in continuous corn versus the corn-soybean rotation, suggesting intensified management as a method to mitigate the CCYP. With select hybrids, intensive management reduced the CCYP by 30 to 80%. Yield advantages to corn rotated with soybean were achieved through both more numerous and heavier kernels. Agronomic management and hybrid selection helped alleviate the CCYP demonstrating continuous corn can be managed for better productivity.

Can the CCYP be alleviated by mechanical and chemical residue management in combination with an intensive agronomic input system?

As grain yield level increased, stover biomass production increased, resulting in additional residue to be managed post-harvest, reinforcing the need to manage crop residue in not only continuous corn but also in high grain yield environments. Sizing down the stover material at harvest improved overwinter residue decomposition. Stress induced by continuous corn was not detected through crop assessments until the R2 reproductive stage. Intensive inputs resulted in additional early season above- and below-ground biomass compared to standard inputs and increased grain yield. Crop rotation, downsized residue, high input agronomic management, and hybrid selection all enhanced final grain yield.

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CHAPTER 1: CORN YIELD RESPONSE TO CROP ROTATION AND RESIDUE MANAGEMENT: A LITERATURE REVIEW

CONTINUOUS CORN VERSUS THE CORN-SOYBEAN ROTATION

Corn (*Zea mays* L.) grown in rotation with soybean [*Glycine max* (L.) Merr.] generally has higher grain yields than when it is grown continuously. Grain yield reductions in continuous corn compared to first-year corn in a corn-soybean rotation typically range from 10 to 15% (Van Doren et al., 1976; Peterson and Varvel, 1989; Meese et al., 1991; Porter et al., 1997; Howard et al., 1998; Katsvairo and Cox, 2000; Pedersen and Lauer, 2003; Pikul et al., 2005; Stanger et al., 2008; Gentry et al., 2013). With various nitrogen rates from 1958-1964, Shrader et al., (1966) documented corn following soybean yielded 19% greater than corn grown continuously. From 1987-1995, a 13% yield reduction was noted from continuous corn cropping compared to corn rotated with soybean, and when grown in what the authors considered low-yielding environments this reduction exceeded 25% (Porter et al., 1997). Environments with minimal rainfall have been documented to increase the magnitude of the continuous corn yield penalty (CCYP) (Peterson and Varvel, 1989; Raimbault and Vyn, 1991; Seifert et al., 2017).

Field scale data from 2007-2012 of commercial farmer’s grain yields were analyzed from Iowa, Illinois, Indiana, Minnesota, Nebraska, and South Dakota to evaluate crop rotation and causative mechanisms of grain yield differences (Seifert et al., 2017). In this study, the CCYP was 4.3%, considerably less than that reported from most small plot research; however, this marginal variation could have been linked to producers’ management of those continuous corn acres that the authors were unable to obtain, such as residue management, agronomic inputs, or hybrid selection. By layering soil and climate data over yield, they found that the magnitude of the penalty was reduced when minimum air temperatures were higher throughout the season. The author attributed this finding to enhanced soil N mineralization from warmer temperatures.

Yield improvement when corn is grown following soybean compared to corn has been attributed to beneficial alterations in soil and residue interactions. Corn rotation with soybean can serve as a pest management practice for reducing weed pressure, insects, and diseases (Crookston et al., 1991). Corn residue can serve as a primary inoculum for major corn yield-reducing diseases such as grey leaf spot (*Cercospora zeae-maydis*) and northern corn leaf blight (*Exserohilum turcicum*) (Perkins and Pedersen, 1987; Ward et al., 1997). Microbial populations in the rhizosphere and their activity increase with soybean residue compared to corn residue (Fryson and Oaks, 1990; Vanotti and Bundy, 1995). Nitrogen in soybean residue is promptly mineralized and the subsequent crop takes up nearly all of it (Power et al., 1986). Decaying corn residue can have an autotoxic effect on corn seedlings (Yakle and Cruse, 1983), reducing plant growth and yield potential. Additionally, corn residue has a relatively high C:N ratio (Iritani and Arnold, 1960; Havlin et al., 2007; Johnson et al., 2007) that promotes immobilization of nitrogen.

Using no-till management tends to exaggerate the CCYP compared to other tillage methods (moldboard plow, chisel plow, and ridge till) by 12-18% (Griffith et al., 1988; Lund et al., 1993; West et al., 1996). Soil temperature reduction and/or seed germination and emergence delay can occur with increasing amounts of surface residue in no-till systems that can magnify the CCYP (Licht and Al-Kaisi, 2005; Halvorson and Reule, 2006; Karlen et al., 2013; Sindelar et al., 2013). Increased residue in no-till mimics that of increased residue accumulation in continuous corn compared to corn rotated with soybean.

Corn in rotation with soybean has a lower nitrogen requirement for maximum yields than corn following corn (Baldock et al., 1981; Peterson and Varvel, 1989; Bundy et al., 1993; Ding et al., 1998; Varvel and Wilhelm, 2003; Gentry et al., 2013). Cumulative mineralization of nitrogen is less with continuous corn compared to the corn-soybean rotation during the V10 to R2 growth stages, which are critical for nitrogen uptake (Gentry et al., 2001). The improved grain yield of corn rotated with soybean has been attributed to nitrogen from symbiotic N_2 fixation of soybean and increased mineralized nitrogen; however, biologically fixed nitrogen from the soybean/rhizobia relationship only accounts for half of the nitrogen taken up by the soybean plant (Johnson et al., 1975; Salvagiotti et al., 2008) and 73% of the nitrogen taken up is removed with the grain at harvest (Bender et al., 2015), resulting in depletion of soil nitrogen due to soybean production.

CORN AND SOYBEAN RESIDUE AND MANAGEMENT

Grain removal at harvest results in varying amounts of residue returned to the soil surface. Corn biomass returned to the field at harvest can average 5.0 tons acre^{-1}, while soybean stubble can average 2.5 tons acre^{-1} (Wilhelm et al., 1986; Bender et al., 2013a, 2013b; Bender et al., 2015; Sindelar et al., 2015). Additionally, in corn when grain yield increases, stover (surface residue) amount increases (Huggins and Fuchs, 1997; Lorenz et al., 2010). The quantity of corn residue can increase with the addition of N (Huggins and Fuchs, 1997; Wilts et al., 2004), P, and K fertilizer (Gregorich et al., 1996).

In addition to the large differences in the quantity of organic material produced between corn and soybean crops, the quality also differs. Residue quality can be characterized by cell wall constituents and carbon to nitrogen ratios. Soybean residue has a lower C:N ratio and lignin level than corn that results in an increased rate of microbial decomposition (Juma, 1993; Broder and Wagner, 1988; Torstensson, 1998). Verma et al. (2005) documented that no-till corn residue decomposes 10 to 24% slower than soybean stubble.

Corn residue is comprised of cell wall components (cellulose, hemicellulose, and lignin) that are complex insoluble polymers (Wolf and Wagner, 2005). Select fungi species are the only microbes that can degrade lignin, and as a result, residues with a high lignin content (corn residue) have slow microbial decomposition (Heal et al., 1997; Dick and Gregorich, 2004). In addition to complex cell wall components, plant-derived organic carbon compounds can include insoluble protein and starch, and labile compounds including amino and organic acids and simple sugars (Wolf and Wagner, 2005). Simple compounds easily pass through microbial cell membranes, while the complex insoluble polymers must go through a multistep degradation process. Soil microorganisms synthesize extracellular enzymes or exoenzymes that are secreted to hydrolyze the polymers into monomers. These monomers are then absorbed into the microbial cells where they can be oxidized further. Bacteria and sugar fungi rapidly decompose the simple soluble carbon compounds, while oliotrophs, that are primarily fungi, slowly decompose the complex insoluble polymers (Wolf and Wagner, 2005).

Plant material age also plays a role on how rapidly decay of the residue occurs. Because there is a larger faction of water-soluble material in immature green plant parts, degradation occurs faster in younger plant material than in mature plant material (Waksman and Tenny, 1927). Fresh green corn material decomposes at a more rapid rate than when that same material has been dried or when it is compared to more mature material (Oberlander 1973).

Several studies have investigated the effect of residue removal in continuous corn on soil quality and/or subsequent yields. Removal of corn residue compared to retaining the residue can reduce soil organic carbon and carbon-based matter levels (Larson et al., 1972; Barber, 1979; Wilts et al., 2004; Blanco-Canqui et al., 2006; Liska et al., 2014). Additionally, in most soils, erosion is reduced when at least 30% of residue is remaining after planting (Mann et al., 2002); and soil detachment is reduced when surface residue intercepts raindrops (Hayes and Kimberlin, 1978). It has been reported that removing corn residue results in a decline in the subsequent crop grain yield (Wilhelm et al., 1986), with the majority of the yield response being soil-moisture dependent (Linden et al., 2000; Coulter and Nafziger, 2008). Greater residue cover from retained residue treatments reduces soil water evaporation during dry years resulting in increased grain yield. Although emergence and seedling growth can sometimes be improved with residue removal (Swan et al., 1987; Dam et al., 2005; Blanco-Canqui et al., 2006), many of these results suggested that additional residue produced in conjunction with increased grain yields should be managed in place.

Crop residue is sliced into smaller pieces during tillage; and with increased surface area exposed to soil microbes, decomposition is fostered (Brady and Weil, 2002). Alternatively, corn residue fragment size can be mechanically truncated at grain harvest to influence residue decay. Residue fragment size reduction increases microbial respiration of corn pith (Sims and Frederick, 1970) and wheat straw (Angers and Recous, 1997). Stetson et al. (2018) determined that initial nitrogen immobilization was greater with smaller particles of corn residue. However, over time, the larger corn residue fragments promoted nitrogen immobilization, while the smaller particles mineralized nitrogen. None of this research, however, has been conducted in-field, nor have the effects of down-sized corn residue fragments on subsequent grain yield been investigated.

Fall nitrogen applications to narrow the C:N ratio of the surface residue as a means to promote decomposition have been documented previously with varied results (Conde et al., 2005; Knorr et al., 2005; Chen et al., 2007; Al-Kaisi and Guzman, 2013; Al-Kaisi et al., 2017). With nitrogen additions, corn residue decomposition rates have been reported to increase (Conde et al., 2005), initially increase then decline (Chen et al., 2007), or have no overall significant effect (Al-Kaisi and Guzman, 2013; Al-Kaisi et al., 2017). Potential reasons for why nitrogen additions could be hindering decomposition are: 1) altered microbial communities, 2) lignin decomposition slowed by the ammonia compounds suppressing the production of required enzymes, and 3) the formation of more recalcitrant material (resistant to decomposition) with the interaction between ammonia and organic matter (Fog, 1988). Additionally, the nitrification of ammonium containing fertilizers acidifies the soil (Pierre, 1928), which can reduce microbial activity and slow residue decay (Eno et al., 1955; Omar and Ismail, 1999; Geisseler and Scow, 2014).

AGRONOMIC MANAGEMENT ON CONTINUOUS CORN GRAIN YIELD

Intensification of agronomic management plays a critical role in offsetting the negative causative effects of continuously grown corn (Riedell et al., 1998; Katsvairo and Cox, 2000), and promotes greater yields (Ruffo et al., 2015). Riedel et al (1998) reported that the high input level (targeting the highest yield level with additional nitrogen, pesticide, and tillage) resulted in similar grain yields in both continuous corn and corn rotated with soybean. Although yields increased, with a high input system, Katsvairo and Cox (2000) could not eliminate the continuous corn yield penalty.

CONCLUSIONS

Corn grown following corn routinely yields less grain than when grown following soybean (Peterson and Varvel, 1989; Meese et al., 1991; Porter et al., 1997; Howard et al., 1998; Katsvairo and Cox, 2000; Pedersen and Lauer, 2003; Pikul et al., 2005; Stanger et al., 2008; Gentry et al., 2013). Soil erosion can be significantly reduced by corn residue remaining at grain harvest (Adviento-Borbe et al., 2007), with the increased moisture retention by residue coverage being particularly vital to corn yield in dry years (Linden et al., 2000; Coulter and Nafziger, 2008). Corn residue, however, encourages nitrogen immobilization (Gentry et al., 2001; Bergerou et al., 2004), and can act as an autotoxic material toward other corn plants (Yakle and Cruse, 1983), as well as being a primary source of inoculum for harmful plant diseases (Perkins and Pedersen, 1987; Ward et al., 1997). The research conducted for this dissertation investigated managing the continuous corn yield penalty by increasing grain yield through agronomic input level, hybrid selection, and residue management.

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CHAPTER 2: HYBRID SELECTION AND CROP MANAGEMENT TO LESSEN THE CONTINUOUS CORN YIELD PENALTY[1]

ABSTRACT

Yield reductions occur when corn (*Zea mays* L.) is continuously grown compared to when it is rotated with soybean [*Glycine max* (L.) Merr.]; primarily due to soil nitrogen availability, corn residue accumulation, and the weather. This study was conducted to determine if a combination of agronomic practices could help overcome these causative factors of the continuous corn yield penalty (CCYP) to obtain increased corn yields. Field experiments conducted during 2014 and 2015 at Champaign, IL, assessed the yield penalty associated with continuous corn versus long-term corn following soybean. Agronomic management was assessed at a standard level receiving only a base rate of nitrogen fertilizer, and compared to an intensive level, which consisted of additional N, P, K, S, Zn, and B fertility at planting, sidedressed nitrogen fertilizer, and a foliar fungicide application. Two levels of plant population (32,000 versus 45,000 plants acre^{-1}) and eight different commercially-available hybrids were evaluated each year. Across all treatments, the CCYP was 29 and 51 bu acre^{-1} in 2014 and 2015, respectively. Intensive agronomic management improved grain yield across rotations (41 bu acre^{-1} in 2014 and 43 bu acre^{-1} in 2015), and there was a 40 to 60% greater yield response to intensive management in continuous corn versus the corn-soybean rotation, suggesting intensified management as a method to mitigate the CCYP. With select hybrids, intensive management reduced the CCYP by 30 to 80%. Agronomic management and hybrid selection helped alleviate the CCYP demonstrating continuous corn can be managed for better productivity.

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INTRODUCTION

Crop rotation is a decision that can affect the productivity and profitability of agriculture production systems. Global trade tensions and crop demand can alter commodity prices that can allow grain price to offset the typical lost productivity of corn monocropping. The grain yield reduction when corn is grown continuously (corn grown after previous-crop corn, i.e., continuous corn) compared to when it is rotated with soybean has been widely reported (Peterson and Varvel, 1989; Meese et al., 1991; Porter et al., 1997; Howard et al., 1998; Katsvairo and Cox, 2000; Pedersen and Lauer, 2003; Pikul et al., 2005; Stanger et al., 2008; Gentry et al., 2013; Al-Kaisi et al., 2015). Factors primarily contributing to the continuous corn yield penalty (CCYP) are soil nitrogen availability or immobilization, residue accumulation, and the weather (Gentry et al., 2013). The consequence of adverse environmental effects are more detrimental on continuous corn grain yield than corn grown in rotation with soybean (Varvel, 1994; Wilhelm and Wortmann, 2004; Gentry et al., 2013). Environments with minimal rainfall have been documented to increase the magnitude of the CCYP (Peterson and Varvel, 1989; Raimbault and Vyn, 1991; Porter et al., 1997; Seifert et al., 2017), along with cooler than average spring temperatures (Wilhelm and Wortmann, 2004), and excessive warmth during the summer (Wilhelm and Wortmann, 2004; Gentry et al., 2013). Although weather cannot be controlled, there are many crop inputs that increase yields, and may mitigate the CCYP, including hybrid selection, plant population, fertilizer, and foliar fungicides.

Yield potential is greater with modern corn hybrids as a result of improved tolerance to stresses, such as those associated with increased plant population, reduced soil nitrogen, and low soil moisture (Carlone and Russell, 1987; Sangoi et al., 2002; Tollenaar and Lee, 2002; Tokatlidis and Koutroubas, 2004; Duvick, 2005; Hammer et al., 2009). Hybrids vary in their growth and yield response to different management factors (Mastrodomenico et al, 2018), including crop rotation (Meese et al., 1991). Yet, the greatest yield potential cannot be achieved with newer corn genetics unless grown at higher plant populations than older corn genetics (Tollenaar 1991; Tokatlidis and Koutroubas, 2004). Nitrogen (N) and phosphorus (P) use efficiency (Boomsma et al. 2009; Clay et al. 2009), water-use efficiency (Kuchenbuch et al. 2009), and the value of fungicide and insecticide applications, have been shown to improve with increased planting population. Future improvement of corn yield will focus on increased tolerance to even higher plant populations, due to corn's inadequate input use at lower plant populations (Tollenaar and Lee, 2002). However, increased plant population results in a more stressful environment, which could exacerbate the yield-reducing effects of continuously-grown corn.

Nitrogen is the nutrient required in the greatest quantities for corn (Bender et al., 2013) and is the most frequently limited nutrient for corn production (Ciampitti and Vyn, 2012). After N, the second highest quantity of mineral nutrient acquired by corn during the growing season is potassium (K) (Bender et al., 2013). Additionally, phosphorus (P) is the least mobile macronutrient and least available in the soil (Kovar and Claasen, 2005); however, P has the highest nutrient removal rate from the field at harvest with corn grain (Bender et al., 2013). Other nutrients found to limit U.S. Corn Belt yields are sulfur (S), zinc (Zn), and boron (B) (Berger et al., 1957; Karlen et al. 1988; Bell and Dell, 2008; Alloway, 2009; David et al., 2016; Camberato and Casteel, 2017).

A more recent tool for increasing grain yields is through foliar fungicide applications (Bartlett et al., 2002; Jeschke and Doerge, 2010). Strobilurin fungicides are effective against fungal pathogens that induce foliar fungal diseases in susceptible corn germplasm (Grossman and Retzlaff, 1997). Corn residue on the soil surface from previous crops can serve as an overwintering inoculum for several important foliar diseases, such as grey leaf spot (*Cercospora zeae-maydis*) and northern leaf blight (*Exserohilum turcicum*) (Wise and Mueller, 2011). Residue accumulation can increase through continuous corn rotations (Meese et al., 1991; Gentry et al., 2013), no- or reduced-tillage (Bockus and Shroyer, 1998), higher plant density (Shapiro and Wortmann, 2006), and greater grain yields (Graham et al., 2007). Furthermore, growth regulator effects induced by a strobilurin fungicide application have also been documented to increase grain yield even when fungal disease is not present (Jeschke and Doerge, 2010).

Intensification of agronomic management, including hybrid selection, and additional plant population, fertilizer, and fungicide application, may offset the negative causative effects of continuously grown corn (Riedell et al., 1998; Katsvairo and Cox, 2000) and promote greater yields (Ruffo et al., 2015). The objectives of this research were to (i) demonstrate the CCYP and quantify the impact of different crop management practices on the reduction of the CCYP, (ii) determine the effect of these management factors on in-season biomass accumulation and plant health, and (iii) assess the effect of these practices on yield components to ascertain when these yield responses are occurring. To achieve these objectives, multiple corn hybrids were grown under two crop rotations (previous crop corn versus soybean), at two population densities and crop management levels (standard versus intensive). In this trial, intensive management (i.e., high input) encompassed additional nitrogen fertilizer, broadcast (i.e., K and B source) and banded (i.e., P, S, Zn, and N source) fertility, and a foliar fungicide.

