Identifying Factors Controlling the Continuous Corn Yield Penalty

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ABSTRACT

It is widely accepted that yields decline when corn (*Zea mays* L.) is grown continuously vs. in rotation with soybean [*Glycine max* (L.) Merr.], although causes for the yield reduction are unclear. The primary objective of this study was to elucidate the source(s) of the continuous corn yield penalty (CCYP). The experiment was conducted from 2005 to 2010 in east-central Illinois beginning with third-year continuous corn (CC) or a soybean–corn (SC) rotation at six N fertilizer rates. Averaged across all years, yield at the agronomic optimum N rate for CC was 8.84 Mg ha^{-1} and for SC was 10.20 Mg ha^{-1}, resulting in a CCYP of 1.36 Mg ha^{-1}; values ranged yearly from 0.47 to 2.23 Mg ha^{-1}. Using a regression model, three significant and independent predictors explained >99% of the variability in the CCYP: unfertilized CC yield (0NCCYD), years in CC (CCYRS), and the difference between CC and SC delta yields (maximum yield – unfertilized yield) (DELTADIFF). The strongest predictor, 0NCCYD, reflects net soil N mineralization and demonstrates that it decreases in CC systems. The CCYRS was strongly and positively correlated with CCYP, indicating that the CCYP increased through Year 7. We believe that CCYRS measures the effects of accumulated corn residue in CC systems. Finally, we consider DELTADIFF to be a measure of the interaction between yearly weather patterns and crop rotation, which results in more negative yield responses for CC than SC under hot or dry conditions. This study concluded that the primary causative agents of the CCYP are N availability, corn residue accumulation, and weather.

The USDA-Economic Research Service's Regional Environmental and Agriculture Programming (REAP) model predicts that CC—i.e., planting corn on the same land for three or more consecutive years—will account for 30% of the total U.S. corn hectares by 2015 according to the baseline ("business as usual") scenario and as much as 50% of corn hectares under the 57 billion L biofuel scenario presented by the enactment of the Energy Independence and Security Act (EISA) of 2007 (Malcolm et al., 2009). The EISA mandate has substantially increased domestic demand for corn grain. Meeting the EISA biofuel targets without loss of livestock, animal feedstock, or grain for human consumption will require additional increases in corn production on existing farmland (Mehaffey et al., 2012). If projected increases for corn demand are substantiated, CC production will inevitably increase.

Studies conducted during the past 40 yr have clearly established that yields are less when corn is grown continuously relative to a cropping rotation. The reduction in grain yields observed in CC systems is not clearly understood. This study was conducted to elucidate the source(s) of the yield loss commonly observed when corn is grown continuously relative to SC, a yield difference we designate as the CCYP. A greater understanding of the agents and mechanisms underlying the CCYP is needed as a result of domestic and international issues that are increasing the demand for U.S. corn grain.

In a summary of 28 U.S. studies comparing CC with SC, Erickson (2008) determined that all but two studies resulted in a yield decrease for CC, with reductions ranging from 2 to 19%. Porter et al. (1997) combined data from 29 site-years in the northern Great Plains and determined that corn yields from SC rotations yielded 13% greater than CC systems. In a 4-yr study conducted by Peterson and Varvel (1989) in eastern Nebraska under rainfed conditions, corn yields were 29% greater for SC than for CC. Additionally, in a 16-yr study conducted in southeastern Nebraska under rainfed conditions, Wilhelm and Wortmann (2004) measured 22% greater yield for SC than CC.

Nitrogen availability is often thought to play the dominant role in explaining the CCYP (Shrader et al., 1966; Baldock and Musgrave, 1980; Stanger and Lauer, 2008). Corn residue management, which affects plant-available N among other things, can also control the CCYP. The larger C/N ratio of corn residues and the greater quantity of biomass remaining after corn harvest compared with soybean production explains observations of reduced net soil N mineralization in CC systems (Kaboneka et al., 1997; Gentry et al., 2001). Additionally, increased residue-induced N immobilization (Varvel and Peterson 1990; Kaboneka et al., 1997) and differences in the timing of immobilization (Green and Blackmer, 1995) may also explain differences in N fertilizer

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Abbreviations: 0NCCYD, unfertilized continuous corn yield; AONR, agronomically optimum nitrogen rate; CC, continuous corn; CCYP, continuous corn yield penalty; CCYRS, years in continuous corn; DELTADIFF, difference between continuous corn and soybean–corn rotation delta yields; SC, soybean–corn rotation.

requirements between CC and SC systems. Because of the unpredictable nature of organic N mineralization, growers often apply an additional 45 kg N ha^{-1} or more to assure sufficient crop N availability in CC systems (Blackmer et al., 1997; Ding et al., 1998).

