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Hybrid Selection and Agronomic Management to Lessen the Continuous Corn Yield Penalty

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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, U.S.A. assessed the yield penalty associated with continuous corn verses 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 (79,000 verses 111,000 plants ha^{-1}) and eight different commercially-available hybrids were evaluated each year. Across all treatments, the CCYP was 1.53 and 2.72 Mg ha^{-1} in 2014 and 2015, respectively. Intensive agronomic management improved grain yield across rotations (2.17 Mg ha^{-1} in 2014 and 2.28 Mg ha^{-1} in 2015), and there was a 40 to 60% greater yield response to intensive management in continuous corn verses 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.

Keywords: continuous corn yield penalty (CCYP); corn-soybean rotation; hybrid; intensive management; maize; population

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1. Introduction

Crop rotation is a decision that can affect the productivity and profitability of agriculture production systems. Global trade tentions and crop demand can alter commodity prices that can allow grain price to offset 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 [1–10]. Factors primarily contributing to the continuous corn yield penalty (CCYP) are soil nitrogen availability or immobilization, residue accumulation, and the weather [9]. The consequence of adverse environmental effects are more determential on continuous corn grain yield than corn grown in rotation with soybean [9,11,12]. Environments with minimal rainfall have been documented to increase the magnitude of the CCYP [1,3,13,14], along with cooler than average spring temperatures [12], and excessive warmth during the summer [9,12]. 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 the stresses, such as those associated with increased plant population, reduced soil nitrogen, and low soil moisture [15–20]. Hybrids vary in their growth and yield response to different management factors, including crop rotation [2,21]. Yet, the greatest yield potential cannot be achieved with newer corn genetics unless grown at higher plant populations than older corn genetics [18,22]. Nitrogen (N) and phosphorus (P) use efficiency [23,24], water-use efficiency [25], 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 [17]. 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 [26] and is the most frequently limited nutrient for corn production [27]. After N, the second highest quantity of mineral nutrient acquired by corn during the growing season is potassium (K) [26]. Additionally, phosphorus (P) is the least mobile macronutrient and least available in the soil [28]; however, P has the highest nutrient removal rate from the field at harvest with corn grain [26]. Other nutrients found to limit U.S. Corn Belt yields are sulfur (S), zinc (Zn), and boron (B) [29–34].

A more recent tool for increasing grain yields is through foliar fungicide applications [35,36]. Strobilurin fungicides are effective against fungal pathogens that induce foliar fungal diseases in susceptible corn germplasm [37]. 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*) [38]. Residue accumulation can increase through continuous corn rotations [2,9], no- or reduced-tillage [39], higher plant density [40], and greater grain yields [41]. Furthermore, foliar protection by a strobilurin fungicide has also been documented to increase grain yield even when fungal disease is not present [35].

Intelligent 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 [5,42] and promote greater yields [43]. 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 verses soybean), at two population densities and crop management levels (standard verses 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.

2. Materials and Methods

2.1. Agronomic Practices

Field experiments were conducted in 2014 and 2015 at Champaign, IL, U.S.A. using a long-term site dedicated to crop rotation. Due to the rotation treatment in this study, two comparable field sites of approximately 2 ha each were established within 4.5 km of each other and 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 15-cm depth for 2014 and 2015 included, respectively, 39 and 41 g kg^{-1} organic matter, pH 6.1 and 5.5, 19 and 37.1 mg kg^{-1} P, and 101 and 126 mg kg^{-1} 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 vs. long-term corn following soybean rotation. The 11th and 13th year continuous corn were considered as similar treatments in line with other rotational experiments [3,14]. 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, 5.3-m in length with 76-cm spacing, and planted with a precision ALMACO SeedPro 360 research plot planter (Nevada, IA, USA). 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 input level and population at the sub-sub plot level.

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, USA].