MATERIALS AND METHODS

Agronomic practices

Field experiments were conducted in 2014 and 2015 at Champaign, IL, using two long-term sites dedicated to crop rotation. Due to the rotation treatment in this study, two comparable field sites of approximately 5 acres each were established within 2.8 miles of each other and were both predominantly (>75%) consisted of a Flanagan silt loam (a fine, smectitic, mesic Aquic Argiudoll) with 0 to 2% slope. The sites were tile drained and unirrigated. The preplanting soil properties at the 0- to 6-inch depth for 2014 and 2015 included, respectively, 3.9 and 4.1 % organic matter, pH 6.1 and 5.5, 19 and 37 ppm P, and 101 and 126 ppm K. The minerals P and K were extracted using Mehlich III solution. The study alternated between the two field sites each year, generating for this study 11th (2014) or 13th (2015) year continuous corn versus long-term corn following soybean rotation. The 11th and 13th year continuous corn were considered as similar treatments in line with other rotational experiments (Porter et al., 1997; Seifert et al., 2017). The setup site (the site not used for the current year) established the replicated blocks of corn and soybean that served as the previous crop for the following year's experiment. The corn and soybean blocks in the setup site were maintained with minimal crop management inputs through maturity, harvested, and tilled in preparation for the upcoming year's study. Individual experimental plots consisted of four rows, 37.5-ft in length with 30-in spacing, and planted with a precision ALMACO SeedPro 360 research plot planter (Nevada, IA).

The hybrids evaluated represented a range of maturities (106- to 113-day relative maturity; RM), as well as two seed brands, that represented varying genetic backgrounds and potential tolerance to continuous corn. In 2014, the hybrids grown included DKC58-87SSRIB (108 RM), DKC60-67RIB (110 RM), DKC62-08 RIB (112 RM), DKC64-87RIB (114 RM), DKC63-33RIB (113 RM), 209-53STXRIB (109 RM), 212-86STXRIB (112 RM), and DKC63-55RIB (113 RM) [Bayer, Leverkusen, Germany]; hybrids grown in 2015 included 5415SS (106 RM), 5887VT3P (108 RM), 5975VT3P (109 RM), 6110SS (110 RM), 6065SS (111 RM), 6265SS (112 RM), 6594SS (113 RM), and 6640VT3P (113 RM) [WinField United, LLC., Arden Hills, MN].

Tillage included a chisel plow in fall with field cultivations in spring for the entire seedbed preparation. Plots were planted on 27 April 2014 and 24 April 2015 to achieve an approximate final stand of 32,000 or 45,000 plants acre^{-1}, denoted as standard and high density, respectively. All plots received an in-furrow application of tefluthrin ((1*S*,3*S*)-2,3,5,6-tetrafluoro-4-methylbenzyl 3-((Z)-2-chloro-3,3,3-trifluoroprop-1-en-1-yl)-2,2-dimethylcyclopropanecarboxylate) at a rate of 0.12 lb a.i. acre^{-1} for additional control of seedling insect pests. Weed control consisted of a pre-emergence application of S-metolachlor (2-chloro-*N*-(2-ethyl-6-methylphenyl)-*N*-(2-methoxy-1-methylethyl) acetamide), atrazine (6-chloro-*N*-ethyl-*N′*-(1-methylethyl)-1,3,5-triazine-2,4-diamine), and mesotrione ([2-[4-(methylsulfonyl)-2-nitrobenzoyl]-1,3-cyclohexanedione), and a post-emergence application of glyphosate [*N*-(phosphonomethyl)glycine].

One week before planting, 180 lb N acre^{-1} as urea ammonium nitrate (UAN; 28-0-0) was applied to all plots and incorporated by shallow cultivation. The standard management treatment only received this N fertilizer. The intensive management system included additional fertilizer (containing N, P, K, S, Zn, and B) and a foliar fungicide application. Immediately prior to planting in the intensive management plots, 100 lb P_2O_5 acre^{-1} was banded (2-4 inches beneath the row) by a toolbar fitted with Dawn Equipment 6000 Series Universal Fertilizer Applicator (Dawn Equipment, Sycamore, IL) as MESZ [MicroEssentials SZ; 12-40-0-10S-1Zn] (The Mosaic Company, Plymouth, MN) also supplying an additional 30 lb N acre^{-1}, 25 lb S acre^{-1}, and 2.5 lb Zn acre^{-1}. Additionally at planting, 75 lb K_2O acre^{-1} was broadcast applied (Aspire, 0-0-58-0.5B, The Mosaic Company, Plymouth, MN) supplying an additional 6.5 lb B acre^{-1}. At the V6 growth stage (six fully formed leaves), a side-dress application of 60 lb N acre^{-1} was applied to these plots as urea with a urease inhibitor [$CO(NH_2)_2$ + n-(n-butyl) thiophosphoric triamide; Agrotain urea;

46-0-0] (Koch Agronomic Services, LLC, Wichita, KS) on 6 June 2014 and 4 June 2015. When plants were approximately between the VT to R1 growth stages (tasseling to silk emergence) (9 July 2014 and 13 July 2015), intensive management plots received an application of Headline AMP (BASF, Florham Park, NJ), a product containing pyraclostrobin (carbamic acid, [2-[[[1-(4-chlorophenyl)-1*H*-pyrazol-3-yl]oxy]methyl]phenyl]methoxy-, methyl ester) and metconazole (5-[(4-chlorophenyl)methyl]-2,2-dimethyl-1-(1*H*-1,2,4-triazol-1-ylmethyl)cyclopentanol), at the labeled rates of 0.14 and 0.05 lb a. i. acre^{-1}, respectively. The fungicide was applied using a CO_2-pressurized backpack sprayer via an aqueous suspension at 15 gallon H_2O acre^{-1} and mixed with a nonionic surfactant (MasterLock, WinField Solutions, LLC, St. Paul, MN) at 6.4 oz acre^{-1}.

Plant biomass samplings, health assessment, and harvest

To evaluate seasonal aboveground biomass, plants were sampled at two growth stages: V6 (six leaves with collars visible) and R6 (physiological maturity) (Abendroth et al., 2011). Corn tissue sampling was conducted on 2 June 2014 (V6), 3 June 2015 (V6), 9 September 2014 (R6), and 31 August 2015 (R6). Sampling consisted of manually excising random plants from the outer two rows at V6 (10 plants per plot), and from the center two rows of each plot at R6 (6 plants per plot) to determine biomass. Plants at the V6 growth stage were dried to 0% moisture and weighed. The plants at R6 were partitioned into grain and stover (including husk) components, and biomass was determined by weighing the total fresh stover then processing it through a wood chipper (BC600XL, Vermeer Corporation, Pella, IA) to obtain representative stover subsamples. The stover subsamples were immediately weighed to determine aliquot fresh weight, and then weighed again after drying to 0% moisture in a forced air oven at 167°F, to determine subsample aliquot dry weight and calculate dry biomass. Corn ears were dried and then weighed to obtain grain and cob weight. The grain was removed using a corn sheller (AEC Group, St. Charles, IA) and analyzed for moisture content using a moisture reader (Dickey John, GSF, Ankeny, IA). Cob weight was obtained by difference, and dry stover and cob weights were summed to calculate the overall R6 stover biomass. All biomass and grain weight measurements are presented on a 0% moisture basis.

To assess treatment effects on plant health, leaf greenness was measured at the R2 growth stage (kernel blister) (29 July 2014 and 20 July 2015) using a Minolta SPAD-502 chlorophyll meter (Spectrum Technologies, East-Plainfield, IL), on the lamina at the midleaf region of five ear leaves (with no lesions) per plot. SPAD values were used to estimate differences in leaf N concentration among treatments, given that N is a main element in chlorophyll molecules, and therefore related to leaf greenness (Daughtry et al., 2000).

Plant stand counts were tallied to confirm plant populations at the R6 plant growth stage. The center two rows of each plot were mechanically harvested for determination of grain yield at physiological maturity, and yield values are presented at 15.5% moisture. Grain subsamples from each plot were collected from the plot combine at harvest and 300 randomly selected kernels were weighed to estimate average individual kernel weight, also expressed at 0% moisture. Kernel number was estimated by dividing grain yield by the average individual kernel weight of each plot.

Statistical analysis

Treatments were arranged in a split-split plot in a randomized complete block design with four replications; crop rotation was the main plot and the subplot was hybrid with a factorial arrangement of input level and population at the sub-sub plot level. Biomass accumulation, leaf greenness, grain yield, and yield components (kernel number and kernel weight) were analyzed using the PROC MIXED procedure (SAS 9.4, SAS Institute, Cary, NC). Rotation, hybrid, agronomic management, and population were included as fixed effects and replication as a random effect. Due to differences in years of continuous corn and hybrid, years were analyzed separately. Least square means were separated using the PDIFF option of LSMEANS in SAS PROC MIXED. Unless indicated, fixed effects were considered significant in all statistical calculations if $P \leq 0.05$. Pearson's correlation coefficient was used to evaluate the linear association between grain yield and measured parameters across all treatments and within each rotation, using the CORR procedure of SAS. Additional least significant differences are presented in the appendix (Table 21).

RESULTS AND DISCUSSION

Temperature and precipitation

The weather conditions of 2014 and 2015 in Champaign, IL resulted in varied temperatures and levels of precipitation (Table 1). In 2014, June and July experienced above-average precipitation. Temperatures were at or below normal in July, August, and September of 2014. Illinois experienced a warm April and May in 2015, with a cooler than average June, July, and August. Rainfall in May 2015 was slightly above average in Champaign, but in June, the whole state of Illinois experienced rainfall amounts breaking records that date back to 1886. Champaign received 4.8 inches of rainfall above the 30-year average. Pollination and grain-filling conditions were good with a drier July and August. Overall, the 2014 and 2015 production years experienced very little weather-induced heat or moisture stress. As a result, conditions were generally conducive to favorable grain yields.

Plant biomass accumulation and plant health assessment

Agronomic input level significantly impacted early season (V6 growth stage) biomass accumulation (Table 2). Compared to standard input, intensive management led to 42 to 56%

greater aboveground biomass accumulation when averaged across both planting densities and rotations (Table 3). A significant increase in early season corn biomass accumulation with increased fertilizer inputs is well known (Riedell et al., 2009; Ciampitti and Vyn, 2012). Since this sampling was completed immediately prior to the additional sidedressed N, management responses were primarily from the broadcasted K and B and banded P, N, S, and Zn supplied at planting.

When assessed at V6, accumulation of biomass was comparable, but tended to be greater in the continuous corn rotation relative to the corn-soybean rotation, similar to previous reports (Crookston et al., 1991). Regardless of rotation, the 40% greater planting population of the high population treatment increased the early season biomass accumulation per area by 19 to 20% in both years. Hybrid selection influenced early season biomass accumulation; there was a difference of 96 lb acre^{-1} and 114 lb acre^{-1} in 2014 and 2015, respectively, between the smallest and largest hybrids at V6.

At the R2 growth stage, the corn-soybean rotation led to enhanced ear leaf greenness compared to continuous corn (Table 4). Visual in-season differences between continuous corn and corn rotated with soybean were readily apparent (Figure 1). In 2014 and 2015, leaf greenness was 59.1 versus 52.9 and 62.5 versus 57.9 SPAD relative units from corn-soybean rotation versus continuous corn, respectively, when averaged over density and management system (Table 4). Intensive management increased leaf greenness in continuous corn, but not of those plants grown in the corn-soybean rotation. Increased population reduced the leaf greenness levels. When averaged across hybrids, the least leaf greenness was measured in continuous corn cultivated with standard agronomic management and the higher planting density.

Hybrid selection also impacted these R2 measurements, thirteen of the sixteen hybrids had significantly reduced ear leaf greenness when grown following corn rather than after soybean, while the other hybrids exhibited that tendency. Greater leaf chlorophyll concentrations and boosted levels of plant N have also been found when corn was rotated with soybean compared to grown continuously, which have been attributed to the greater N availability observed in non-continuous corn systems (Ennin and Clegg, 2001). Leaf chlorophyll concentration, photosynthetic potential of the plant, and leaf N nutrient status are closely related (Filella et al., 1995; Moran et al., 2000; Hatfield et al., 2008). These treatment-induced differences in leaf chlorophyll resulting from cropping system and management level changes suggest that N uptake and N availability play key roles in the continuous corn yield penalty and indicate potential ways to mitigate it.

Stover biomass accumulation at the R6 growth stage was 11% and 17% greater from the intensive management when compared to the standard input level, in 2014 and 2015 respectively (Table 3). On an individual plant basis, the intensive input level led to an additional 17 g plant^{-1} of dry weight in 2014 and 18 g plant^{-1} of dry weight in 2015 (data not shown). The increased population treatment provided an additional 13,000 plants acre^{-1} and resulted in increased overall biomass production per area (Table 3). Conversely, individual plants' R6 stover accumulation at the two populations were 139 and 125 g plant^{-1} when grown at 32,000 plants acre^{-1} compared to 110 and 100 g plant^{-1} when grown at 45,000 plants acre^{-1} in 2014 and 2015, respectively (data not shown). Previous crop minimally (P = 0.15 and P = 0.17), or slightly increased final stover biomass with alternating rotation. It has been previously reported that 75% of the time, corn grown after soybean produced greater dry matter than when grown following corn (Sindelar et al., 2015). Combined with the data presented here, these results indicate that corn stover grown with crop rotation will often produce at least similar, if not greater, stover biomass, than when grown continuously.

Grain yield and yield components

Rotation, hybrid, management, and population treatments significantly influenced grain yield (Table 2). When averaged across all treatment combinations, the CCYP associated with continuous corn compared to first year corn following soybean was 29 bu acre^{-1} (-13%; $P < 0.0001$) in 2014 and 51 bu acre^{-1} (-22%; $P = 0.0018$) in 2015 (Table 5). Although increased planting densities decreased yield by an average of 4 and 7 bu acre^{-1} in 2014 and 2015, respectively, the continuous corn rotation did not magnify this response as originally predicted. The increased inter-plant competition of higher planting densities tended to reduce corn yield more when grown under standard management (-4 bu acre^{-1} in 2014 and -12 bu acre^{-1} in 2015) compared to when grown under the high input management (-3 bu acre^{-1} in 2014 and -1 bu acre^{-1} in 2015, non-significant) when averaged across rotations. The lowest yield was observed when corn was grown after corn with standard agronomic management and the higher plant density.

Intensive agronomic management significantly improved grain yield when averaged across crop rotations (41 and 43 bu acre^{-1} in 2014 and 2015, respectively), but the effect was 40–60% greater in continuous corn versus the corn-soybean rotation (50 versus 32 bu acre^{-1} in 2014 and 50 versus 36 bu acre^{-1} in 2015) (Table 5). These findings are consistent with other studies that found additional fertilizer inputs are needed to achieve continuous corn yields that approach or are similar to rotated corn yields (Peterson and Varvel, 1989; Varvel and Wilhelm, 2003; Ciampitti and Vyn, 2012). These data indicate that the continuous corn yield penalty can be partially ameliorated with agronomic management. Although the highest yields were consistently achieved in the corn-soybean rotation using intensive management and standard planting densities, individual hybrids were found to respond differently to management. Select hybrids, for example, were able to nearly overcome the CCYP when grown with intensive management (Figure 2). The CCYP was reduced by 17 to 36 bu acre^{-1} with intensive management for seven hybrids: 6265SS (34%), DKC58-87 (37%), 6640VT3P (38%), DKC64-87 (54%), 212-86STX (72%), 209-53STX (75%), and DKC63-55 (77%).

Grain yield is derived from yield components (i.e., kernel number and individual kernel weight) that may be altered by changes in fertility, planting population, and germplasm (Cox, 1996; D'Andrea et al., 2008; Boomsma et al., 2009). The improved grain yields as a result of intensified agronomic management increased both kernel number and kernel weight (Table 6). Similarly, the consistently greater yields resulting from the corn-soybean rotation compared to the continuously grown corn yields were derived from a combination of increased kernel number and heavier kernel weight.

When combined, the 40–60% greater yield response in continuous corn versus corn-soybean rotation when grown with high input management was linked to a greater production in the amount and weight of those kernels (Table 6). When plants in continuous corn were grown with intensive management, kernel weight was equivalent to that of the corn rotated with soybean managed with standard input levels. It has been previously documented that corn in rotation with soybean, regardless of if they were nodulated or non-nondulated, resulted in both larger and more numerous kernels compared to when grown continuously (Bergerou et al., 2004). These results indicate that throughout much of the growing season corn in rotation was more successful at setting and maintaining yield potential than corn following corn. As early as the V5 (five leaf) growth stage, the number of kernel rows is determined, followed by spikelet pairs that produce kernel ovules at V6, with the number of ovules (potential kernels) and the size of the ear set at V12 (12 leaves) (Abendroth, 2011). Kernel number can be altered by the degree of pollination or through kernel abortion in response to any stress from environmental conditions or plant competition (Ritchie et al., 1986). Later in the season, the sink capacity of the individual kernels is set (R2), followed by the expansion and filling of those kernels with starch (Abendroth, 2011). Rotation of corn with soybean either increased the duration of the grain-filling period or the rate of grain-filling that resulted in heavier kernels. Part of this response can be attributed to the additional N availability in rotated corn compared to corn on corn (Ennin and Clegg, 2001; Gentry et al., 2013), which influences both the production and size of kernels (Pearson and Jacobs, 1987).

Increased planting populations resulted in minimal yield reductions regardless of the previous crop (Table 5). Under high input management, the yield penalty from the continuous corn rotation was not magnified with the higher planting density. Regardless of rotation, the increased kernel numbers produced per area from higher planting densities was offset by lesser kernel weights (Table 6). These compensatory patterns resulted in no overall yield advantage from the increased planting population.

Correlations between crop growth and final grain yield

Early season plant growth assessments at the V6 growth stage had a stronger positive correlation to final grain yield in the corn-soybean rotation than in continuous corn (Table 7). Leaf greenness at the R2 growth stage was strongly positively correlated to final grain yield in continuous corn but not in the corn-soybean rotation. Similar to previous findings, leaf greenness had this stronger correlation to grain yield when assessed in continuous corn compared to corn in rotation with soybean (Attia et al., 2015). Kernel number had a strong to very strong positive correlation to grain yield in the continuous corn plots. Setting the highest potential kernels and decreasing kernel abortion is essential in maintaining and improving grain yield (Ruffo et al., 2015). When corn was rotated with soybean, kernel weight was moderately correlated to grain yield and the correlation was strong when grown continuously. Harvest index, the ratio of grain to total aboveground biomass, was strongly correlated to grain yield in continuous corn. Overall, these correlations show the importance of interactions within the crop throughout the growing season to maintain grain yield potential; with kernel number being determined earlier in the growing season and kernel weight later in crop development.

CONCLUSIONS

In central Illinois, cropping rotation, hybrid selection, agronomic management, and plant population all significantly influenced the measured parameters in corn, with numerous interactions. The highest yields of this study were achieved in the corn-soybean rotation grown with intensive management and at the standard planting density. The data presented here suggest that the CCYP can be mitigated with intensified management. Without enhanced fertility (i.e., standard management) continuous corn production yielded significantly less grain than corn grown following soybean. Intensive agronomic management increased grain yield by enhancing both kernel number and kernel weight. Through growth responses both pre-and post-pollination, there was a 40–60% greater yield response to intensive management in continuous corn compared to the corn-soybean rotation. As a result of certain genetic predispositions, corn germplasm varied in growth and yield response and magnitude of responses to rotation, input level, and population, emphasizing the importance of hybrid selection in continuous corn acres. When population was increased, continuous corn grain yields were maintained when treated with the high input level. Improvement in crop health (i.e., leaf greenness and biomass accumulation) and productivity was made using both crop rotation and intensive management. Enhanced fertility and leaf protection (i.e., intensive management level) in combination with select hybrids resulted in a multifaceted approach to reduce the CCYP and increase yields.