Although N availability is a critical factor for managing CC systems, the following issues have also been demonstrated to exacerbate the CCYP: reduced seed germination or seedling emergence and other establishment issues (Wilhelm and Wortmann, 2004), impoverished rhizosphere microorganism community (Vanotti and Bundy, 1995), increased sensitivity to weather stressors (Varvel, 1994; Wilhelm and Wortmann, 2004), and autotoxicity (Yakle and Cruse, 1983; Anderson and Cruse, 1995). Before the release of genetically engineered insect resistance and glyphosate [*N*-(phosphonomethyl)glycine] tolerance traits, some studies concluded that reduced stress from pests was a factor in improved yield from crop rotations (Peterson and Varvel, 1989; Varvel and Peterson, 1990). Excellent weed control and biotechnological trait resistance to the most challenging insect pests in modern corn production systems makes it unlikely that pests are a primary cause of reduced yields in CC systems.

Crop breeding innovations (e.g., herbicide and insect resistance traits) and agricultural technology advancements (e.g., reduced tillage, equipment guidance technology, less biotoxic chemicals) have made it possible to produce corn in monoculture with fewer negative environmental consequences than just a decade ago (Haney et al., 2000; Busse et al., 2001; Hart et al., 2009); however, there are still concerns associated with corn monoculture. Water quality degradation is a concern because CC requires yearly N fertilizer application rates 45 to 60 kg N ha^{-1} greater than corn in SC rotations (Blackmer et al., 1997; Ding et al., 1998). Insecticide use also increases when corn is planted continuously, particularly in countries where corn hybrids with genetically modified insect-resistance traits are not grown. Many plant diseases (e.g., gray leaf spot, northern corn leaf blight, anthracnose leaf blight, seedling rots) pose greater problems in CC systems, especially when residue remains in place through the winter (Thomison et al., 2011). Weeds are a greater challenge to manage in monoculture than in diverse crop rotations, resulting in greater use of herbicides. Although direct evidence is lacking, corn monocultures are generally thought to reduce soil biological diversity, potentially causing a reduction in or loss of biocontrol services and creating greater need for pesticides (Landis et al., 2008).

Despite these concerns regarding corn monocultures, and particularly considered within the context of the strain placed on global food security systems by a burgeoning human population (Cassman, 1999; Keyzer et al., 2005; Lobell et al., 2009), there are a number of reasons to reconsider the value of CC in combination with appropriate management practices. As a C_4 plant, corn is well adapted for growth in high-light, high-heat environments, allowing greater grain production from corn than the other major U.S. commodity crops under the climatic conditions of the country's most agriculturally productive region, the Midwest. For example, typical yields for soybean, the second most commonly grown crop in the United States, are only 28 to 34% of corn yields (Egli, 2008; National Agricultural Statistics Service, 2012). Corn is versatile in terms of its use potential; both grain and stover are used for animal feed and show promise as bioenergy feedstocks. Corn is also receptive to breeding efforts, both traditional and transgenic, making it possible to create hybrids adapted to a range of environmental conditions and resistant to a variety of pests and diseases (Duvick, 2005). Hybrid improvements, increased plant populations, greater N fertilizer rates, and other management practices have resulted in a nearly sevenfold increase in corn yields since 1924 (Duvick, 2005) and an annual yield growth rate of about 1.5% since 1970 (Egli, 2008).

Without a better understanding of the CCYP, it is possible that previous and future advancements in corn yield potential will be underutilized, being partially canceled out by the reduction in yield resulting from CC production. The objectives of this study were (i) to quantify the CCYP relative to SC during 7 yr in the highly productive soils of Illinois, (ii) to evaluate the effect of N fertilizer on the CCYP and identify the conditions under which additional N can alleviate the penalty, (iii) to track the CCYP with time in CC culture, and (iv) to construct a model identifying significant factors controlling the CCYP.