Tillage included a chisel plow in fall with field cultivations in spring for entire seedbed preparation. Plots were planted on 27 April 2014 and 24 April 2015 to achieve an approximate final stand of 79,000 or 111,000 plants ha^{-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 0.11 kg a.i. ha^{-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, 202 kg N ha^{-1} as urea ammonium nitrate was applied to all plots and incorporated by shallow cultivation. The standard management treatment only received this N fertilizer. The additional products utilized in the intensive management system included additional fertilizer (containing N, P, K, S, Zn, and B) and a foliar fungicide application. Immediately prior to planting the intensive management plots, 112 kg P_2O_5 ha^{-1} was banded (10–15 cm beneath the row) by a toolbar fitted with Dawn Equipment 6000 Series Universal Fertilizer Applicators (Dawn Equipment, Sycamore, IL, USA) as MESZ [MicroEssentials SZ; 12-40-0-10S-1Zn] (The Mosaic Company, Plymouth, MN, USA) supplying an additional 34 kg N ha^{-1}, 28 kg S ha^{-1}, and 2.8 kg Zn ha^{-1}. Additionally at planting, 84 kg K_2O ha^{-1} was broadcast applied (Aspire, 0-0-58-0.5B, The Mosaic Company, Plymouth, MN, USA) supplying an additional 0.4 kg B ha^{-1}. At the V6 growth stage (six fully formed leaves), a side-dress application of 67 kg N ha^{-1} was applied to these plots as urea with urease inhibitors [$CO(NH_2)_2$ + n-(n-butyl) thiophosphoric triamide; Agrotain urea; 46-0-0] (Koch Agronomic Services, LLC, Wichita, KS, USA) on 6 June 2014 and 4 June 2015. When plants were approximately between the VT to R1 growth stages (tasseling to silk emergence) (6 June 2014 and 13 July 2015), intensive management plots received an application of Headline AMP (BASF, Florham Park, NJ, USA), 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 0.15 and 0.06 kg a.i. ha^{-1}, respectively. The fungicide was applied using a CO_2-pressurized backpack sprayer via an aqueous suspension at 140 L H_2O ha^{-1} and mixed with the surfactant MasterLock (WinField Solutions, LLC, St. Paul, MN, USA) at 0.45 kg ha^{-1}.

2.2. 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) [44]. 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 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, USA) 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 75 °C, 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, USA) and analyzed for moisture content using a moisture reader (Dickey John, GSF, Ankeny, IA, USA). 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 g kg^{-1} moisture concentration 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, USA), 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 [45].

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 0% 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.

2.3. Statistical Analysis

Biomass accumulation, leaf greenness, grain yield, and yield Fcomponents (kernel number and kernel weight) were analyzed using the PROC MIXED procedure [46]. All units are expressed on a 0 g kg^{-1} moisture concentration basis. 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.

3. Results and Discussion

3.1. 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, temperatures were below-average with above-average precipitation, particularly in June and July. 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 122.7 mm 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.

Table 1. Monthly weather data for Champaign, IL, USA 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).

Year	Month					
	April	May	June	July	Aug.	Sept.
			2014			
Temperature, °C	11.5 (0.4)	17.7 (0.8)	22.8 (0.4)	21.0 (−2.8)	23.0 (0.0)	18.1 (−0.9)
Precipitation, mm	100.1 (6.6)	111.3 (−13)	208.5 (98.3)	221.2 (101.9)	38.6 (−61.2)	87.4 (7.9)
			2015			
Temperature, °C	12.0 (1.1)	18.6 (1.7)	22.2 (−0.1)	23.0 (−0.8)	22.1 (−0.9)	21.0 (2.0)
Precipitation, mm	91.9 (−1.5)	154.2 (30.0)	232.9 (122.7)	107.2 (−12.2)	80.3 (−19.6)	163.6 (84.1)

3.2. 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 corn early season biomass accumulation with increased fertilizer inputs is well known [27,47]. 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.