TABLES AND FIGURES

Table 1. Monthly weather data for Champaign, IL during the production seasons of 2014 and 2015. Temperature is the average daily air temperature and precipitation is the average monthly accumulated rainfall. Values were obtained from the U.S. National Oceanic and Atmospheric Administration and values in parentheses are the deviations from the 30-year average (1981-2010).

	Month					
Year	**April**	**May**	**June**	**July**	**Aug.**	**Sept.**
2014						
Temperature, °F	52.7 (0.8)	63.9 (1.4)	73.0 (0.8)	69.8 (-5.1)	73.4 (0.0)	64.6 (-1.6)
Precipitation, in.	3.9 (0.3)	4.4 (-0.5)	8.2 (3.9)	8.7 (4.0)	1.5 (-2.4)	3.4 (0.3)
2015						
Temperature, °F	53.8 (1.9)	65.5 (3.0)	72.0 (-0.2)	73.4 (-1.5)	71.8 (-1.6)	69.8 (3.6)
Precipitation, in.	3.6 (-0.1)	6.1 (1.2)	9.2 (4.8)	4.2 (-0.5)	3.2 (-0.8)	6.4 (3.3)

Table 2. Tests of fixed sources of variation on early and late season biomass accumulation, in-season leaf greenness, final grain yield, and yield components for the continuous corn trial conducted at Champaign, IL during 2014 and 2015. Rotation (R), hybrid (H), management (M), and population (P) served as fixed effects.

Year/Fixed Effect	**V6 Biomass**	**R2 SPAD**	**R6 Stover**	**Grain Yield**	**Kernel Number**	**Kernel Weight**
	P > F					
2014						
Rotation (R)	0.3407	0.0004	0.1487	<.0001	0.0670	0.0121
Hybrid (H)	0.0015	0.0186	0.0827	<.0001	<.0001	<.0001
R x H	0.0270	0.4260	0.1861	0.0057	0.0205	0.1536
Management (M)	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
R x M	0.4083	<.0001	0.6366	<.0001	0.0003	0.1309
H x M	0.1088	0.5741	0.4072	0.0971	0.4142	0.3174
R x H x M	0.0302	0.1897	0.7955	0.0665	0.1201	0.4127
Population (P)	<.0001	<.0001	0.0053	0.0093	0.0104	<.0001
R x P	0.4215	0.0133	0.8181	0.2644	<.0001	<.0001
H x P	0.2080	0.7575	0.6459	0.0998	0.0635	0.5584
R x H x P	0.8140	0.7686	0.6102	0.8172	0.0474	0.0786
M x P	0.1084	0.2811	0.0919	0.6485	0.2868	0.4939
R x M x P	0.2410	0.0795	0.1966	0.6369	0.9993	0.7101
H x M x P	0.5074	0.5361	0.9915	0.6744	0.8588	0.9917
R x H x M x P	0.0442	0.6956	0.9135	0.1519	0.3386	0.6266
2015						
Rotation (R)	0.0469	0.0099	0.1655	0.0018	0.0016	0.0022
Hybrid (H)	0.0150	0.1512	0.0278	0.0453	<.0001	<.0001
R x H	0.5081	0.6912	0.7316	0.1713	0.0587	0.1215
Management (M)	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
R x M	0.1449	<.0001	0.2669	0.0015	0.0013	0.0228
H x M	0.0223	0.0154	0.6895	0.4599	0.1188	0.0017
R x H x M	0.1975	0.3037	0.1246	0.2247	0.0265	0.6136
Population (P)	<.0001	<.0001	<.0001	0.0026	<.0001	<.0001
R x P	0.4649	0.3326	0.5698	0.7829	0.9614	0.0960
H x P	0.5189	0.3828	0.5145	0.0997	0.1563	<.0001
R x H x P	0.8911	0.2649	0.3833	0.0915	0.3801	0.2294
M x P	0.7745	0.5340	0.2152	0.0140	0.0025	0.6258
R x M x P	0.9055	0.6813	0.9914	0.2584	0.5078	0.3064
H x M x P	0.5882	0.3390	0.5763	0.9153	0.7468	0.7456
R x H x M x P	0.7129	0.1925	0.9442	0.1882	0.0234	0.3173

Table 3. Aboveground biomass accumulation as influenced by crop rotation, hybrid, agronomic input level, and population at Champaign, IL in 2014 and 2015. All values are reported at 0% moisture.

		V6 Shoot Biomass				**R6 Stover Biomass**			
		Input Level [§]							
		Standard		**Intensive**		**Standard**		**Intensive**	
	Year/	**Planting Density (x 1000 plants acre^{-1}) [¶]**							
Rotation [†]	**Hybrid [‡]**	**32**	**45**	**32**	**45**	**32**	**45**	**32**	**45**
		lb acre^{-1}							
Cont. Corn	**2014**								
	209-53STX	341	458	497	704	8530	9975	11340	10811
	212-86STX	297	460	581	763	10014	11547	11375	11286
	DKC58-87	327	403	504	672	9415	10714	10863	10245
	DKC60-67	282	489	582	609	8276	9612	10448	10739
	DKC62-08	349	509	760	770	10740	9869	11025	9407
	DKC63-33	363	372	661	779	8158	9220	10383	10100
	DKC63-55	323	429	586	680	9222	10792	10840	11530
	DKC64-87	377	469	562	746	8182	10016	10109	11629
	2014 Means	**332**	**448**	**592**	**716**	**9067**	**10218**	**10798**	**10718**
	2015								
	5415SS	249	297	590	831	7203	8330	8898	10332
	5887VT3P	281	332	548	794	6895	7721	7801	8060
	5975VT3P	259	332	708	737	7583	7604	8300	9477
	6065SS	277	338	641	879	8387	8659	10454	9997
	6110SS	297	357	752	915	7698	7077	8600	9504
	6265SS	376	524	859	908	7850	7863	9214	10174
	6594SS	432	505	606	924	6823	8145	8538	9683
	6640VT3P	297	423	704	839	6111	6855	8984	9904
	2015 Means	**309**	**388**	**676**	**853**	**7319**	**7782**	**8849**	**9641**
Corn-Soybean	**2014**								
	209-53STX	319	422	562	729	8103	8401	10540	11358
	212-86STX	286	359	599	722	9608	9899	10205	11564
	DKC58-87	288	363	498	611	9610	10350	10382	11356
	DKC60-67	281	330	533	670	8694	10653	9744	10785
	DKC62-08	322	369	508	635	9764	11419	12018	11419
	DKC63-33	352	433	635	670	9105	9246	11500	11241
	DKC63-55	264	384	551	731	9601	10365	10618	11615
	DKC64-87	377	483	630	791	10281	10132	10894	10945
	2014 Means	**311**	**393**	**565**	**695**	**9346**	**10058**	**10738**	**11285**
	2015								
	5415SS	291	335	724	701	8217	8756	9358	9554
	5887VT3P	193	282	587	855	7606	7371	9440	9211
	5975VT3P	256	283	666	786	7373	7526	8172	10230
	6065SS	240	336	581	740	8487	8870	10021	10302
	6110SS	300	322	667	822	7426	7946	7840	8929
	6265SS	280	322	700	814	8045	8461	9399	9407
	6594SS	361	386	601	849	8077	7865	10041	10055
	6640VT3P	264	367	619	678	7937	8902	8816	10518
	2015 Means	**273**	**329**	**643**	**781**	**7896**	**8212**	**9136**	**9776**

[†] Rotation V6 LSD ($P \leq 0.05$) = nonsignificant (NS) in 2014 and 48 lb acre^{-1} in 2015; Rotation R6 LSD ($P \leq 0.05$) = NS.

[‡] Hybrid V6 LSD ($P \leq 0.05$) = 43 lb acre^{-1} in 2014 and 61 lb acre^{-1} in 2015; Hybrid R6 LSD ($P \leq 0.05$) = NS in 2014 and 803 lb acre^{-1} in 2015.

[§] Input level V6 LSD ($P \leq 0.05$) = 17 lb acre^{-1} in 2014 and 31 lb acre^{-1} in 2015; Input level R6 LSD ($P \leq 0.05$) = 406 lb acre^{-1} in 2014 and 260 lb acre^{-1} in 2015.

[¶] Plant density V6 LSD ($P \leq 0.05$) = 17 lb acre^{-1} in 2014 and 31 lb acre^{-1} in 2015; Plant density R6 LSD ($P \leq 0.05$) = 406 lb acre^{-1} in 2014 and 260 lb acre^{-1} in 2015.

Table 4. Leaf greenness for hybrids as influenced by crop rotation, agronomic input level, and population at the R2 growth stage of the ear leaf. Hybrids were grown in continuous corn and following soybean rotations at Champaign, IL in 2014 and 2015.

	Crop Rotation ‡							
	Continuous Corn				**Corn-Soybean**			
	Input Level §							
	Standard		**Intensive**		**Standard**		**Intensive**	
Year/ Hybrid †	**Plant Density (plant acre^{-1}) ¶**							
	32,000	**45,000**	**32,000**	**45,000**	**32,000**	**45,000**	**32,000**	**45,000**
	SPAD relative unit							
2014								
209-53STX	58.1	50.1	60.6	56.2	61.9	59.4	63.0	59.4
212-86STX	56.1	47.1	60.0	57.1	62.4	57.9	63.0	59.4
DKC58-87	50.5	46.4	59.1	54.1	59.5	57.8	58.6	57.2
DKC60-67	54.1	50.5	57.6	55.1	59.6	55.9	60.0	57.5
DKC62-08	51.4	44.2	51.3	50.3	60.6	58.2	60.8	57.4
DKC63-33	51.5	43.8	57.3	55.0	59.7	59.0	59.5	57.7
DKC63-55	48.7	44.5	57.1	51.1	58.1	57.5	59.3	56.2
DKC64-87	52.9	49.6	58.0	52.4	60.8	55.9	61.6	56.0
2014 Means	**52.9**	**47.0**	**57.6**	**53.9**	**60.3**	**57.7**	**60.7**	**57.6**
2015								
5415SS	59.3	55.6	65.3	60.4	64.7	62.8	65.6	64.1
5887VT3P	57.3	53.5	62.4	55.3	64.7	62.5	64.3	62.4
5975VT3P	54.6	50.1	62.0	57.7	63.0	58.1	62.2	60.4
6065SS	61.4	55.8	62.1	60.7	63.6	63.2	64.3	60.6
6110SS	60.7	57.9	60.0	58.9	65.0	60.7	62.4	61.1
6265SS	54.0	53.8	60.7	58.3	64.0	60.5	62.8	60.1
6594SS	55.7	57.2	61.1	58.5	62.5	59.8	63.5	60.8
6640VT3P	56.9	49.2	59.2	57.2	65.4	61.1	64.2	61.0
2015 Means	**57.5**	**54.1**	**61.6**	**58.4**	**64.1**	**61.1**	**63.7**	**61.3**

† Hybrid LSD ($P \leq 0.05$) = 2.7 SPAD unit in 2014 and nonsignificant (NS) in 2015.

‡ Rotation LSD ($P \leq 0.05$) = 0.7 SPAD unit in 2014 and 2.5 SPAD unit in 2015.

§ Input level LSD ($P \leq 0.05$) = 0.8 SPAD unit in 2014 and 0.6 SPAD unit in 2015.

¶ Plant density LSD ($P \leq 0.05$) = 0.8 SPAD unit in 2014 and 0.6 SPAD unit in 2015.

Table 5. Corn grain yield for hybrids as influenced by crop rotation, agronomic input level, and population. Hybrids were grown in continuous corn and following soybean rotations at Champaign, IL in 2014 and 2015. All values are reported at 15.5% moisture.

	Crop Rotation ‡							
	Continuous Corn				**Corn-Soybean**			
	Input Level §							
	Standard		**Intensive**		**Standard**		**Intensive**	
Year/	**Plant Density (plant acre^{-1}) ¶**							
Hybrid †	**32,000**	**45,000**	**32,000**	**45,000**	**32,000**	**45,000**	**32,000**	**45,000**
	bu acre^{-1}							
2014								
209-53STX	182	185	237	237	218	204	243	245
212-86STX	164	160	219	228	201	212	244	228
DKC58-87	159	162	211	211	202	210	233	247
DKC60-67	178	169	221	228	209	200	237	238
DKC62-08	151	152	185	174	194	181	223	216
DKC63-33	170	166	218	211	217	209	249	243
DKC63-55	165	161	217	208	197	189	224	214
DKC64-87	174	171	233	227	223	208	254	246
2014 Means	**168**	**166**	**218**	**216**	**208**	**201**	**238**	**235**
2015								
5415SS	178	151	215	215	202	205	245	244
5887VT3P	172	133	199	182	219	185	246	241
5975VT3P	155	150	211	196	215	191	254	244
6065SS	185	181	211	231	220	208	252	250
6110SS	188	171	220	229	227	237	253	255
6265SS	145	127	202	188	226	232	253	258
6594SS	148	162	209	220	227	197	260	258
6640VT3P	130	113	172	192	217	215	251	229
2015 Means	**163**	**148**	**205**	**207**	**219**	**209**	**252**	**247**

† Hybrid LSD ($P \leq 0.05$) = 6.6 bu acre^{-1} in 2014 and 19.8 bu acre^{-1} in 2015.

‡ Rotation LSD ($P \leq 0.05$) = 1.1 bu acre^{-1} in 2014 and 15.3 bu acre^{-1} in 2015.

§ Input level LSD ($P \leq 0.05$) = 2.7 bu acre^{-1} in 2014 and 4.4 bu acre^{-1} in 2015.

¶ Plant density LSD ($P \leq 0.05$) = 2.7 bu acre^{-1} in 2014 and 4.4 bu acre^{-1} in 2015.

Table 6. Grain yield components as influenced by crop rotation, hybrid, agronomic input level, and population at Champaign, IL in 2014 and 2015. All values are reported at 0% moisture.

		Kernel Number				**Kernel Weight**			
		Input Level §							
		Standard		**Intensive**		**Standard**		**Intensive**	
	Year/	**Planting Density (x 1000 plants acre^{-1})** ¶							
Rotation †	**Hybrid** ‡	**32**	**45**	**32**	**45**	**32**	**45**	**32**	**45**
		kernel m^{-2}				mg kernel^{-1}			
Cont. Corn	**2014**								
	209-53STX	4394	4736	4779	5346	219	207	264	236
	212-86STX	3984	4169	4618	5200	218	204	253	233
	DKC58-87	4047	4307	4632	5032	208	199	241	223
	DKC60-67	4146	4455	4533	5031	228	202	259	241
	DKC62-08	3398	3852	3629	3866	235	210	271	240
	DKC63-33	4155	4800	4897	5512	219	183	237	204
	DKC63-55	4341	4433	4986	5331	201	193	231	207
	DKC64-87	4597	4704	5374	5388	201	192	230	226
	2014 Means	**4133**	**4432**	**4681**	**5088**	**216**	**199**	**248**	**226**
	2015								
	5415SS	4749	5102	4962	5485	199	171	230	207
	5887VT3P	4441	4522	4584	5015	206	177	230	209
	5975VT3P	4129	4670	4978	5252	199	169	226	198
	6065SS	4307	4741	4555	5378	228	202	247	228
	6110SS	4320	4649	4782	5603	230	195	244	217
	6265SS	3352	3197	4129	4120	230	209	258	241
	6594SS	4335	4750	5117	5923	184	180	217	196
	6640VT3P	3424	3226	4095	5203	199	183	220	195
	2015 Means	**4132**	**4357**	**4650**	**5247**	**209**	**186**	**234**	**212**
Corn-Soybean	**2014**								
	209-53STX	5282	4844	5101	5027	220	227	253	263
	212-86STX	4390	4612	4923	4460	243	246	264	273
	DKC58-87	4280	5022	4873	5549	251	222	254	237
	DKC60-67	4442	4375	4355	4583	250	244	289	277
	DKC62-08	4025	3752	4526	4203	257	259	263	274
	DKC63-33	5375	4784	5084	4936	215	234	260	261
	DKC63-55	4512	4514	4958	4731	232	222	240	241
	DKC64-87	5690	4912	5585	5598	209	227	244	234
	2014 Means	**4750**	**4602**	**4926**	**4886**	**235**	**235**	**258**	**257**
	2015								
	5415SS	5009	5410	5189	5738	214	201	251	227
	5887VT3P	4779	4567	4865	5566	243	215	269	230
	5975VT3P	4861	5078	4936	5851	236	199	273	221
	6065SS	4636	4721	4988	5499	252	234	268	242
	6110SS	4797	5858	5084	5729	251	213	265	236
	6265SS	4224	4558	4507	4799	284	270	298	286
	6594SS	5488	5316	5786	6251	220	197	239	220
	6640VT3P	4646	5222	5143	5275	247	219	258	230
	2015 Means	**4805**	**5091**	**5062**	**5589**	**243**	**218**	**265**	**236**

† Rotation kernel number LSD ($P \leq 0.05$) = nonsignificant (NS) in 2014 and 161 m^{-2} in 2015; Rotation kernel weight LSD ($P \leq 0.05$) = 9.0 mg kernel^{-1} in 2014 and 10.2 mg kernel^{-1} in 2015. ‡ Hybrid kernel number LSD ($P \leq 0.05$) = 198 m^{-2} in 2014 and 297 m^{-2} in 2015; Hybrid kernel weight LSD ($P \leq 0.05$) = 8.7 mg kernel^{-1} in 2014 and 11.2 mg kernel^{-1} in 2015. § Input level kernel number LSD ($P \leq 0.05$) = 98 m^{-2} in both 2014 and 2015; Input level kernel weight LSD ($P \leq 0.05$) = 4.4 mg kernel^{-1} in 2014 and 2.3 mg kernel^{-1} in 2015. ¶ Plant density kernel number LSD ($P \leq 0.05$) = 99 m^{-2} in both 2014 and 2015; Plant density kernel weight LSD ($P \leq 0.05$) = 4.4 mg kernel^{-1} in 2014 and 2.3 mg kernel^{-1} in 2015.

Table 7. Pearson correlation coefficients and associated significance level for final grain yield between selected corn growth parameters as influenced by crop rotation and averaged across all other treatments.

	2014		**2015**	
Corn Parameter	**CC** †	**CS**	**CC**	**CS**
V6 Biomass	0.69 ***	0.76 ***	0.42 ***	0.57 ***
R2 SPAD	0.70 ***	0.12	0.72 ***	0.09
Harvest Index	0.64 ***	0.46 ***	0.65 ***	0.36 ***
Kernel Number	0.76 ***	0.59 ***	0.84 ***	0.49 ***
Kernel Weight	0.55 ***	0.24 *	0.62 ***	0.56 ***

*** Significant at the 0.001 probability level.

* Significant at the 0.05 probability level.

† CC, Continuous corn; CS, Corn-soybean rotation.

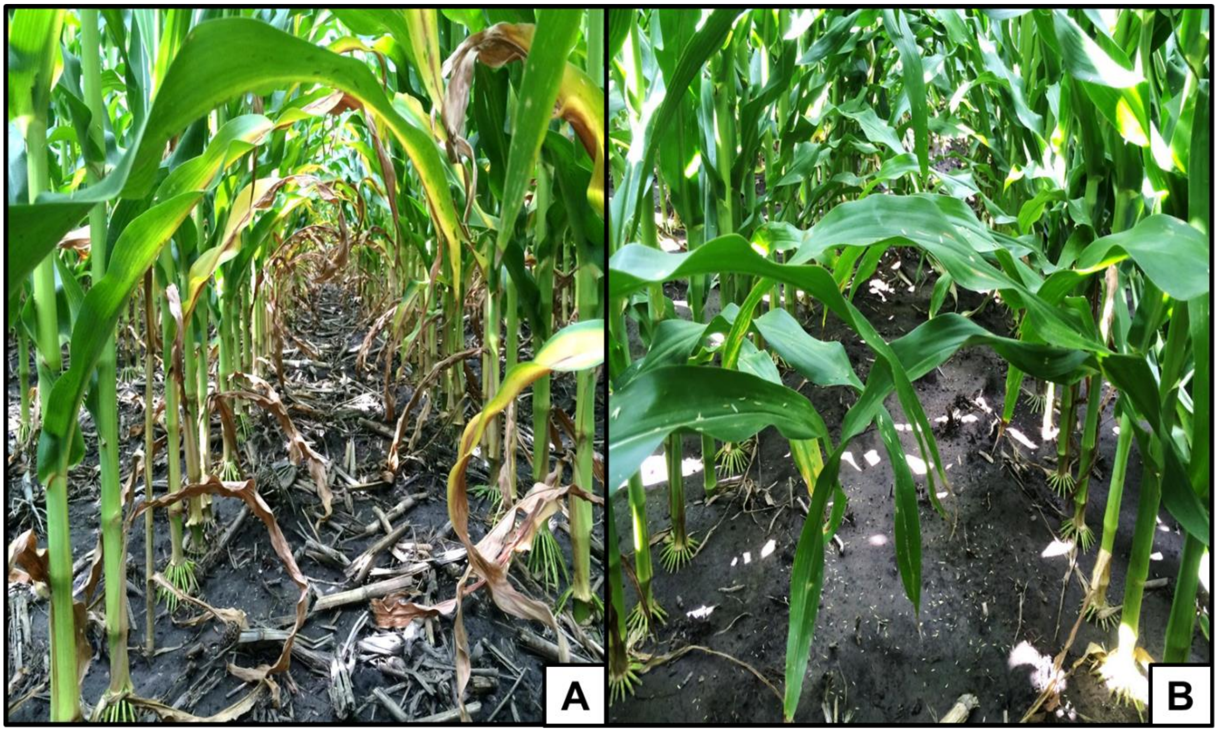

Figure 1. Late-season (R2 growth stage) differences between continuous corn (A) and corn in rotation with soybean (B) at Champaign, IL.

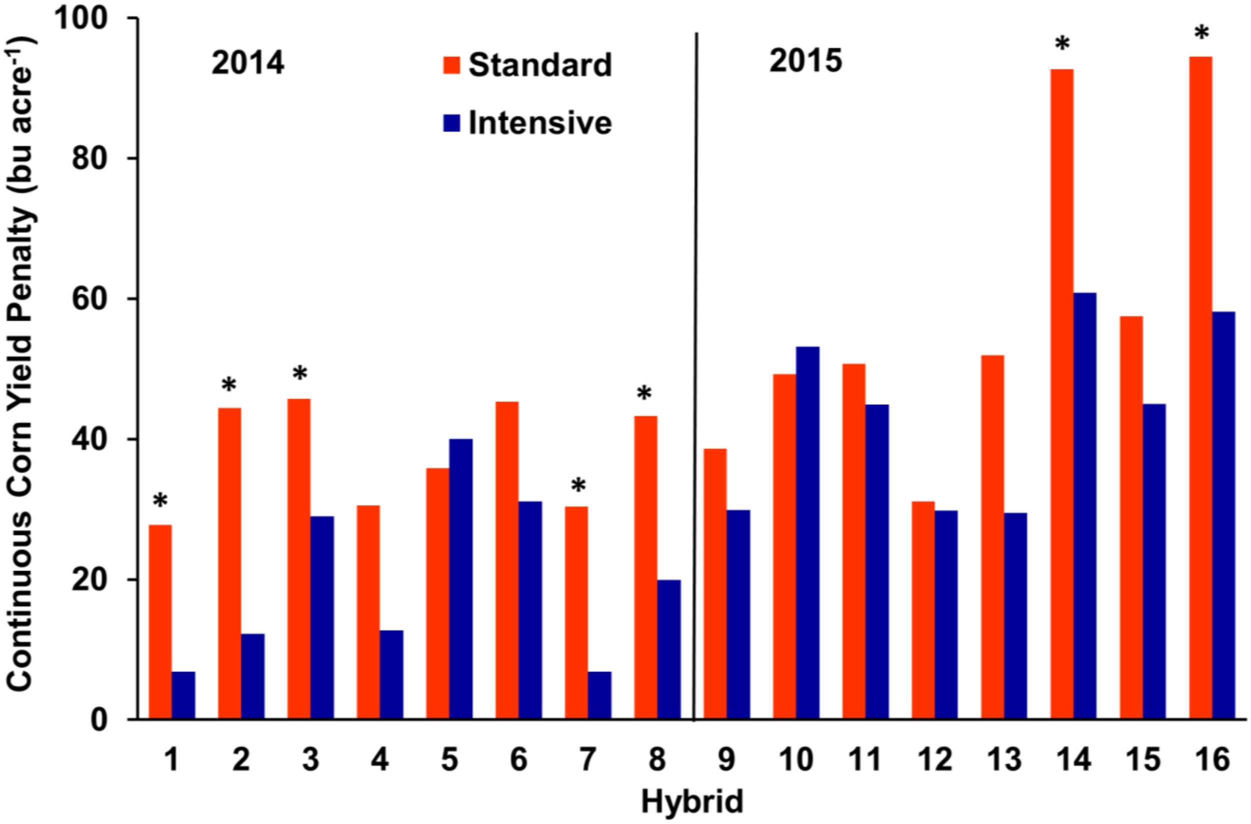

Figure 2. The yield penalty (yield difference between corn-soybean and continuous corn rotation) as influenced by two levels of management (standard versus intensive) at Champaign, IL during 2014 (hybrids 1–8) and 2015 (hybrids 9–16). Hybrids 1–16 follow the order hybrids were presented in Tables 3–6. Values represent the average of two planting populations. * CCYP (continuous corn yield penalty) significantly different at $P \leq 0.05$, due to crop management for each hybrid.

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CHAPTER 3: RESIDUE AND AGRONOMIC MANAGEMENT TO REDUCE THE CONTINUOUS CORN YIELD PENALTY

ABSTRACT

Accelerated residue degradation and nutrient cycling will be necessary to maximize yield potential in corn (*Zea mays* L.) grown continuously, in addition to other high volume residue situations such as increased planting density and crops that annually produce much greater than average yields. The objective of this study was to test if residue management and the level of agronomic inputs could lessen the continuous corn yield penalty (CCYP). Field experiments conducted during 2017 and 2018 at Champaign, IL assessed the yield penalty associated with 15th year continuous corn versus long-term corn following soybean [*Glycine max* (L.) Merr.] grown in either a standard or an intensive management system, both with contrasting mechanical and chemical residue treatments. For the mechanical residue treatments, the previous year's corn crop was harvested with a combine head equipped with Calmer BT Chopper stalk rollers (to produce downsized, i.e., 'sized' residue) or with standard knife rollers, and both mechanical treatments were managed chemically with Extract Powered by Accomplish, or with ammonium sulfate, and compared to an untreated control. Across rotation and mechanical residue blocks, the standard management system was seeded to achieve a final stand of 32,000 plants acre^{-1} and received a base rate of nitrogen fertilizer, no additional fertility, and no fungicide application, while the intensive management system was seeded at 45,000 plants acre^{-1} and consisted of additional sidedressed nitrogen fertilizer, broadcast and banded fertility, and a foliar fungicide application. Overwinter residue decomposition improved with chopped versus standard residue harvest (residue reduced by 46% versus 39%). Intensive inputs resulted in 41% additional early season biomass compared to standard inputs (777 lb acre^{-1} versus 460 lb acre^{-1}), and increased grain yield by 39 bu acre^{-1}. Crop rotation or residue management did not alter early season biomass accumulation, however,

ear leaf greenness at the R2 reproductive stage was enhanced in corn rotated with soybean, grown in sized residue, or in those plots that received fall chemicals. Although the stress induced by continuous corn was not detected through crop assessments until R2, the CCYP was 25 bu acre^{-1}. Sized residue increased yield by 6 bu acre^{-1} overall, and 10 bu acre^{-1} in continuous corn. Inherent yield losses of continuous corn were alleviated by residue and agronomic management, demonstrating the potential to manage the CCYP.

INTRODUCTION

In high volume corn (*Zea mays* L.) residue producing situations, such as increased planting density, reduced tillage, corn following corn systems, and increased grain yields, the need could arise for accelerated residue degradation and nutrient cycling to maximize subsequent crop yield potential. Although it is widely accepted that grain yields of continuously grown corn are generally less than when corn is rotated with soybean [*Glycine max* (L.) Merr.], denoted as the continuous corn yield penalty (CCYP), continuous corn remains a viable cropping system for many Midwestern producers. Grain yield reductions in continuous corn compared to first-year corn in a corn-soybean rotation typically range from 10 to 15% (Van Doren et al., 1976; Peterson and Varvel, 1989; Meese et al., 1991; Porter et al., 1997; Howard et al., 1998; Katsvairo and Cox, 2000; Pedersen and Lauer, 2003; Pikul et al., 2005; Stanger et al., 2008; Gentry et al., 2013). Residue accumulation, along with soil nitrogen availability or immobilization, and the weather have been documented as the primary agents of the CCYP (Gentry et al., 2013). Additionally, the penalty is not moderated by successive years of continuous corn production, and can actually intensify due to the accumulation of residue (Meese et al., 1991; Gentry et al., 2013). Potential options to increase corn yields and reduce the causative factors of the CCYP are mechanical and chemical residue management and enhanced fertility and agronomic systems. The objective of this research was to identify residue and agronomic management practices that lessen yield losses due to high crop residue environments.

With increasing yield levels, planting densities, and reduced or no tillage practices, the quantity of residue remaining after harvest is increasing and residue management is becoming more important for production sustainability. Additional corn residue remaining in the spring can cause delayed and more variable emergence due to slower soil warming (Swan et al., 1987; Liu et al., 2004) and impedes seedling emergence (Mehdi et al., 1999), resulting in uneven emergence and reduced final grain yield potential (Nafziger et al., 1991; Blanco-Canqui et al., 2006). Residue removal is one option for residue management, although removal could deplete the soil of the natural recycling of residue into essential nutrients and utilization by the following crop for plant growth (Blanco-Canqui and Lal 2009).

Previous crop residue type and quantity remaining on the soil surface impacts soil water evaporation, soil temperature, nutrient cycling, and soil organic matter formation, all of which have a role in soil quality and crop productivity (Karlen et al., 1984; Wilhelm et al., 2004). Residue C:N ratio plays a large role in the initial rates of residue degradation, with ratios below 20 to 30 promoting decomposition rate and nutrient release (Janzen and Kucey, 1988; Kumar and Goh, 1999; Havlin et al., 2007). Corn residue has a C:N ratio of approximately 31 for leaves and 78 for stalk material, bolstering nitrogen immobilization (Aulakh et al., 1991; Havlin et al., 2007; Johnson et al., 2007). Net soil nitrogen mineralization is reduced in continuous corn production compared to corn following soybean because of differences in the quality (C:N ratio) and quantity of the previous crops residue (Gentry et al., 2001; Bergerou et al., 2004). As a result, to enhance seedling emergence uniformity and early season plant vigor, synchronizing the timing when crop residue nutrients become readily available, rather than when they are immobilized, to early growth could offset the negative effects of high volume residue environments. To reduce the lingering immobilization of nutrients by the time of planting of the subsequent year's crop, management practices that potentially increase the residue decomposition rate were investigated in this study. One of the available management practices is to use specialty combine heads at harvest that mechanically chop the corn residue to a smaller average fragment size, known as 'sizing'. This sizing increases the surface area of residue exposed to soil microbes, which, in turn would increase the rate of residue decomposition (Ambus and Jensen, 1997). Shattering stalks, sizing them, and evenly distributing residue helps promote the biological processes of decomposition during mild fall and early spring temperatures when residue decay is active (Ambus and Jensen, 1997; Kumar and Goh, 1999). Microorganisms can quickly colonize the easily digestible and exposed inner pith of the stalk material when sized, presumably enhancing residue decomposition. As fungi, bacteria, and actinomycetes proliferate, they further digest the more resistant cellulose, then lastly the toughest lignin of the outer stalk rind (Broder and Wagner, 1988; Kumar and Goh, 1999).

Although several companies in the agricultural sector promote products that contain microorganisms or biocatalysts to enhance residue degradation and nutrient cycling, scientific field studies and publications documenting their effectiveness are limited. These products are designated as biostimulants or biorationals and are utilized to stimulate and/or enhance natural processes to improve nutrient availability to the plant or allow plants to better tolerate stresses (Calvo et al., 2014; Adesemoye et al., 2017). There is a large diversity of products that fall into this category that encompass microorganisms, humic acids, amino acids, or seaweed extracts that can be applied to the soil, seed, or plant. These products can be isolated or derived from manure, plant residues, or the soil. Extract powered by Accomplish is a microbial-based biostimulant derived from a bioreactor system (biologically active environment) with a continuously maintained microbial community. It is designed to help growers manage crop residue by promoting microbial activity and nutrient release from crop residue. The final product contains bacteria and bacterial metabolites combined with ammonium thiosulfate. The bacteria in the final product primarily consist of *Acidovorax facilis*, *Bacillus licheniformis*, *Bacillus marinus*, *Bacillus megaterium*, *Bacillus oleronius*, *Bacillus subtilis*, and *Rhodococcus rhodochrous* (Adesemoye et al., 2017). The bacterial metabolites consist of organic acids, peptides, and enzymes that have been documented to enhance the solubility of phosphorus (Rodriguez and Fraga, 1999; Rodriguez et al., 2006), potassium (Friedrich et al., 1991; Han and Lee, 2005; Sheng and He, 2006), and other macro- and micro-nutrients (Calvo et al., 2014). Based on increased CO_2 emissions, the microbial activity appears to be further enhanced with microbial-based treatments (similar to Extract powered by Accomplish) when combined with UAN (Calvo et al., 2013). Fall nitrogen applications to promote decomposition by narrowing the C:N ratio of the surface residue have been examined previously with varied results (Knorr et al., 2005; Al-Kaisi and Guzman, 2013). To further investigate the impact of chemical management of residue, this study evaluated the product Extract powered by Accomplish mixed with urea ammonium nitrate versus ammonium sulfate alone.

Agronomic management intensification plays a critical role in offsetting the negative causative effects of continuously grown corn (Riedell et al., 1998) and promotes greater yields (Ruffo et al., 2015). Therefore this study included intensive management (i.e., high input) consisting of additional seeding rate, broadcast and banded fertilizer, and a foliar fungicide. Compared to standard management practices, intensive management has been found to extend the growing season of the crop, including the grain-filling period (Ruffo et al., 2015). Improved agronomic management combined with ideal weather conditions may improve both the kernel number and kernel weight yield components compared to those of the typically-stressed growing environments of continuous-corn.

Hybrid selection has been shown to significantly influence the magnitude of the CCYP (Meese et al., 1991). Hybrids that can tolerate continuous corn situations are probably those that are more competitive for resources, and therefore, the proper hybrid selection in combination with intensive management practices will contribute to a multifaceted approach to alleviate the continuous corn yield penalty. These principal factors – residue management (i.e., mechanical and chemical applications), input level (i.e., adding fertility and leaf protection), and hybrid selection – were evaluated to determine their roles in increasing yield, and as methods of reducing the continuous corn yield penalty.

MATERIALS AND METHODS

Agronomic practices

Field experiments at Champaign, IL, in 2017 and 2018 assessed the yield penalty associated with 15th year continuous corn versus a long-term corn following soybean rotation grown in either a standard or intensive management system, and included contrasting mechanical and chemical residue treatments (Table 8). The CCYP was evaluated using two commercially-available hybrids that have been previously characterized as contrasting in their tolerance to fields planted to continuously grown corn (Table 9). The trial was planted 25 April 2017 and 8 May 2018 at the Crop Sciences Research and Education Center in Champaign, IL, using two long-term sites dedicated to crop rotation research, and consisting of a Flanagan-Drummer-Catlin soil association. The site was maintained weed- and disease-free, is level and well-drained, and well-suited to provide evenly distributed soil fertility, pH, soil organic matter, and water availability. Plots were 37.5 feet in length with 30-inch row spacing and four rows in width.

For the mechanical residue treatments (i.e., harvest method), the previous year's corn crop was harvested 4 October 2016 and 21 September 2017 with a combine head equipped with Calmer BT Chopper® stalk rollers (sizing residue to 1 ¼ inch maximum fragments) or with standard knife rollers (not sized). Both mechanical residue treatments were managed chemically in the fall with Extract Powered by Accomplish™ (Extract; 6-0-0-13S, Loveland Products/Nutrien Ag Solutions), or with ammonium sulfate (AMS; 21-0-0-24S) applied 11 November 2016 and 20 October 2017 over the crop residue, and compared to an untreated control. According to the label, Extract was sprayed at 2 gallons acre^{-1} mixed with 1 gallon acre^{-1} urea ammonium nitrate (UAN; 28-0-0) using a total spray solution rate of 15 gallons per acre^{-1} (providing 4.2 lb N acre^{-1} total). Granular AMS was broadcast applied at 200 lb acre^{-1} to provide 42 lb N acre^{-1}. Where soybean was the previous crop, i.e., first year corn in the corn-soybean rotation, mechanical treatments could not be implemented on the soybean residue, but this residue also received both chemical treatments in October and the corn residue had been sized the previous fall.

Across rotation and mechanical residue treatments, the standard management system (i.e., standard input) was seeded to achieve a final stand of 32,000 plants acre^{-1} and received a base rate of nitrogen fertilizer (180 lb N acre^{-1} as UAN) preplant, with no additional fertility, and no fungicide application. The intensive management system was seeded at 45,000 plants acre^{-1} and consisted of broadcast potassium (75 lb K_2O acre^{-1} as Mosaic's Aspire; 0-0-58-0.5B) and phosphorus (100 lb P_2O_5 acre^{-1} as Mosaic's MicroEssentials SZ; 12-40-0-10S-1Zn) banded 4 to 6 inches directly beneath the crop row preplant with a toolbar fitted with Dawn Equipment 6000 Series Universal Fertilizer Applicators (Dawn Equipment, Sycamore, IL), additional sidedressed

(V5 growth stage; 8 June 2017 and 1 June 2018) nitrogen fertilizer (60 lb N acre^{-1} as stabilized Limus urea; 46-0-0; 240 lb N acre^{-1} total), and a foliar fungicide application of Headline AMP® (BASF, Florham Park, NJ), a product containing pyraclostrobin (carbamic acid, [2-[[[1-(4-chlorophenyl)-1H-pyrazol-3-yl]oxy]methyl]phenyl]methoxy-, methyl ester) and metconazole (5-[(4-chlorophenyl)methyl]-2,2-dimethyl-1-(1H-1,2,4-triazol-1-ylmethyl)cyclopentanol), at the labeled rates of 1.22 and 0.46 lb a. i. acre^{-1}, respectively. The fungicide was applied using a CO_2-pressurized backpack sprayer via an aqueous suspension at 15 gallons acre^{-1} and mixed with a nonionic surfactant (MasterLock, WinField Solutions, LLC, St. Paul, MN) at 6.4 oz acre^{-1} at plant growth stage VT/R1 (14 July 2017 and 5 July 2018).