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	<0.0001	0.0670	0.0121
Hybrid (H)	0.0015	0.0186	0.0827	<0.0001	<0.0001	<0.0001
R × H	0.0270	0.4260	0.1861	0.0057	0.0205	0.1536
Management (M)	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
R × M	0.4083	<0.0001	0.6366	<0.0001	0.0003	0.1309
H × M	0.1088	0.5741	0.4072	0.0971	0.4142	0.3174
R × H × M	0.0302	0.1897	0.7955	0.0665	0.1201	0.4127
Population (P)	<0.0001	<0.0001	0.0053	0.0093	0.0104	<0.0001
R × P	0.4215	0.0133	0.8181	0.2644	<0.0001	<0.0001
H × P	0.2080	0.7575	0.6459	0.0998	0.0635	0.5584
R × H × P	0.8140	0.7686	0.6102	0.8172	0.0474	0.0786
M × P	0.1084	0.2811	0.0919	0.6485	0.2868	0.4939
R × M × P	0.2410	0.0795	0.1966	0.6369	0.9993	0.7101
H × M × P	0.5074	0.5361	0.9915	0.6744	0.8588	0.9917
R × H × M × 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	<0.0001	<0.0001
R × H	0.5081	0.6912	0.7316	0.1713	0.0587	0.1215
Management (M)	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
R × M	0.1449	<0.0001	0.2669	0.0015	0.0013	0.0228
H × M	0.0223	0.0154	0.6895	0.4599	0.1188	0.0017
R v H × M	0.1975	0.3037	0.1246	0.2247	0.0265	0.6136
Population (P)	<0.0001	<0.0001	<0.0001	0.0026	<0.0001	<0.0001
R × P	0.4649	0.3326	0.5698	0.7829	0.9614	0.0960
H × P	0.5189	0.3828	0.5145	0.0997	0.1563	<0.0001
R × H × P	0.8911	0.2649	0.3833	0.0915	0.3801	0.2294
M × P	0.7745	0.5340	0.2152	0.0140	0.0025	0.6258
R × M × P	0.9055	0.6813	0.9914	0.2584	0.5078	0.3064
H × M × P	0.5882	0.3390	0.5763	0.9153	0.7468	0.7456
R × H × M × 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 g kg^{-1} moisture concentration.

		V6 Shoot Biomass				**R6 Stover Biomass**			
		Input Level §							
		Standard		**Intensive**		**Standard**		**Intensive**	
		Planting Density (× **1000 plants ha^{-1}**) ¶							
Rotation †	**Year/ Hybrid** ‡	**79**	**111**	**79**	**111**	**79**	**111**	**79**	**111**
		kg ha^{-1}							
Cont. Corn	**2014**								
	209-53STX	382	513	557	789	9561	11,180	12,710	12,118
	212-86STX	332	516	651	855	11,224	12,942	12,750	12,650
	DKC58-87	366	452	565	754	10,552	12,009	12,176	11,483
	DKC60-67	316	548	653	683	9276	10,774	11,711	12,037
	DKC62-08	391	570	852	864	12,038	11,061	12,357	10,543
	DKC63-33	407	417	741	874	9144	10,334	11,638	11,321
	DKC63-55	362	480	657	763	10,337	12,096	12,150	12,923
	DKC64-87	423	525	630	836	9170	11,226	11,331	13,034
	2014 Means	**372**	**503**	**663**	**802**	**10,163**	**11,453**	**12,103**	**12,014**
	2015								
	5415SS	279	332	661	931	8073	9337	9973	11,581
	5887VT3P	315	372	614	890	7728	8655	8743	9034
	5975VT3P	290	372	793	827	8500	8523	9303	10,623
	6065SS	310	379	719	986	9400	9705	11,717	11,205
	6110SS	333	400	843	1025	8628	7933	9640	10,652
	6265SS	421	587	963	1017	8799	8813	10,327	11,404
	6594SS	485	565	680	1036	7648	9130	9570	10,853
	6640VT3P	332	474	789	940	6849	7684	10,070	11,100
	2015 Means	**346**	**435**	**758**	**957**	**8203**	**8722**	**9918**	**10,806**
Corn-Soybean	**2014**								
	209-53STX	357	473	630	817	9082	9416	11,814	12,731
	212-86STX	321	402	671	809	10,769	11,096	11,438	12,962
	DKC58-87	322	407	559	684	10,771	11,601	11,637	12,728
	DKC60-67	315	370	598	751	9745	11,940	10,921	12,088
	DKC62-08	361	413	569	712	10,943	12,799	13,470	12,799
	DKC63-33	395	486	712	751	10,206	10,363	12,890	12,599
	DKC63-55	295	431	618	819	10,761	11,618	11,901	13,019
	DKC64-87	423	541	706	887	11,523	11,356	12,211	12,268
	2014 Means	**349**	**440**	**633**	**779**	**10,475**	**11,274**	**12,035**	**12,649**
	2015								
	5415SS	327	376	812	785	9210	9814	10,489	10,709
	5887VT3P	217	316	658	958	8525	8262	10,581	10,324
	5975VT3P	287	317	747	880	8264	8435	9160	11,466
	6065SS	269	376	651	829	9512	9942	11,232	11,547
	6110SS	336	361	747	921	8323	8907	8787	10,009
	6265SS	314	361	785	913	9018	9484	10,535	10,544
	6594SS	404	432	673	952	9054	8815	11,254	11,270
	6640VT3P	296	412	693	760	8896	9977	9882	11,789
	2015 Means	**306**	**369**	**721**	**875**	**8850**	**9205**	**10,240**	**10,957**