To assess the hybrid variation in response to rotation (i.e., CCYP), hybrids were selected to provide contrasting yield responses when grown in a continuous corn situation (Table 9). The selection was based on previously determined ratings by WinField® United with values ranging from 1-3 indicating that the hybrid is suitable for a continuous corn production system (potentially less CCYP), while ratings of 7-9 indicate that extra management is necessary to overcome the CCYP (therefore, potentially greater CCYP). Additionally, they were selected as hybrids that would remain accessible for the duration of the study.

Statistical analysis

Treatments were arranged as a split-split plot in a randomized complete block design with crop rotation (R) as the whole plot factor. Mechanical residue management (M) was the sub-plot factor, with chemical residue management (C), input level (I), and hybrid (H) randomized in a complete factorial at the sub-sub plot level. Four replications were evaluated for a total of 192 plots each year. The CCYP was calculated as the difference in yield when a hybrid was grown in the corn-soybean rotation minus the yield when grown in continuous corn, and was averaged across mechanical residue management unless otherwise specified.

Parameters were analyzed using the PROC MIXED procedure (SAS 9.4, SAS Institute, Cary, NC). Rotation, mechanical residue management, chemical residue management, input level, and hybrid were included as fixed effects and year and replication as random effects. Least square means were separated using the PDIFF option of LSMEANS in SAS PROC MIXED. Due to the fastidious nature of biostimulants and the limited field-based research conducted with them, significance was declared at $P \leq 0.10$ to be more certain that we would not miss detecting a difference that may exist. Pearson's correlation coefficient was used to evaluate the linear association between grain yield and measured parameters across all treatments using the CORR procedure of SAS. Additional least significant differences are presented in the appendix (Tables 22, 23, & 24).

To assess additional residue parameters, a similar site used as setup for the following year's study was kept in no-till and all mechanical and chemical treatments were applied to first year corn and continuous corn crop residue and monitored from harvest, over the winter, and then measurements (detailed below) were terminated immediately prior to planting of the corn or soybean in rotation at this site. Treatments were arranged at this setup site in a split-split plot design with crop rotation (first year corn in a corn-soybean rotation and 15th year continuous corn) as the main plot, mechanical residue management as the sub-plot, with chemical residue management randomized within each sub-sub plot. Four replications were evaluated for a total of 48 plots per year.

Measured parameters

To determine percent dry weight reduction over the winter from mechanical and chemical residue management treatments, corn residue (leaves and stalks) was collected in all relevant treatments. Two samples per plot (from an area of 144 in^2 each) were collected post-harvest and post-chemical application (20 October 2016 and 19 October 20), placed in nylon mesh bags and weighed, with one sample placed back in-field on the soil surface to overwinter, the other dried to 0% moisture in a forced air oven at 167°F for a week to determine initial moisture concentrations. Immediately prior to planting (25 April 2017 and 19 April 2018) the in-field samples were collected, re-weighed, and dried at 167°F for a week to determine moisture concentration. Overwintered samples were not dried until after collection since the drying process with heat as low as 122 to 140°F can produce additional lignin through nonenzymatic browning (Goering and Van Soest, 1970; Moore et al., 1988), altering microbial decay.

Soil samples were taken from in-between rows of plot areas at the setup site and current trial site of continuous corn and corn following soybean at: 1) post-harvest (18 October 2016 and 10 October 2017) and 2) pre-plant (23 April 2017 and 19 April 2018). Soil samples were obtained from a depth of 0 to 12 in (8 cores per sample). A representative 1 lb subsample was taken from the combined cores to make a composite sample. Samples were immediately frozen until further processing. Soil samples were analyzed for soil pH, organic matter, and fertility levels by A & L Great Lakes Laboratories (Fort Wayne, IN).

John Deere Field Connects soil moisture probes (John Deere, Moline, IL) were placed within a border row after corn crop emergence (25 May 2017 and 15 May 2018) in the standard mechanical and no chemical residue management plots only, including both rotations and input levels (without replication). Cumulative soil moisture level was measured by sensors at depths of

4, 8, 12, 20, and 40 inches every 30 minutes. Moisture readings were averaged to obtain daily total soil moisture levels for the top 40 inches of soil.

Seedling emergence data were obtained daily from a 10-feet row section of the second yield row and compared to the known planting density. Corn plant sampling for biomass accumulation was conducted on 12 June 2017 and 6 June 2018 (V6; both shoots and roots) and 14 September 2017 and 5 September 2018 (R6; aboveground-plant only). Sampling consisted of manually excising six plants from the outer two rows at V6, and from the center two rows of each plot at R6 to determine biomass. Plants at the V6 growth stage were dried to 0% moisture, divided into shoot and root fractions, and weighed. The plants at R6 were partitioned into grain and stover (including husk) components, and biomass was determined by weighing the total fresh stover and then processing it through a Vermeer BC600XL chipper (Vermeer Corporation, Pella, IA) to obtain representative stover subsamples. The stover subsamples were immediately weighed to determine aliquot fresh weight, and then weighed again after drying to 0% moisture in a forced air oven at 167°F, to determine subsample aliquot dry weight and calculate dry biomass. Corn ears were dried and then weighed to obtain grain and cob weight. The grain was removed using a corn sheller (AEC Group, St Charles, IA) and analyzed for moisture content using a Dickey John moisture reader (GSF, Ankeny, IA). Cob weight was obtained by difference, and dry stover and cob weights were summed to calculate the overall R6 stover biomass.

To assess treatment effects on plant health, canopy greenness (normalized difference vegetation index, NDVI) was measured at the V8 growth stage (23 June 2017 and 14 June 2018) with a Crop Circle ACS-201 sensor (Holland Scientific, Lincoln, NE) positioned approximately 20 inches over the plant canopy (at 10 readings per second) and walking at a constant speed in each plot. Additionally, leaf greenness was measured at the R2 growth stage (3 August 2017 and

26 July 2018) with a Minolta SPAD-502 chlorophyll meter (Spectrum Technologies, East-Plainfield, IL), on the lamina at the midleaf region of 10 ear leaves (with no lesions) per plot. Prior to harvest, final stand count was tallied from the center two yield rows of each plot to confirm plant populations.

The center two rows of each plot were mechanically harvested for determination of grain yield at physiological maturity, and values are presented at 15.5% moisture. Subsamples of harvested grain were evaluated for grain quality (i.e., protein, oil, and starch concentrations) using a near-infrare transmittance spectroscopy (NIT) (Infratec 1241 Grain Analyzer, FOSS, Hillerod, Denmark), with values presented at 0 % moisture. Yield components (i.e., average weight per seed and seed number) were also quantified for each plot, with values presented at 0% moisture.

RESULTS AND DISCUSSION

Temperature, precipitation, and soil fertility

The 2017 crop growing season experienced excessive rainfall from late April through early May during crop emergence, while the 2018 crop growing season experienced excessive rainfall in June (Table 10). During the remainder of the 2017 growing season (June through September) rainfall was limited while in 2018 rainfall was similar to the 30-year average. Temperature for each month of the growing season in 2017 was similar to the long-term average. In 2018, corn development rapidly progressed in May due to warmer than average temperatures. Soil organic matter, CEC, and pH were equivalent in both rotations and mechanical residue management treatments suggesting that soil quality was evenly distributed throughout the trial (Table 11). Nitrate levels were generally greater in the spring compared to the fall, while other soil test levels remained constant.

Throughout the majority of the 2017 growing season, continuous corn plots tended to have lower soil water levels, with the standard input level in particular having more water later in the growing season (Figure 3). At the start of the 2018 growing season, rotated plots tended to have higher soil water levels, and remained higher during times when average soil moisture dropped (Figure 4). Soil moisture was at the deficient water level for crop growth (as established by John Deere) from mid-July through the remainder of the growing season in 2017, and in 2018 dropped below the deficient level only briefly in July in the continuous corn and high input plots, and again in mid-August for all treatments (Figures 3 & 4). Cropping rotation, mechanical residue management, hybrid, and agronomic management significantly influenced crop growth and development, and grain yield, (Tables 12 & 13).

Residue degradation

Overwinter residue degradation was influenced by mechanical residue treatment, with the chopped treatment enhancing residue decay by 7% on average (46% reduction in residue remaining in spring when chopped compared to a 39% reduction with the standard stalk rollers; Tables 14 & 15). Other studies have shown similar results of enhanced degradation with reduced residue fragment size (Ambus and Jensen, 1997; Angers and Recous, 1997). Although not statistically significant, degradation tended to improve with fall chemical applications (i.e., Extract and AMS) compared to that of the untreated control. According to Bender et al. (2013), grain yields of 230 bu acre^{-1} produce 5.4 tons of residue acre^{-1}. Assuming similar yields of the previous corn crop for this study, nutrients tied up within the initial aboveground stover residue would amount to 20.8 lb N, 4.0 lb P_2O_5, and 23.3 lbs K_2O per ton of dry matter. Therefore, enhanced residue degradation over winter by sizing (chopping) of the residue would result in an additional

7.9 lb N, 1.5 lb P_2O_5, and 8.8 lb K_2O acre^{-1} of readily available mineral nutrients at planting (based on the 7% increase in degradation compared to standard mechanical harvest method).

Seedling emergence

Time to 50% emergence and total emergence was similar for continuous corn and corn in rotation with soybean, as well as standard or chopped corn residue (Table 16). Conversely, findings from Mehdi et al. (1999) and Blanco-Canqui et al. (2006) documented slower emergence with increased surface residue, and we speculate the conventional tillage implemented within our trial helped overcome obstacles of the sheer volume of corn residue at planting. Meese et al. (1991) reported similar emergence with rotated and continuous corn when grown in conventional tillage compared to delayed emergence of continuous corn when grown in no-tillage conditions. In the current study, high input management increased the time to 50% emergence and total emergence by 0.2 and 0.6 days compared to standard input, respectively. This emergence delay could be from the addition of potassium chloride (KCl), which has the highest salt index compared to other common fertilizer sources (Havlin et al., 2007). In the laboratory, Ouyang et al. (1998) found with additions of KCl, corn seedling germination was delayed and with triple superphosphate (TSP) germination was unaffected.

When comparing the known seed number planted within a 10-feet yield row section to the total emerged, average percent emergence was 94% (Table 16). Percent seedling emergence was improved with chopped mechanical residue management compared to standard (95% compared to 94%), and Sindelar et al. (2013) reported similar results after residue was chopped and 79% was removed. At completion of seedling emergence, the high input level led to slightly lower percent emerged plants than standard agronomic management.

Plant biomass accumulation and vigor assessments

Agronomic input level and hybrid both significantly impacted above- and below-ground early season (V6 growth stage) biomass accumulation (Tables 12 & 17). High input management visually increased early season plant growth (Figure 5), similar to an increase in early season biomass accumulation of corn previously documented with increased fertilizer inputs (Riedell et al., 2009; Ciampitti and Vyn, 2012). In this study, compared to the standard management, the intensive management led to 42% greater aboveground (381 lb acre^{-1} versus 653 lb acre^{-1}) and 36% greater belowground biomass accumulation (79 lb acre^{-1} versus 124 lb acre^{-1}) (Table 17). Since this V6 sampling occurred immediately after the additional sidedressed nitrogen, agronomic management responses were primarily from the broadcasted Aspire and banded MESZ at planting. On an individual plant basis, weight increased by 1.6 g plant^{-1} above- (7.3 versus 5.7 g plant^{-1}) and 0.2 g plant^{-1} below-ground (1.4 versus 1.2 g plant^{-1}) from high input versus standard agronomic management (data not shown). Shoot biomass accumulation was less with hybrid 6110SS compared to 6594SS (497 lb acre^{-1} compared to 537 lb acre^{-1}), along with root biomass accumulation (96 lb acre^{-1} compared to 107 lb acre^{-1}) (Table 17). Regardless of crop rotation, above- and below-ground biomass were comparable, which is similar to data previously reported by Crookston et al., (1991). Shoot to root ratios were greatest when plants were grown in the intensive management system, and although both shoot and root biomass was greater with the high input level compared to standard, the magnitude of gain was greater aboveground (Table 17).

No difference was detected in V8 canopy greenness from crop rotation or residue management (Table 17). This lack of early season difference with residue management agrees with results obtained in conventional tillage with partially removed and sized corn residue versus retained (Sindelar et al., 2013). Canopy greenness at the V8 growth stage increased by 11% from the intensive input level (average NDVI of 0.65 with intensive input compared to 0.57 with standard input) (Table 17). Additionally, hybrid impacted canopy greenness, with 6110SS exhibiting NDVI of 0.60 versus 6594SS at 0.62. Shanahan et al., (2001) also reported NDVI variation with varying hybrid and nitrogen input.

At the R2 growth stage, ear leaf greenness was altered by rotation, mechanical and chemical residue management, input level, and hybrid (Table 12). The corn-soybean rotation led to enhanced ear leaf greenness compared to continuous corn (58.6 versus 55.3 SPAD relative units, respectively) (Table 17). Similar rotational responses of leaf chlorophyll concentration have been documented at V10 (Attia et al., 2015) and R2/R3 (Ennin and Clegg, 2001; Attia et al., 2015; Vogel and Below, 2018). This result has been attributed to improved N availability, and although soybean production removes nitrogen from the soil (Johnson et al., 1975; Bender et al., 2015), the majority of nitrogen in soybean residue that remains at harvest is taken up by the subsequent crop (Power et al., 1986). Additionally, cumulative mineralization of nitrogen is less with continuous corn compared to the corn-soybean rotation during the V10 to R2 growth stages, which are critical for nitrogen uptake (Gentry et al., 2001).

Plots that received chopped corn residue had increased ear leaf greenness compared to standard-processed residue (Table 17). Leaf chlorophyll concentration, photosynthetic potential of the plant, and leaf N nutrient status have a high correlation (Blackmer et al., 1994; Hatfield et al., 2008). Cropping system and mechanical residue management treatment-induced differences in leaf chlorophyll suggest that N uptake and N availability play critical roles in the continuous corn yield penalty and indicate potential ways to help mitigate it.

Although there was additional fertility and foliar protection, intensive management reduced leaf greenness (SPAD readings) due to the increased planting population (Table 17). Hashemi-

Dezfouli and Herbert (1992) and Vogel and Below (2018) documented significant reductions in leaf chlorophyll levels as population density increased. Further, nitrogen additions did not overcome reduced SPAD readings (assessed 90 days after planting) induced by increased planting population in research investigating nitrogen by population interactions (Tajul et al., 2013). Hybrid selection also impacted R2 measurements, with the higher-yielding 6110SS having higher levels of greenness (57.4 SPAD relative units) than the lower yielding 6594SS with lower values (56.6 SPAD relative units). Previous studies have also documented genetic variation in leaf chlorophyll levels (Shanahan et al., 2001; Subedi and Ma, 2005; Hokmalipour and Darbandi, 2011).

Fall chemical treatments increased ear leaf greenness compared to the untreated control, with the largest positive responses to AMS and Extract occurring in continuous corn compared to rotated corn (Table 17). At the R2 growth stage, SPAD readings of rotation by chemical followed this pattern: rotated corn with fall AMS (58.9 SPAD relative units) = rotated corn with fall Extract (58.9 SPAD relative units) > rotated corn with no fall application (58.2 SPAD relative units) > continuous corn with fall AMS (56.5 SPAD relative units) > continuous corn with fall Extract (55.1 SPAD relative units) > continuous corn with no fall application (54.4 SPAD relative units).

Stover biomass accumulation at the R6 growth stage was 23% greater when plants were grown in the intensive management compared to the standard input level (9,513 lb acre^{-1} compared to 7,318 lb acre^{-1}) (Table 17). On an individual plant basis, the standard input level led to an additional 4 g plant^{-1} in dry weight (109 g plant^{-1} with standard input versus 105 g plant^{-1} with high input; data not shown). However, the intensive input level had 13,000 more plants acre^{-1}, resulting in an increased overall biomass production. Although Sindelar et al. (2015) reported that more stover dry matter was accumulated at harvest with corn rotated with soybean 75% of the time, both this study and the previous chapter from work conducted in Illinois resulted in similar stover levels produced in continuous and rotated corn, with the latter displaying only a tendency to increase stover accumulation.

Grain yield and harvest index

Crop rotation, mechanical residue management, input level, and hybrid all significantly influenced grain yield (Table 13). When averaged across all other treatments, the CCYP associated with 15th year continuous corn compared to first year corn following soybean decreased yield by 25 bu acre^{-1} ($P = 0.0002$) (Tables 18 & 19).

Mechanical residue treatments generated visual differences in residue after harvest (Figures 6A and 6B), in-season on the soil surface (Figures 6C and 6D), and at the R6 growth stage on ear size (Figures 6E and 6F). Chopped residue management increased yield by 6 bu acre^{-1} (Tables 18 & 19). In continuous corn, chopped residue enhanced grain yield by 10 bu acre^{-1}. With standard agronomic management, mechanically sizing the residue alone (no chemical application) improved corn grain yield by 10 bu acre^{-1}. Conversely, chemical residue management had no effect on grain yield. Hybrid 6594SS tended to respond positively to fall chemical applications with a 4 bu acre^{-1} increase from the AMS treatment and an 8 bu acre^{-1} response to Extract; however, hybrid 6110SS did not respond positively with trends of -1 bu acre^{-1} and -2 bu acre^{-1} with AMS and Extract, respectively.

Intensive agronomic management significantly improved grain yield when averaged across crop rotations (39 bu acre^{-1}; $P = <0.0001$) (Tables 18 & 19). Continuous corn grain yield managed intensively was similar to corn grown in rotation with soybean and standard inputs. These data emphasize the importance of agronomic management in continuous corn and reflect results documented in other studies (Katsvairo and Cox, 2000; Riedell et al., 1998). Across agronomic input levels and residue management, the CCYP was 23 and 26 bu acre^{-1} with 6110SS and 6594SS, respectively (Tables 18 & 19). The yield responses observed in this trial from crop rotation reflect Winfield United's RTCC ratings (Table 2). The CCYP was reduced with mechanical residue management for both hybrids: 6110SS (CCYP of 28 bu acre^{-1} with standard residue versus 19 bu acre^{-1} with chopped residue) and 6594SS (CCYP of 30 bu acre^{-1} with standard residue versus 22 bu acre^{-1} with chopped residue).

As grain yield level increased, stover biomass production increased (Tables 17, 18, & 19), resulting in additional residue to be managed post-harvest, reinforcing the need to manage residue in not only continuous corn but also in high grain yield environments. This finding that in corn when grain yield increases, stover (surface residue) amount increases has been reported previously (Huggins and Fuchs, 1997; Lorenz et al., 2010), as well as that the quantity of corn residue increases with additional nitrogen, phosphorus, and potassium fertilization (Gregorich et al., 1996; Huggins and Fuchs, 1997; Wilts et al., 2004); such as in the high input system used for the study presented here.

Harvest index was impacted by crop rotation, input level, and hybrid (Tables 13 & 17). Averaged across the trial, harvest index was 56%, consistent with Tollenaar (1989). Continuous corn plants had a lower harvest index than corn in rotation with soybean as a result of decreased grain yield and constant stover biomass, suggesting that continuous corn did not have enough resources to allocate to grain biomass. Attia et al. (2015) also reported reduced harvest index from continuous corn plots. Compared to high input, standard agronomic management led to a higher harvest index as a result of the significantly reduced stover biomass accumulation with the standard input level, along with reduced grain yield. Hybrid 6110SS had a higher harvest index compared to hybrid 6594SS, in agreement with other studies that document differences in harvest index with genetic variation (Tollenaar, 1989; Subedui and Ma, 2005).

Yield components and grain quality

Both kernel number and kernel weight were significantly altered by crop rotation, input level, and hybrid, with mechanical residue management impacting kernel number (Table 13). Kernel number was 5% greater in plots rotated with soybean compared to following corn (4932 kernels m^{-2} versus 4685 kernels m^{-2}, respectively), and 3% greater in plots that received chopped residue compared to standard residue management (4880 kernels m^{-2} versus 4737 kernels m^{-2}, respectively) (Table 19). With mechanical residue management, kernel weight remained constant, similar to findings Sindelar et al., (2013) documented of an increased kernel number and no change in kernel weight with residue management. Individual kernel weight of corn grown continuously was 6% lower than when grown in rotation with soybean (236 mg $kernel^{-1}$ with continuous corn compared to 251 mg $kernel^{-1}$ with corn-soybean). It has been previously shown that corn in rotation with soybean resulted in both heavier (Maloney et al., 1999; Bergerou et al., 2004) and more numerous kernels than when grown continuously (Bergerou et al., 2004). As a result, the higher yields of the corn-soybean rotation compared to the continuously grown corn yields were derived from a combination of both greater kernel number and weight (Table 19).

Input level had the largest treatment effect on kernel number with a nearly 18% increase from intensive input compared to the standard input level (5264 kernels m^{-2} versus 4354 kernels m^{-2}, respectively) (Table 19). Compared to standard management, high input management reduced kernel weight by 4 mg $kernel^{-1}$. When corn was rotated with soybean, both input levels achieved the same kernel weight (251 mg $kernel^{-1}$), whereas continuous corn grown with standard management resulted in 240 mg $kernel^{-1}$ and the high input level kernels weighed 232 mg $kernel^{-1}$. The improved grain yields with intensified agronomic management were a result of increased kernel number (Table 19).

Hybrid 6110SS had 7% heavier and 4% more kernels than hybrid 6594SS, resulting in the enhanced grain yield of 6110SS over 6594SS (Table 19). Kernel weight remained constant for hybrid 6594SS regardless of input level (235 mg kernel^{-1}) and hybrid 6110SS increased kernel weight with the standard versus intensive management (257 versus 248 mg kernel^{-1} with standard versus intensive management, respectively).

Chemical residue management had a significant effect on grain oil and starch concentrations (Table 13). Plots that received a fall application of AMS led to lower percent oil in the grain compared to untreated or Extract-treated plots (Table 19). The Extract treatment reduced grain starch concentration compared to the untreated control, while AMS-treated residue generated grain that had starch concentrations similar to both Extract-treated and untreated plots. Grain protein levels were higher from plants grown in the corn-soybean rotation versus continuous corn (6.69% versus 6.56%, respectively), as well as plants grown in chopped residue versus standard residue (6.69% versus 6.56%, respectively), suggesting additional nitrogen availability from these treatments for protein production. The increase in grain protein concentration with corn following soybean rather than corn is reflected in Maloney et al. (1999) as increased grain nitrogen levels. Standard agronomic management resulted in a lower grain protein percentage than the high input system (6.57% with standard versus 6.69% with high input). In continuously grown corn, the standard input level resulted in lower percent protein in the grain compared to the high input, while rotated corn only trended in that direction.

Hybrid altered all grain quality parameters (oil, protein, and starch levels) (Tables 13 & 19). With the higher yield of 6110SS, oil concentrations were higher and protein concentrations were lower in the grain (4.16% oil and 6.32% protein) compared to those of hybrid 6594SS (4.09% oil and 6.94% protein). The highest grain starch percentage was achieved with hybrid 6110SS

(73.46%) over that of hybrid 6594SS (73.33%). Starch levels at both input levels were similar for 6595SS, while 6110SS had elevated starch levels with high input management. Continuous corn plots exhibited a higher level of starch in the grain compared to rotated corn plots (73.45% versus 73.34%, respectively). Hybrid 6594SS had equivalent percent oil in the grain regardless of input level, unlike 6110SS that increased oil levels with standard agronomic management compared to high input management.

Correlations between crop growth and final grain yield

Early season plant growth assessments at the V6 growth stage, whether above- or below-ground, correlated to final grain yield (Table 20). Shoot biomass and grain yield had a positive weak correlation, while root biomass and grain yield had a positive moderate correlation. Shoot to root ratios had a negative weak correlation to grain yield. Intensive management reduced SPAD readings due to the increased planting population, conversely, crop rotation increased SPAD readings; however, both treatments significantly increased grain yield, resulting in a weak but significant positive correlation to grain yield. Kernel number had a very strong positive correlation to final grain yield, as demonstrated in other studies (Ennin and Clegg, 2001; Bergerou et al., 2004; Haegele et al., 2014; Ruffo et al., 2015), in addition to a weak positive correlation between kernel weight and final grain yield. As R6 stover biomass increased, grain yield increased, resulting in additional residue accumulation on the soil surface (r = 0.80; P = <0.0001). Overall, these correlations show the importance of interactions with the crop throughout the growing season to maintain grain yield potential.

CONCLUSIONS

From fall to spring, residue degradation improved with chopped versus standard mechanical residue management. With an additional 7% of the residue degraded from the mechanical chopping, more nutrients could be released and readily accessible to the current crop. Furthermore, increased residue decomposition would lessen residue impediment on early season growth.

Crop rotation did not affect days to 50% or total emergence, or final percent emerged. Seedling emergence completion was 1.3% greater when following sized residue compared to plots with standard residue treatments. This finding suggests that crop stress induced from larger corn residue pieces should be managed mechanically to decrease fragment size for better crop production.

At the V6 growth stage, enhanced fertility (i.e., high input level) resulted in nearly 40% more early season above- and below-ground biomass accumulation compared to standard management. Although root biomass production at the V6 growth stage had a moderate positive correlation with final grain yield (V6 root biomass $r = 0.53$, $P = <0.001$), there were no notable differences in early season biomass with crop rotation. Canopy greenness at the V8 growth stage was increased when plants were grown with the intensive input level; however, at this growth stage, NDVI readings were similar regardless of crop rotation. Conversely, treatment responses to crop rotation were demonstrated at the R2 growth stage through ear leaf greenness assessment. Stover biomass at the end of the season had a strong positive correlation with final grain yield, documenting that higher grain yields will result in increased residue remaining in the field at harvest ($r = 0.80$; $P = <0.001$).

The highest yields of this study were achieved in the corn-soybean rotation with intensive management (i.e., enhanced fertility and leaf protection). Without enhanced fertility (i.e., standard management), continuous corn plots yielded significantly less than corn following soybean. Both kernel number and kernel weight were increased with crop rotation, presumably from improved pollination, reduced kernel abortion, and increased rate of grain-filling or extended grain-filling period.

In both crop rotations, there was an increased kernel number from the intensive input system; however, in continuous corn this was offset by a lower kernel weight, while corn in rotation with soybean the kernel weight was maintained. Rotation, down-sized residue, and high input management all enhanced percent grain protein. Additionally, there were notable differences in grain quality components as a function of genetics.

Interestingly, the stress induced by continuous corn compared to corn in rotation was not detected until the R2 reproductive stage, based on assessments throughout the season from emergence to final biomass accumulation. The impact of key factors – residue management and hybrid selection - on the magnitude of the CCYP in this study shows that continuous corn can be managed for better productivity. Additionally, as yield levels and planting densities increase, and more growers adopt conservation tillage practices, the quantity of residue remaining after harvest is escalating and residue management is becoming vital for maximized crop production.

TABLES AND FIGURES

Table 8. Treatments used in the evaluation of corn residue management and input intensity influences on the continuous corn yield penalty (CCYP) at Champaign, IL during 2017 and 2018. Two rotations each received two mechanical and three chemical residue management treatments, in combination with two input levels described in the Materials and Methods section.

	Residue Management		**Input**
Rotation	**Mechanical**	**Chemical**	**Level**
Continuous Corn	Standard stalk rollers	Untreated	Standard
Corn-Soybean	Calmer's BT Choppers	Extract Powered by Accomplish	Intensive
		Ammonium Sulfate	

Table 9. Two CROPLAN® WinField® United corn hybrids with a range of relative maturity and response to continuously grown corn (RTCC) were grown in continuous corn (15th year) and following soybean rotations at Champaign, IL in 2017 and 2018. The RTCC ratings are on a scale of 1 = suitable for continuous corn to 9 = needs extra management to overcome CCYP.

Hybrid	**Relative Maturity**	**RTCC**
6110SS	110	5
6594SS	113	7

Table 10. Precipitation and temperature during the production season at Champaign, IL in 2017 and 2018 compared to the 30-year average. Values were obtained from the U.S. National Oceanic and Atmospheric Administration and values in parentheses are the deviations from the 30-year average.

	Precipitation		**Temperature**	
Month	**2017**	**2018**	**2017**	**2018**
	inches		°F	
April	6.2 (+2.6)	2.5 (-1.1)	57 (+5)	46 (-6)
May	5.6 (+0.7)	4.2 (-0.7)	61 (-2)	72 (+9)
June	2.5 (-1.8)	7.3 (+3.0)	73 (+1)	75 (+3)
July	2.2 (-2.5)	3.2 (-1.5)	77 (+2)	75 (0)
August	2.2 (-1.7)	4.0 (+0.1)	72 (-1)	75 (+2)
September	0.8 (-2.3)	4.7 (-1.6)	69 (+3)	71 (+5)

Table 11. Pre-plant and post-harvest soil properties and Mehlich 3-extraction-based mineral test results as affected by crop rotation and mechanical residue management in Champaign, IL during 2017 and 2018. Soil samples were taken to a depth of 12 inches from no chemical residue management and standard agronomic input level plots.

Site 1

Timing	Crop Rotation	Mechanical Res. Mgmt.	Organic Matter	CEC	pH	NO_3	NH_4	P	K	Ca	Mg	S	Zn	B
			%	meq/100g	units	ppm								
Post-Harvest Fall 2016	CC	Standard	3.8	19.3	6.3	6.1	2.0	32	149	2870	346	7.8	2.2	0.7
	“	Chopped	3.8	19.9	6.6	6.3	2.6	30	164	2993	365	7.2	2.0	0.7
	CS	Standard	3.8	18.3	6.1	6.2	1.8	30	123	2645	352	9.2	1.8	0.6
	“	Chopped	3.8	19.1	6.2	6.3	2.3	21	106	2761	367	8.3	1.4	0.5
Fall 2016 Means			3.8	19.2	6.3	6.2	2.2	28	136	2817	358	8.1	1.9	0.6
Pre-Plant Spring 2017	CC	Standard	3.9	18.6	6.2	7.0	3.7	26	158	2713	334	8.4	1.6	0.6
	“	Chopped	3.8	18.4	6.1	6.5	3.6	27	164	2689	342	8.0	1.5	0.6
	CS	Standard	3.9	19.7	6.0	9.4	2.8	26	134	2715	354	9.0	1.6	0.6
	“	Chopped	3.9	19.6	6.0	9.0	2.9	25	106	2685	349	9.0	1.6	0.6
Spring 2017 Means			3.9	19.1	6.1	8.0	3.3	26	141	2701	345	8.6	1.6	0.6
Site 2														
Post-Harvest Fall 2017	CC	Standard	3.2	17.5	6.0	7.6	2.7	24	96	2218	463	8.8	2.1	0.4
	“	Chopped	4.0	18.2	6.3	8.9	2.2	22	99	2547	522	8.7	1.9	0.6
	CS	Standard	3.6	18.6	6.3	5.5	2.1	25	94	2798	513	7.1	1.6	0.6
	“	Chopped	3.7	19.0	6.3	6.1	1.8	27	111	2959	539	7.7	1.7	0.7
Fall 2017 Means			3.6	18.3	6.2	7.0	2.2	25	100	2631	509	8.1	1.8	0.6
Pre-Plant Spring 2018	CC	Standard	3.7	20.1	6.1	8.0	1.6	28	106	2424	487	7.7	1.6	0.5
	“	Chopped	3.9	22.1	6.4	9.5	2.0	23	104	2875	566	8.0	1.6	0.6
	CS	Standard	3.7	19.1	6.4	9.7	2.4	23	78	2595	458	6.3	1.4	0.4
	“	Chopped	3.7	21.0	6.4	9.1	2.0	23	90	2787	495	6.3	1.6	0.5
Spring 2018 Means			3.8	20.6	6.3	9.1	2.0	24	95	2670	502	7.1	1.6	0.5

[†] CC, continuous corn; CS, corn-soybean rotation.

‡ Minerals P, K, Ca, Mg, S, Zn, and B were extracted using Mehlich III solution and are reported as raw means.

Table 12. Tests of fixed sources of variation on corn seedling emergence, biomass accumulation, and leaf greenness (crop vigor) at various plant growth stages (V6, V8, R2, and R6) as affected by two crop rotations, two mechanical and three chemical residue managements, two input levels, and two hybrids at Champaign, Illinois during 2017 and 2018.

	Emergence			**Early Season Biomass**			**Leaf greenness**		**Late Bio.**
Source of variation	**Days to 50%**	**Days to Max**	**% at Completion**	**V6 Shoots**	**V6 Roots**	**V6 Shoot:Root**	**V8 NDVI**	**R2 SPAD**	**R6 Stover**
				P > F					
Rotation (R)	0.1565	0.1274	0.2896	0.7798	0.3565	0.3307	0.6817	0.0012	0.3855
Mechanical (M)	0.1231	0.1027	0.0357	0.8989	0.8234	0.6159	0.2413	0.0427	0.4131
R x M	0.1536	0.5458	0.7653	0.7196	0.2977	0.1202	0.2439	0.9106	0.7942
Chemical (C)	0.2442	0.7839	0.8671	0.7179	0.6631	0.2710	0.7223	<.0001	0.1952
R x C	0.5051	0.5261	0.2126	0.6808	0.3519	0.0819	0.9135	0.0347	0.7378
R x M	0.8607	0.6636	0.2113	0.6340	0.3338	0.1004	0.4169	0.7360	0.4048
R x M x C	0.6110	0.5060	0.3414	0.5827	0.8952	0.5107	0.7269	0.8304	0.3692
Input Level (I)	0.0078	0.0109	0.0139	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
R x I	0.1174	0.0717	0.3504	0.2338	0.1239	0.9293	0.7138	0.5185	0.7990
M x I	0.4878	0.5039	0.7109	0.3153	0.7307	0.1714	0.5235	0.6474	0.5453
R x M x I	0.8226	0.4358	0.4686	0.2733	0.7897	0.5797	0.0003	0.6477	0.8096
C x I	0.8893	0.2107	0.5268	0.3702	0.4680	0.4270	0.2499	0.0093	0.1152
R x C x I	0.4751	0.9215	0.7097	0.6078	0.4434	0.7877	0.3800	0.4781	0.7723
M x C x I	0.4113	0.2534	0.1827	0.4753	0.5974	0.7011	0.5125	0.7107	0.8253
R x M x C x I	0.2296	0.4438	0.3848	0.9647	0.4729	0.3453	0.4865	0.7642	0.3777
Hybrid (H)	0.6785	0.4773	0.1042	0.0008	<.0001	0.8358	<.0001	0.0015	0.8021
R x H	0.0056	0.1715	0.9071	0.8008	0.6464	0.6752	0.3192	0.1637	0.5007
M x H	0.7735	0.5212	0.0043	0.7451	0.7463	0.9703	0.9138	0.6959	0.6208
R x M x H	0.2767	0.0493	0.6248	0.8790	0.3113	0.0672	0.4544	0.9509	0.9819
C x H	0.4975	0.2307	0.3025	0.1030	0.0393	0.4525	0.8564	0.2154	0.4430
R x C x H	0.5981	0.0350	0.5704	0.9346	0.7368	0.9753	0.8950	0.1160	0.9294
M x C x H	0.1025	0.1928	0.3903	0.9740	0.3072	0.8358	0.8778	0.2848	0.7999
R x M x C x H	0.2522	0.3161	0.0773	0.7912	0.4894	0.5227	0.9749	0.5867	0.8895
I x H	0.6150	0.5116	0.9395	0.6930	0.5138	0.5938	0.8513	0.3289	0.8472
R x I x H	0.9843	0.9193	0.8686	0.6646	0.2437	0.6497	0.6629	0.6325	0.8766
M x I x H	0.4878	0.2742	0.2464	0.6651	0.7252	0.6446	0.8705	0.7563	0.4796
R x M x I x H	0.4662	0.0378	0.2528	0.7776	0.2767	0.9096	0.5229	0.8730	0.3123
C x I x H	0.2907	0.4613	0.6272	0.0119	0.0118	0.6771	0.8874	0.3353	0.7815
R x C x I x H	0.0213	0.9876	0.7396	0.1128	0.2934	0.6651	0.3724	0.8353	0.2942
M x C x I x H	0.6544	0.0127	0.4734	0.9593	0.9025	0.4283	0.8308	0.3338	0.9325
R x M x C x I x H	0.7251	0.3065	0.2320	0.9253	0.3776	0.2107	0.6780	0.8806	0.2254

Table 13. Tests of fixed sources of variation on corn grain yield, harvest index, yield components, and grain quality as affected by two crop rotations, two mechanical and three chemical residue managements, two input levels, and two hybrids at Champaign, Illinois during 2017 and 2018.

			Yield Component		**Grain quality**		
Source of variation	**Yield**	**Harvest Index**	**Kernel Number**	**Kernel Weight**	**Oil**	**Protein**	**Starch**
				P > F			
Rotation (R)	0.0002	0.0214	0.0010	0.0015	0.3341	0.0779	0.0806
Mechanical (M)	0.0818	0.1879	0.0082	0.5783	0.1382	0.0357	0.9907
R x M	0.1936	0.1836	0.2202	0.4137	0.2912	0.1322	0.3406
Chemical (C)	0.6004	0.1956	0.5321	0.4623	0.0018	0.1571	0.0495
R x C	0.2558	0.8874	0.0819	0.8843	0.5450	0.1645	0.7453
R x M	0.6235	0.6744	0.7391	0.3476	0.6565	0.9027	0.9584
R x M x C	0.5092	0.2593	0.3432	0.8542	0.1502	0.2285	0.5909
Input Level (I)	<.0001	<.0001	<.0001	0.0042	0.4969	0.0006	0.1146
R x I	0.2937	0.6228	0.2845	0.0141	0.6696	0.0889	0.3000
M x I	0.8738	0.3413	0.3870	0.3129	0.6078	0.3458	0.1818
R x M x I	0.5914	0.8535	0.8231	0.6203	0.2152	0.7580	0.3918
C x I	0.4971	0.4108	0.9579	0.2279	0.2383	0.4203	0.6573
R x C x I	0.5739	0.4513	0.8496	0.4125	0.6202	0.5090	0.5270
M x C x I	0.7787	0.6162	0.6233	0.8912	0.3953	0.9670	0.5033
R x M x C x I	0.4934	0.1940	0.4328	0.8470	0.1911	0.3985	0.1818
Hybrid (H)	0.0014	0.0078	<.0001	<.0001	0.0059	<.0001	0.0318
R x H	0.6079	0.3514	0.3422	0.9809	0.4951	0.0923	0.5322
M x H	0.4555	0.9742	0.0998	0.5765	0.3407	0.8541	0.2341
R x M x H	0.9513	0.8715	0.5490	0.4131	0.9359	0.8246	0.5854
C x H	0.1805	0.8000	0.1417	0.4084	0.5192	0.8141	0.7864
R x C x H	0.8534	0.9714	0.2120	0.1660	0.2290	0.9228	0.4422
M x C x H	0.9007	0.9775	0.7812	0.8685	0.8440	0.7883	0.8506
R x M x C x H	0.9678	0.7207	0.9848	0.9330	0.5710	0.8026	0.5981
I x H	0.1618	0.2828	0.7569	0.0002	0.0057	0.1305	0.0018
R x I x H	0.5361	0.5021	0.9173	0.3873	0.2282	0.9451	0.2495
M x I x H	0.5865	0.2448	0.4981	0.9788	0.8698	0.1793	0.5334
R x M x I x H	0.5621	0.4477	0.4409	0.7780	0.2113	0.1547	0.2559
C x I x H	0.9776	0.5457	0.9540	0.9980	0.7654	0.9979	0.5890
R x C x I x H	0.8853	0.2224	0.7447	0.9772	0.3482	0.5545	0.8929
M x C x I x H	0.8689	0.9217	0.3573	0.6877	0.9897	0.9136	0.3539
R x M x C x I x H	0.7555	0.1204	0.6109	0.9910	0.7726	0.8401	0.7851

Table 14. Tests of fixed sources of variation on corn residue degradation of the setup field for the continuous corn trial conducted at Champaign, Illinois during 2017 and 2018.