† Rotation V6 LSD ($p \leq 0.05$) = nonsignificant (NS) in 2014 and 54 kg ha^{-1} in 2015; Rotation R6 LSD ($p \leq 0.05$) = NS. ‡ Hybrid V6 LSD ($p \leq 0.05$) = 48 kg ha^{-1} in 2014 and 68 kg ha^{-1} in 2015; Hybrid R6 LSD ($p \leq 0.05$) = NS in 2014 and 900 kg ha^{-1} in 2015. § Input level V6 LSD ($p \leq 0.05$) = 19 kg ha^{-1} in 2014 and 34 kg ha^{-1} in 2015; Input level R6 LSD ($p \leq 0.05$) = 455 kg ha^{-1} in 2014 and 291 kg ha^{-1} in 2015. ¶ Plant density V6 LSD ($p \leq 0.05$) = 19 kg ha^{-1} in 2014 and 34 kg ha^{-1} in 2015; Plant density R6 LSD ($p \leq 0.05$) = 455 kg ha^{-1} in 2014 and 292 kg ha^{-1} in 2015.

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 [48]. 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 108 kg ha^{-1} and 127 kg ha^{-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). In 2014 and 2015, leaf greenness was 59.1 vs. 52.9 and 62.5 vs. 57.9 SPAD relative units from corn-soybean rotation vs. continuous corn, respectively (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 the hybrids, the least leaf greenness was measured in continuous corn cultivated with standard agronomic management and the higher planting density.

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/	**Plant Density (plant ha^{-1}) ¶**							
Hybrid †	**79,000**	**111,000**	**79,000**	**111,000**	**79,000**	**111,000**	**79,000**	**111,000**
	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.

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 [49]. Leaf chlorophyll concentration, photosynthetic potential of the plant, and leaf N nutrient status are closely related [50–52]. These treatment-induced differences in leaf chlorophyll resulting from cropping system and management level changes suggest that N uptake and N availability play a key role 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 4). 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 32,000 plants ha^{-1} and resulted in increased overall biomass production per area (Table 4). Conversely, individual plants' R6 stover accumulation at the two populations were 139 and 125 g plant^{-1} when grown at 79,000 plants ha^{-1} compared to 110 and 100 g plant^{-1} when grown at 111,000 plants ha^{-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 [53]. 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.