Source of variation	**Residue Degradation**
	P* > *F
Rotation (R)	0.6812
Mechanical (M)	0.0104
R x M	0.8541
Chemical (C)	0.1886
R x C	0.4729
M x C	0.7766
R x M x C	0.9119

Table 15. Corn residue degradation over winter as influenced by rotation and mechanical or chemical residue management. Data represents dry matter weight reduction of residue subsamples from the initial previous season post-harvest (fall 2016 and 2017) versus remaining preplant (spring 2017 and 2018) in field-located mesh bags at Champaign, IL.

	Mechanical Res. Mgmt.	
Rotation/Chemical Res. Mgmt.	**Standard**	**Chopped**
	% Reduction	
Continuous Corn		
Untreated	34	43
Extract	40	43
AMS	42	49
Corn-Soybean		
Untreated	39	47
Extract	40	46
AMS	40	49

[†] Rotation LSD ($P \leq 0.10$) = nonsignificant (NS).
[‡] Mechanical Res. Mgmt.LSD ($P \leq 0.10$) = 4%.
[§] Chemical Res. Mgmt. LSD ($P \leq 0.10$) = NS.

Table 16. Days to 50% and maximum emergence and percentage of total emerged at completion of emergence as influenced by crop rotation, mechanical and chemical residue management, input level, and corn hybrid when grown at Champaign, IL during 2017 and 2018.

Input Level	**Hybrid**	**Chemical**	**Days to 50% Emergence**	**Days to Max Emergence**	**Percent Emerged at Emergence Completion**
			———days after planting———		%
Continuous Corn – Standard Res. Mgmt.					
Standard	6110SS	Untreated	14.4	19.1	95.4
“	“	Extract	14.3	18.9	95.4
“	“	AMS	14.6	19.6	96.6
“	6594SS	Untreated	14.4	18.0	96.6
“	“	Extract	14.4	16.6	91.4
“	“	AMS	14.3	17.5	92.8
Intensive	6110SS	Untreated	14.6	18.7	93.5
“	“	Extract	14.5	18.0	97.7
“	“	AMS	14.6	18.4	93.1
“	6594SS	Untreated	14.4	19.4	95.8
“	“	Extract	14.3	18.5	92.1
“	“	AMS	14.1	17.7	89.4
Continuous Corn – Chopped Res. Mgmt.					
Standard	6110SS	Untreated	14.6	17.8	97.4
“	“	Extract	14.5	17.4	96.1
“	“	AMS	14.1	18.9	92.8
“	6594SS	Untreated	14.1	18.4	97.4
“	“	Extract	14.3	20.2	95.1
“	“	AMS	14.4	18.8	95.4
Intensive	6110SS	Untreated	14.5	19.6	94.4
“	“	Extract	14.6	18.5	94.9
“	“	AMS	14.3	18.4	94.9
“	6594SS	Untreated	14.6	18.4	94.0
“	“	Extract	14.3	18.6	94.0
“	“	AMS	14.4	19.1	97.7
Corn-Soybean Rotation – Standard Res. Mgmt.					
Standard	6110SS	Untreated	14.1	17.4	92.8
“	“	Extract	14.9	18.1	97.4
“	“	AMS	14.4	17.8	93.4
“	6594SS	Untreated	15.3	19.1	92.1
“	“	Extract	14.9	18.3	93.3
“	“	AMS	14.2	18.8	92.9
Intensive	6110SS	Untreated	14.8	17.5	93.5
“	“	Extract	14.8	20.3	96.3
“	“	AMS	14.6	20.3	93.3
“	6594SS	Untreated	15.1	20.9	88.4
“	“	Extract	14.8	20.3	91.2
“	“	AMS	15.1	19.1	91.0
Corn-Soybean Rotation – Chopped Res. Mgmt.					
Standard	6110SS	Untreated	14.1	17.3	98.0
“	“	Extract	14.4	19.8	94.1
“	“	AMS	14.3	20.9	96.1
“	6594SS	Untreated	14.6	19.3	94.6
“	“	Extract	14.3	18.4	96.1
“	“	AMS	14.3	19.7	95.9
Intensive	6110SS	Untreated	14.8	20.4	89.4
“	“	Extract	14.8	20.6	91.2
“	“	AMS	14.4	18.0	95.4
“	6594SS	Untreated	14.4	20.5	96.3
“	“	Extract	15.0	18.8	93.2
“	“	AMS	14.8	21.4	93.7
Rotation LSD ($P \leq 0.10$)			NS‡	NS	NS
Mechanical Res. Mgmt. LSD ($P \leq 0.10$)			NS	NS	1.2
Chemical Res. Mgmt. LSD ($P \leq 0.10$)			NS	NS	NS
Input Level LSD ($P \leq 0.10$)			0.1	0.5	1.1
Hybrid LSD ($P \leq 0.10$)			NS	NS	NS

† AMS, ammonium sulfate.

‡ NS, nonsignificant.

Table 17. Above- and below- ground biomass accumulation, plant greenness, and harvest index (HI) as influenced by crop rotation, mechanical and chemical residue management, agronomic input level, and hybrid at various plant growth stages (V6, V8, R2, and R6) for corn grown at Champaign, IL during 2017 and 2018.

			Early Season Biomass			Leaf Greenness		Late Biomass	
Input Level	**Hybrid**	**Chemical**	**V6 Shoot**	**V6 Root**	**V6 Shoot:Root**	**V8 NDVI**	**R2 SPAD**	**R6 Stover**	**HI**
			——lb $acre^{-1}$——					lb $acre^{-1}$	%
Continuous Corn – Standard Res. Mgmt									
Standard	6110SS	Untreated	344	70	4.9	0.55	56.2	7516	55.3
“	“	Extract	393	77	5.1	0.57	55.9	6936	55.8
“	“	AMS†	311	63	4.9	0.56	57.8	7227	56.3
“	6594SS	Untreated	378	85	4.4	0.59	54.3	7161	54.0
“	“	Extract	389	77	5.1	0.60	55.8	7177	54.8
“	“	AMS	415	84	4.9	0.59	58.2	6814	56.5
Intensive	6110SS	Untreated	645	126	5.1	0.62	53.2	9098	54.3
“	“	Extract	605	110	5.5	0.62	54.5	9536	53.4
“	“	AMS	683	135	5.1	0.62	55.4	8659	55.5
“	6594SS	Untreated	682	131	5.2	0.65	51.7	8944	53.0
“	“	Extract	730	142	5.1	0.66	53.5	9986	51.8
“	“	AMS	610	119	5.1	0.66	53.5	9275	52.9
Continuous Corn – Chopped Res. Mgmt.									
Standard	6110SS	Untreated	343	68	5.0	0.55	55.7	7628	56.1
“	“	Extract	356	66	5.4	0.54	57.0	6318	59.6
“	“	AMS	352	74	4.8	0.55	59.2	6912	57.9
“	6594SS	Untreated	367	78	4.7	0.58	55.8	7556	55.1
“	“	Extract	371	77	4.8	0.58	55.0	7584	54.4
“	“	AMS	433	88	4.9	0.57	58.2	7066	57.4
Intensive	6110SS	Untreated	662	113	5.9	0.64	54.8	9096	55.8
“	“	Extract	567	107	5.3	0.64	55.5	10021	53.3
“	“	AMS	652	118	5.5	0.64	55.3	9549	54.3
“	6594SS	Untreated	699	140	5.0	0.66	53.5	9765	53.3
“	“	Extract	721	137	5.3	0.67	53.8	9334	54.8
“	“	AMS	633	125	5.1	0.67	54.1	9413	53.8
Corn-Soybean Rotation – Standard Res. Mgmt.									
Standard	6110SS	Untreated	377	77	4.9	0.57	59.4	7687	57.1
“	“	Extract	357	67	5.3	0.55	59.5	7458	58.3
“	“	AMS	396	75	5.3	0.56	59.5	7304	58.3
“	6594SS	Untreated	437	96	4.6	0.58	57.6	7035	57.2
“	“	Extract	426	91	4.7	0.59	59.9	7788	56.2
“	“	AMS	407	77	5.3	0.59	60.4	7504	56.9
Intensive	6110SS	Untreated	635	120	5.3	0.63	57.6	9298	57.1
“	“	Extract	598	120	5.0	0.65	56.8	9609	56.3
“	“	AMS	633	114	5.6	0.65	57.9	10142	54.5
“	6594SS	Untreated	609	118	5.2	0.66	56.5	9096	55.7
“	“	Extract	704	152	4.6	0.67	58.1	9852	55.9
“	“	AMS	624	113	5.5	0.66	56.2	9421	55.7
Corn-Soybean Rotation – Chopped Res. Mgmt.									
Standard	6110SS	Untreated	304	62	4.9	0.58	59.6	7597	58.4
“	“	Extract	359	82	4.4	0.56	59.8	7536	58.2
“	“	AMS	408	79	5.2	0.55	61.6	7319	58.8
“	6594SS	Untreated	383	100	3.8	0.60	59.0	7710	56.5
“	“	Extract	402	83	4.8	0.60	60.4	7426	57.9
“	“	AMS	428	87	4.9	0.57	60.1	7375	56.7
Intensive	6110SS	Untreated	647	119	5.4	0.62	58.2	10010	54.2
“	“	Extract	643	120	5.4	0.63	57.6	10017	54.7
“	“	AMS	655	130	5.0	0.63	58.8	9077	57.0
“	6594SS	Untreated	655	126	5.2	0.64	57.3	9520	54.8
“	“	Extract	727	133	5.5	0.65	58.8	10572	54.2
“	“	AMS	655	117	5.6	0.66	56.7	9033	57.6
Rotation LSD ($P \leq 0.10$)			NS‡	NS	NS	NS	1.2	NS	1.0
Mechanical Res. Mgmt. LSD ($P \leq 0.10$)			NS	NS	NS	NS	0.5	NS	NS
Chemical Res. Mgmt. LSD ($P \leq 0.10$)			NS	NS	NS	NS	0.5	NS	NS
Input Level LSD ($P \leq 0.10$)			19	4	0.1	0.01	0.4	236	0.6
Hybrid LSD ($P \leq 0.10$)			19	4	NS	0.01	0.4	NS	0.6

† AMS, ammonium sulfate.

‡ NS, nonsignificant.

Table 18. Corn grain yield for two hybrids as influenced by crop rotation, mechanical and chemical residue management, and agronomic input level. Hybrids were grown in continuous corn (15th year) and following soybean rotations at Champaign, IL in 2017 and 2018.

	Crop Rotation[†]							
	Continuous Corn				**Corn-Soybean**			
	Mechanical Res. Mgmt[‡]				**Mechanical Res. Mgmt.**			
	Standard		**Chopped**		**Standard**		**Chopped**	
Hybrid[††]/	**Input Level[¶]**		**Input Level**		**Input Level**		**Input Level**	
Chemical Res. Mgmt[§]	**Standard**	**Intensive**	**Standard**	**Intensive**	**Standard**	**Intensive**	**Standard**	**Intensive**
	bu acre^{-1}							
6110SS								
Untreated	193	223	203	239	215	258	223	249
Extract	184	226	194	234	219	257	217	254
AMS	196	226	199	231	212	254	218	254
6594SS								
Untreated	176	211	191	232	200	244	209	244
Extract	179	222	188	230	211	262	213	261
AMS	184	220	192	227	206	246	203	260

[†] Rotation LSD ($P \leq 0.10$) = 6.9 bu acre^{-1}.

[‡] Mechanical Res. Mgmt.LSD ($P \leq 0.10$) = 5.4 bu acre^{-1}.

[§] Chemical Res. Mgmt. LSD ($P \leq 0.10$) = nonsignificant (NS).

[¶] Input level LSD ($P \leq 0.10$) = 3.5 bu acre^{-1}.

[††] Hybrid LSD ($P \leq 0.10$) = 3.5 bu acre^{-1}.

Table 19. Yield components and grain quality as influenced by crop rotation, mechanical and chemical residue management, input level, and corn hybrid when grown at Champaign, IL during 2017 and 2018. Yield is presented at 15.5% moisture, while kernel weight (KW) is shown at 0% moisture.

				Yield Component		**Grain Quality**		
Input Level	**Hybrid**	**Chemical**	**Yield**	**KN†**	**KW**	**Oil**	**Protein**	**Starch**
			bu ac^{-1}	seed m^{-2}	mg seed^{-1}		%	
Continuous Corn – Standard Res. Mgmt.								
Standard	6110SS	Untreated	193	4062	251.9	4.26	6.15	73.17
“	“	Extract	184	3947	248.3	4.09	5.98	73.57
“	“	AMS	196	4165	250.6	3.97	6.11	73.55
“	6594SS	Untreated	176	4081	227.9	3.97	6.55	73.65
“	“	Extract	179	4084	233.1	4.00	6.64	73.46
“	“	AMS	184	4250	231.1	3.91	6.70	73.49
Intensive	6110SS	Untreated	223	4982	237.9	4.15	6.11	73.77
“	“	Extract	226	4973	241.2	4.04	6.10	73.50
“	“	AMS	226	5167	232.3	3.98	6.18	73.80
“	6594SS	Untreated	211	5040	218.9	4.10	6.89	73.45
“	“	Extract	222	5064	232.0	4.10	6.96	73.07
“	“	AMS	220	5190	223.5	3.94	7.07	73.46
Continuous Corn – Chopped Res. Mgmt.								
Standard	6110SS	Untreated	203	4200	255.4	4.17	6.17	73.47
“	“	Extract	194	4192	246.4	4.29	6.28	73.16
“	“	AMS	199	4211	250.8	4.17	6.29	73.45
“	6594SS	Untreated	191	4440	227.2	3.96	6.83	73.42
“	“	Extract	188	4461	224.4	4.38	7.01	72.85
“	“	AMS	192	4442	229.0	4.15	7.03	73.22
Intensive	6110SS	Untreated	239	5191	243.6	4.18	6.31	73.71
“	“	Extract	234	5114	241.9	4.04	6.40	73.76
“	“	AMS	231	5129	238.1	4.14	6.60	73.56
“	6594SS	Untreated	232	5426	225.2	4.18	7.02	73.49
“	“	Extract	230	5268	229.6	4.16	6.99	73.30
“	“	AMS	227	5372	222.6	3.96	7.20	73.55
Corn-Soybean Rotation – Standard Res. Mgmt.								
Standard	6110SS	Untreated	215	4345	262.8	4.22	6.24	73.26
“	“	Extract	219	4365	266.2	4.36	6.49	73.03
“	“	AMS	212	4238	267.3	4.17	6.35	73.24
“	6594SS	Untreated	200	4401	239.9	4.01	6.75	73.70
“	“	Extract	211	4630	243.6	4.19	7.04	73.06
“	“	AMS	206	4631	237.9	3.99	6.85	73.50
Intensive	6110SS	Untreated	258	5364	255.3	4.14	6.40	73.61
“	“	Extract	257	5259	259.2	4.19	6.39	73.36
“	“	AMS	254	5235	257.4	4.15	6.46	73.26
“	6594SS	Untreated	244	5273	244.9	4.08	7.00	73.16
“	“	Extract	262	5630	248.0	4.14	7.04	73.24
“	“	AMS	246	5316	244.6	4.11	7.05	73.18
Corn-Soybean Rotation – Chopped Res. Mgmt.								
Standard	6110SS	Untreated	223	4507	262.4	4.22	6.39	73.54
“	“	Extract	217	4443	259.6	4.36	6.49	73.06
“	“	AMS	218	4406	262.0	4.22	6.46	73.31
“	6594SS	Untreated	209	4626	240.4	4.09	6.99	73.45
“	“	Extract	213	4767	238.2	4.08	6.95	73.46
“	“	AMS	203	4592	235.0	3.99	6.96	73.29
Intensive	6110SS	Untreated	249	5266	251.2	4.16	6.53	73.61
“	“	Extract	254	5282	255.2	4.23	6.36	73.66
“	“	AMS	254	5177	260.1	4.01	6.34	73.73
“	6594SS	Untreated	244	5299	244.0	4.22	7.05	73.18
“	“	Extract	261	5588	247.2	4.25	7.05	73.17
“	“	AMS	260	5731	240.4	4.16	7.00	73.15
Rotation LSD ($P \leq 0.10$)			6.9	91	5.6	NS	0.11	0.10
Mechanical Res. Mgmt. LSD ($P \leq 0.10$)			5.4	82	NS	NS	0.10	NS
Chemical Res. Mgmt. LSD ($P \leq 0.10$)			NS	NS	NS	0.05	NS	0.12
Input Level LSD ($P \leq 0.10$)			3.5	59	2.3	NS	0.06	NS
Hybrid LSD ($P \leq 0.10$)			3.5	58	2.3	0.04	0.06	0.10

† KN, kernel number; KW, kernel weight; AMS, ammonium sulfate.

‡ NS, nonsignificant.

Table 20. Pearson correlation coefficients and associated significance level for final grain yield between selected corn growth parameters for the continuous corn trial conducted at Champaign, IL during 2017 and 2018.

Corn Parameter	**Correlation *r***
V6 Shoot Biomass	0.35 ***
V6 Root Biomass	0.53 ***
V6 Shoot:Root	-0.34 ***
R2 SPAD	0.19 ***
R6 Stover	0.80 ***
Kernel Number	0.92 ***
Kernel Weight	0.37 ***

*** Significant at the 0.001 probability level.

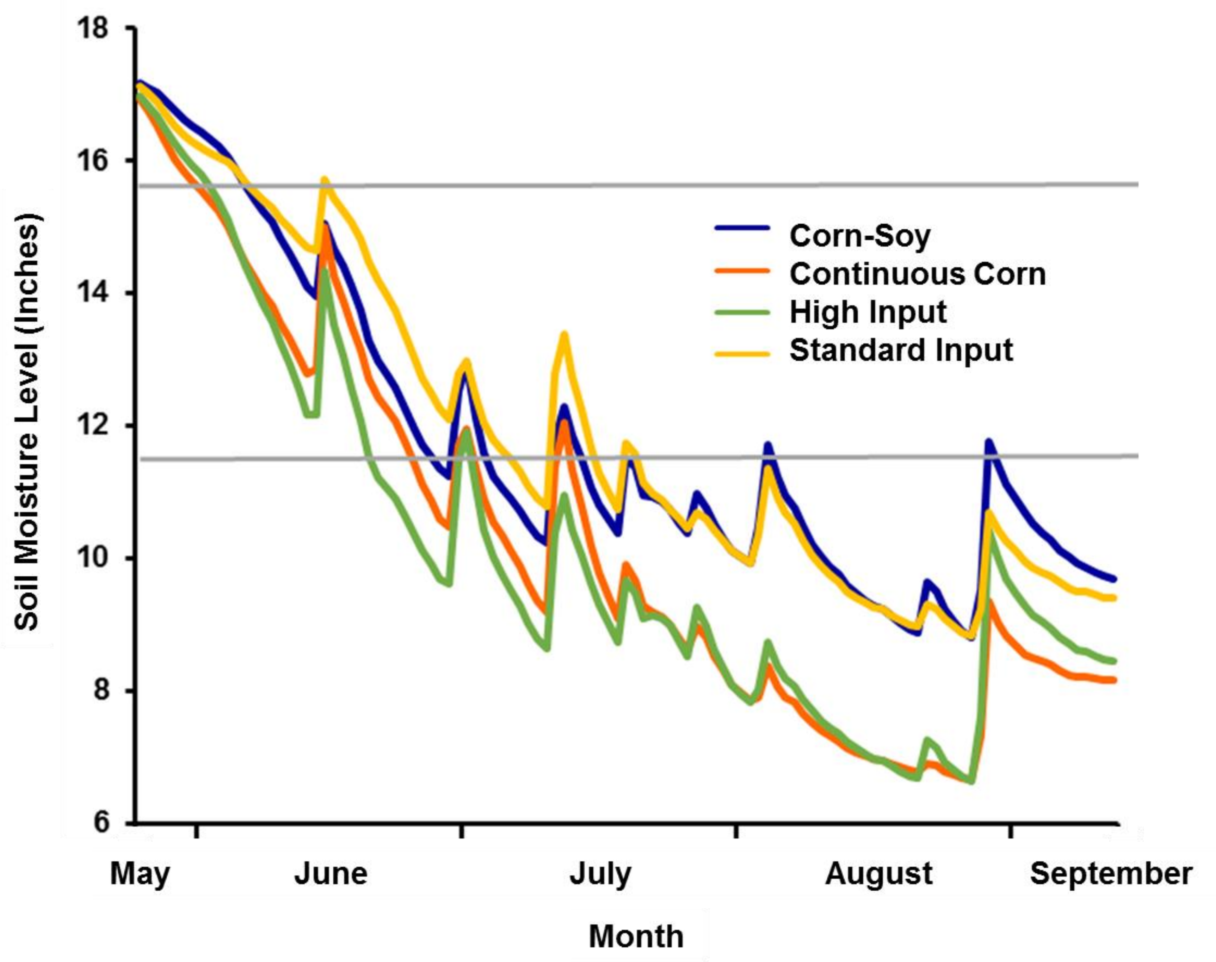

Figure 3. Soil moisture level as influenced by crop rotation and input level at Champaign, IL in 2017. Values were obtained from John Deere moisture probes placed in row after corn crop emergence in standard residue management plots only. Moisture Level is the total average daily measure in the top 40 inches of soil. Gray lines represent deficient (≤11.6 in), responsive (11.7-15.7 in), and adequate (≥15.8 in) water levels for crop growth determined by John Deere.

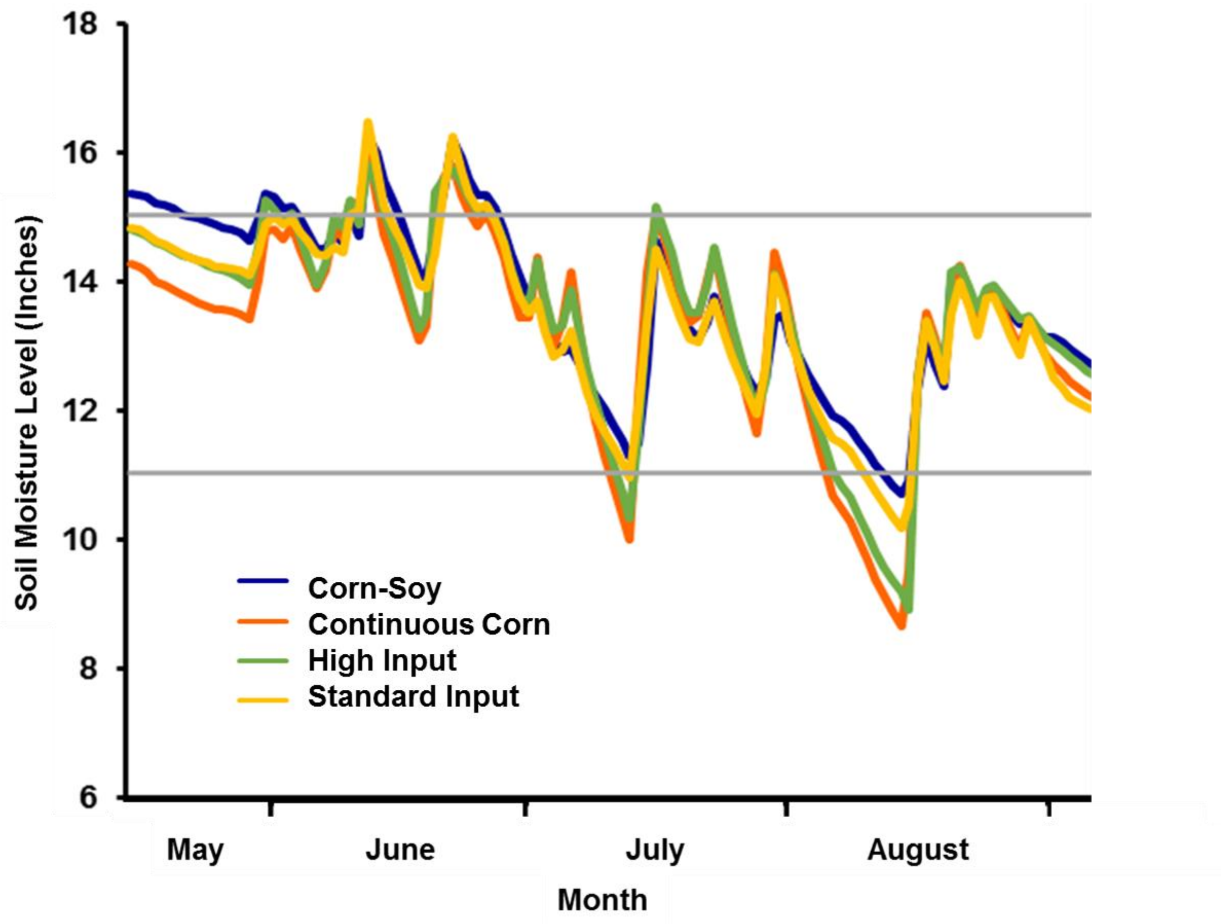

Figure 4. Soil moisture level as influenced by crop rotation and input level on at Champaign, IL in 2018. Values were obtained from John Deere moisture probes placed in row after corn crop emergence in standard- residue management plots only. Moisture Level is the total average daily measure in the top 40 inches of soil. Gray lines represent deficient (≤11.0 in), responsive (11.1-15.0 in), and adequate (≥15.1 in) water levels for crop growth determined by John Deere.

Figure 5. Early-season (V6 growth stage) differences above- and below-ground between standard (left) and intensive (right) agronomic input levels at Champaign, IL.

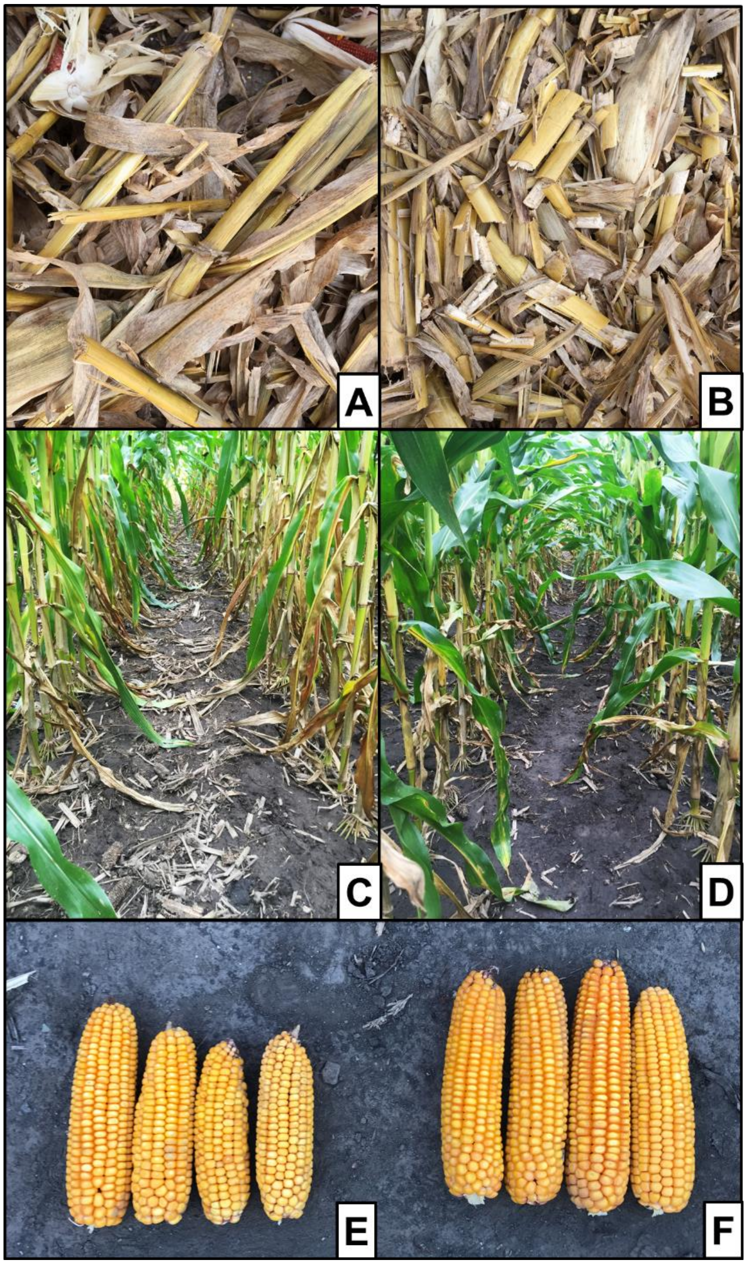

Figure 6. Mechanical residue management effects in continuous corn the previous fall (A and B), at the R3 growth stage the following growing season (C and D), and on ears at the R6 growth stage (E and F) due to Standard stalk rollers (A, C, and E) and Calmer's BT choppers (B, D, and F) in Champaign, IL.

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APPENDIX A: SUPPLEMENTAL TABLES

Table 21. Least significant differences (LSD) declared at $P \leq 0.05$ on early and late season biomass accumulation, in-season leaf greenness, final grain yield, and yield components for the continuous corn trial conducted at Champaign, IL during 2014 and 2015. Rotation (R), hybrid (H), management (M), and population (P) served as fixed effects.

Year/Fixed Effect	V6 Biomass	R2 SPAD	R6 Stover	Grain Yield	Kernel Number	Kernel Weight
	lb acre^{-1}		lb acre^{-1}	bu acre^{-1}	seeds m^{-2}	mg seed^{-1}
2014						
Rotation (R)	NS[†]	0.7	NS	1.1	NS	9.0
Hybrid (H)	43	2.7	NS	6.6	198	8.7
R x H	69	NS	NS	8.9	272	NS
Management (M)	17	0.8	406	2.7	98	4.4
R x M	NS	0.9	NS	3.1	118	NS
H x M	NS	NS	NS	NS	NS	NS
R x H x M	83	NS	NS	NS	NS	NS
Population (P)	17	0.8	406	2.7	99	4.4
R x P	NS	0.9	NS	NS	119	5.5
H x P	NS	NS	NS	NS	NS	NS
R x H x P	NS	NS	NS	NS	392	NS
M x P	NS	NS	NS	NS	NS	NS
R x M x P	NS	NS	NS	NS	NS	NS
H x M x P	NS	NS	NS	NS	NS	NS
R x H x M x P	107	NS	NS	NS	NS	NS
2015						
Rotation (R)	48	2.5	NS	15.3	161	10.2
Hybrid (H)	61	NS	803	19.8	297	11.2
R x H	NS	NS	NS	NS	NS	NS
Management (M)	31	0.6	260	4.4	98	2.3
R x M	NS	1.4	NS	9.0	141	5.6
H x M	86	2.9	NS	NS	NS	11.6
R x H x M	NS	NS	NS	NS	488	NS
Population (P)	31	0.6	260	4.4	99	2.3
R x P	NS	NS	NS	NS	NS	NS
H x P	NS	NS	NS	NS	NS	11.6
R x H x P	NS	NS	NS	NS	NS	NS
M x P	NS	NS	NS	6.2	139	NS
R x M x P	NS	NS	NS	NS	NS	NS
H x M x P	NS	NS	NS	NS	NS	NS
R x H x M x P	NS	NS	NS	NS	624	NS

[†] NS, nonsignificant.

Table 22. Least significant differences (LSD) declared at $P \leq 0.10$ on corn seedling emergence, biomass accumulation, and leaf greenness (crop vigor) at various plant growth stages (V6, V8, R2, and R6) for as affected by two crop rotations, two mechanical and three chemical residue managements, two input levels, and two hybrids at Champaign, Illinois during 2017 and 2018.

	Emergence			**Early Season Biomass**			**Leaf greenness**		**Late Bio.**
Source of variation	**Days to 50%**	**Days to Max**	**% at Completion**	**V6 Shoots**	**V6 Roots**	**V6 Shoot:Root**	**V8 NDVI**	**R2 SPAD**	**R6 Stover**
	——Day——		%	——lb acre^{-1}——					lb acre^{-1}
Rotation (R)	NS[†]	NS	NS	NS	NS	NS	NS	1.2	NS
Mechanical (M)	NS	NS	1.0	NS	NS	NS	NS	0.5	NS
R x M	NS	NS	NS	NS	NS	NS	NS	NS	NS
Chemical (C)	NS	NS	NS	NS	NS	NS	NS	0.5	NS
R x C	NS	NS	NS	NS	NS	0.2	NS	1.1	NS
R x M	NS	NS	NS	NS	NS	NS	NS	NS	NS
R x M x C	NS	NS	NS	NS	NS	NS	NS	NS	NS
Input Level (I)	0.1	0.4	1.0	19	4	0.1	0.01	0.4	236
R x I	NS	0.8	NS	NS	NS	NS	NS	NS	NS
M x I	NS	NS	NS	NS	NS	NS	NS	NS	NS
R x M x I	NS	NS	NS	NS	NS	NS	0.01	NS	NS
C x I	NS	NS	NS	NS	NS	NS	NS	0.7	NS
R x C x I	NS	NS	NS	NS	NS	NS	NS	NS	NS
M x C x I	NS	NS	NS	NS	NS	NS	NS	NS	NS
R x M x C x I	NS	NS	NS	NS	NS	NS	NS	NS	NS
Hybrid (H)	NS	NS	NS	19	4	NS	0.01	0.4	NS
R x H	0.2	NS	NS	NS	NS	NS	NS	NS	NS
M x H	NS	NS	1.3	NS	NS	NS	NS	NS	NS
R x M x H	NS	0.9	NS	NS	NS	NS	NS	NS	NS
C x H	NS	NS	NS	NS	7	NS	NS	NS	NS
R x C x H	NS	1.1	NS	NS	NS	NS	NS	NS	NS
M x C x H	NS	NS	NS	NS	NS	NS	NS	NS	NS
R x M x C x H	NS	NS	3.4	NS	NS	NS	NS	NS	NS
I x H	NS	NS	NS	NS	NS	NS	NS	NS	NS
R x I x H	NS	NS	NS	NS	NS	NS	NS	NS	NS
M x I x H	NS	NS	NS	NS	NS	NS	NS	NS	NS
R x M x I x H	NS	1.5	NS	NS	NS	NS	NS	NS	NS
C x I x H	NS	NS	NS	47	10	NS	NS	NS	NS
R x C x I x H	0.4	NS	NS	NS	NS	NS	NS	NS	NS
M x C x I x H	NS	1.4	NS	NS	NS	NS	NS	NS	NS
R x M x C x I x H	NS	NS	NS	NS	NS	NS	NS	NS	NS

[†] NS, nonsignificant.

Table 23. Least significant differences (LSD) declared at $P \leq 0.10$ on corn grain yield, harvest index, yield components, and grain quality as affected by two crop rotations, two mechanical and three chemical residue managements, two input levels, and two hybrids at Champaign, Illinois during 2017 and 2018.

			Yield Component		**Grain quality**		
Source of variation	**Yield**	**Harvest Index**	**Kernel Number**	**Kernel Weight**	**Oil**	**Protein**	**Starch**
	bu acre^{-1}	%	seeds m^{-2}	mg seed^{-1}		%	
Rotation (R)	6.9	1.0	91	5.6	NS[†]	0.12	0.10
Mechanical (M)	5.4	NS	82	NS	NS	0.10	NS
R x M	NS	NS	NS	NS	NS	NS	NS
Chemical (C)	NS	NS	NS	NS	0.05	NS	0.12
R x C	NS	NS	110	NS	NS	NS	NS
R x M	NS	NS	NS	NS	NS	NS	NS
R x M x C	NS	NS	NS	NS	NS	NS	NS
Input Level (I)	3.5	0.6	56	2.3	NS	0.06	NS
R x I	NS	NS	NS	4.7	NS	0.10	NS
M x I	NS	NS	NS	NS	NS	NS	NS
R x M x I	NS	NS	NS	NS	NS	NS	NS
C x I	NS	NS	NS	NS	NS	NS	NS
R x C x I	NS	NS	NS	NS	NS	NS	NS
M x C x I	NS	NS	NS	NS	NS	NS	NS
R x M x C x I	NS	NS	NS	NS	NS	NS	NS
Hybrid (H)	3.5	0.6	58	2.3	0.04	0.06	0.10
R x H	NS	NS	NS	NS	NS	0.10	NS
M x H	NS	NS	84	NS	NS	NS	NS
R x M x H	NS	NS	NS	NS	NS	NS	NS
C x H	NS	NS	NS	NS	NS	NS	NS
R x C x H	NS	NS	NS	NS	NS	NS	NS
M x C x H	NS	NS	NS	NS	NS	NS	NS
R x M x C x H	NS	NS	NS	NS	NS	NS	NS
I x H	NS	NS	NS	3.2	0.06	NS	0.14
R x I x H	NS	NS	NS	NS	NS	NS	NS
M x I x H	NS	NS	NS	NS	NS	NS	NS
R x M x I x H	NS	NS	NS	NS	NS	NS	NS
C x I x H	NS	NS	NS	NS	NS	NS	NS
R x C x I x H	NS	NS	NS	NS	NS	NS	NS
M x C x I x H	NS	NS	NS	NS	NS	NS	NS
R x M x C x I x H	NS	NS	NS	NS	NS	NS	NS

[†] NS, nonsignificant.

Table 24. Least significant differences (LSD) declared at $P \leq 0.10$ on corn residue degradation for the setup field for the continuous corn trial conducted at Champaign, Illinois during 2017 and 2018.

Source of variation	**Residue Degradation**
	%
Rotation (R)	NS
Mechanical (M)	4
R x M	NS
Chemical (C)	NS
R x C	NS
M x C	NS
R x M x C	NS

[†]NS, nonsignificant.