3.3. 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 1.53 Mg ha^{-1} (−13%; $p < 0.0001$) in 2014 and 2.72 Mg ha^{-1} (−22%; $p = 0.0018$) in 2015 (Table 5). Although increased planting densities decreased yield by an average of 0.19 and 0.36 Mg ha^{-1} in 2014 and 2015, respectively, the continuous corn rotation did not magnify this response as originally predicted. Unexpectedly, the yield reduction associated with increased planting densities tended to be greater in the corn-soybean rotation vs. continuous corn. The increased inter-plant competition of higher planting densities tended to reduce corn yield more when grown under standard management (−0.22 Mg ha^{-1} in 2014 and −0.65 Mg ha^{-1} in 2015) compared to when grown under the high input management (−0.16 Mg ha^{-1} in 2014 and −0.06 Mg ha^{-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 (2.17 and 2.28 Mg ha^{-1} in 2014 and 2015, respectively), but the effect was 40–60% greater in continuous corn vs. the corn-soybean rotation (2.65 vs. 1.69 Mg ha^{-1} in 2014 and 2.67 vs. 1.90 Mg ha^{-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 [1,27,54]. These data indicate that the continuous corn yield penalty can be ameliorated with agronomic management. Although the highest yields were consistently achieved in the corn-soybean rotation using intensive management and low 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 1). The CCYP was reduced by 0.89 to 1.93 Mg ha^{-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%).

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 0 g kg^{-1} moisture concentration.

	Crop Rotation ‡							
	Continuous Corn				**Corn-Soybean**			
	Input Level §							
	Standard		**Intensive**		**Standard**		**Intensive**	
	Plant Density (plant ha^{-1}) ¶							
Year/ Hybrid †	**79,000**	**111,000**	**79,000**	**111,000**	**79,000**	**111,000**	**79,000**	**111,000**
	Mg ha^{-1}							
2014								
209-53STX	9.65	9.81	12.60	12.62	11.59	10.82	12.93	13.02
212-86STX	8.71	8.52	11.67	12.13	10.69	11.27	12.99	12.11
DKC58-87	8.44	8.60	11.20	11.23	10.75	11.16	12.38	13.13
DKC60-67	9.46	9.00	11.76	12.11	11.10	10.61	12.58	12.63
DKC62-08	8.00	8.10	9.84	9.27	10.32	9.59	11.86	11.50
DKC63-33	9.04	8.80	11.59	11.23	11.56	11.10	13.23	12.89
DKC63-55	8.75	8.55	11.53	11.04	10.48	10.05	11.90	11.39
DKC64-87	9.25	9.07	12.37	12.04	11.88	11.05	13.48	13.05
2014 Means	**8.92**	**8.81**	**11.57**	**11.46**	**11.04**	**10.71**	**12.67**	**12.47**
2015								
5415SS	9.46	8.05	11.42	11.40	10.74	10.88	13.03	12.97
5887VT3P	9.15	7.08	10.57	9.66	11.63	9.83	13.07	12.80
5975VT3P	8.24	7.97	11.23	10.44	11.44	10.16	13.49	12.94
6065SS	9.82	9.62	11.24	12.27	11.68	11.06	13.37	13.30
6110SS	10.01	9.09	11.68	12.19	12.05	12.58	13.47	13.53
6265SS	7.73	6.75	10.71	10.01	12.02	12.31	13.46	13.72
6594SS	7.85	8.58	11.10	11.69	12.08	10.48	13.84	13.74
6640VT3P	6.91	5.99	9.14	10.21	11.51	11.43	13.33	12.20
2015 Means	**8.65**	**7.89**	**10.89**	**10.98**	**11.64**	**11.09**	**13.38**	**13.15**

† Hybrid LSD ($p \leq 0.05$) = 0.35 Mg ha^{-1} in 2014 and 1.05 Mg ha^{-1} in 2015. ‡ Rotation LSD ($p \leq 0.05$) = 0.06 Mg ha^{-1} in 2014 and 0.81 Mg ha^{-1} in 2015. § Input level LSD ($p \leq 0.05$) = 0.14 Mg ha^{-1} in 2014 and 0.23 Mg ha^{-1} in 2015. ¶ Plant density LSD ($p \leq 0.05$) = 0.14 Mg ha^{-1} in 2014 and 0.23 Mg ha^{-1} in 2015.

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 [23,55,56]. 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 kernel weight.

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 g kg^{-1} moisture concentration.

		Kernel Number				**Kernel Weight**			
		Input Level §							
		Standard		**Intensive**		**Standard**		**Intensive**	
		Planting Density (× 1000 plants ha^{-1}) ¶							
Rotation †	**Year/ Hybrid** ‡	**79**	**111**	**79**	**111**	**79**	**111**	**79**	**111**
		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.

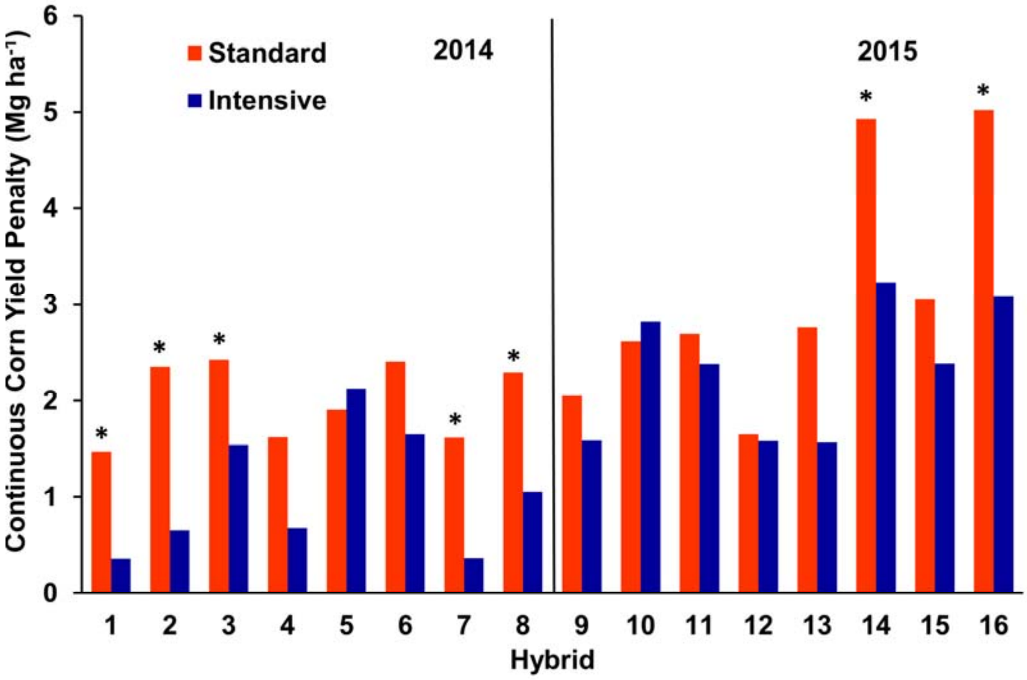

Figure 1. The yield penalty (yield difference between corn-soybean and continuous corn rotation) as influenced by two levels of management (standard vs. intensive) at Champaign, IL during 2014 (hybrids 1–8) and 2015 (hybrids 9–16). Hybrids 1–16 follow the order hybrids were presented in Tables 3–6. Values 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.

When combined, the 40–60% greater yield response in continuous corn vs. corn-soybean rotation when grown with high input management was linked to a greater production in the amount and weight of those kernels. When plants in continuous corn were cultivated 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 [57]. 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 kernels at V6, with the number of ovules (potential kernels) and the size of the ear set at V12 (12 leaves) [44]. Kernel number can be altered by the quality of pollination or through kernel abortion in response to any stress from environmental conditions or plant competition [58]. Later in the season, the size of the individual kernels is set (R2) followed by the expansion and filling of those kernels with starch [44]. Rotation of corn with soybean increased the grain-filling period or 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 [9,49], which influences both the production and size of kernels [59].

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. Kernel number produced per area was greater at the plant population that resulted in more grain yield. While individual kernel number per plant has been found to be reduced as plant population was increased, there was, however, a greater kernel number per unit area produced as a result of more harvestable ears at the higher plant population [60].

3.4. 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. 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 [61]. 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 [43]. 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.

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.

Corn Parameter	2014		2015	
	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.

4. 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.

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