MATERIALS AND METHODS

Due to the rotation treatment in this study, two comparable field sites of approximately 2 ha each were established at the University of Illinois Crop Sciences Research and Education Center in Champaign, IL. Sites were located 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 study alternated between the two field sites each year. The setup site (the site not used for the current year) established the whole blocks of corn and soybean that served as the previous crop for the following year's rotation treatment. The corn and soybean blocks in the setup site were maintained through maturity, harvested, and tilled in preparation for the upcoming year's study. Reported treatments were arranged in a split plot in a randomized complete block design with four replications; rotation was the main plot and N fertilizer rate was the subplot. An experimental unit was the center two rows of a four-row plot (rows 4.58 m long, spaced 76 cm apart).

Both sites had acceptable soil pH levels and adequate P and K levels throughout the study according to Vitosh et al. (1995). To normalize residual soil N levels from one study year to the next, corn planted during the setup year received a modest N rate of 112 kg N ha^{-1} before planting; no N fertilizer was applied to soybean crops. The study was chisel plowed uniformly across all treatments each fall and lightly cultivated in spring to provide an adequate seedbed. For the years 2006 to 2009, S-metolachlor [2-chloro-*N*-(2-ethyl-6-methylphenyl)-*N*-[(1*S*)-2-methoxy-1-methylethyl]acetamide] was applied before planting for early-season and residual weed control, and a post-emergence application of mesotrione (2-[4-(methylsulfonyl)-2-nitrobenzoyl]-1,3-cyclohexanedione) was made in mid-June. In 2010, Lumax (S-metolachlor, atrazine [6-chloro-*N*-ethyl-*N′*-(1-methylethyl)-1,3,5-triazine-2,4-diamine], and mesotrione) was applied preplant and incorporated followed by an in-season (V8 growth stage, Abendroth et al., 2011) application of glyphosate. Aztec soil insecticide (tebupirimfos

Table 1. Treatment levels and management details for each year of the study, 2005 to 2010. Crop rotation was continuous corn (CC) or soybean–corn (SC); the length of time in CC is indicated. Corn hybrids used were commercially available and ranged from 107- to 115-d relative maturity. Six N fertilizer rates were used each year, but specific rates varied from year to year.

Year	Crop rotation	Hybrids†	N fertilization rate	N source(s)‡	Timing
		no.	kg N ha^{-1}		
2005	3rd yr CC and SC	22§	0, 34, 67, 134, 202, 269	$(NH_4)_2SO_4$	spring
2006	3rd yr CC and SC	12¶	0, 56, 112, 168, 224, 280	$(NH_4)_2SO_4$	spring
2007	5th yr CC and SC	4††	0, 56, 112, 168, 224, 280	$(NH_4)_2SO_4$	spring
2008	5th yr CC and SC	15‡‡	0, 56, 112, 168, 224, 280	$(NH_4)_2SO_4$	spring
2009	7th yr CC and SC	1§§	0, 45, 90, 134, 179, 224	$(NH_4)_2SO_4$, ESN, SuperU, urea	fall, spring
2010	7th yr CC and SC	1§§	0, 45, 90, 134, 179, 224	ESN, SuperU, urea	spring

† Hybrids for each year; relative maturity ratings and transgenic traits (where available) in parentheses are provided below.

‡ ESN is a polymer-coated N; SuperU is a urea-based fertilizer containing urease and a nitrification inhibitor.

§ Agrigold: 6417 (107), 6467 (110), 6617 (115); Becks: 5627 (111), 5827 (111), 6827 (114); Burrus 442 (108); DeKalb 63-78 (113); FS: 6735 (113), 6996 (112); Golden Harvest: H-8620 (108), H-8920 (110), H-9166 (113); Pioneer: 31N27 (118), 32D12 (114), 32K22 (116), 33J24 (112), 33K39 (113), 33N09 (114), 34H31 (109); Wyffels: W8540 (114), W8720 (115). Hybrids used in 2005 were mostly RR2 (herbicide tolerant only) or RR2/YGCB (herbicide and corn borer tolerant).

¶ Asgrow: RX655 (107, RR2), RX756 (112); DeKalb 57-79 (107, RR2/YGPL), 58-80 (108, RR2/YGCB), 60-17 (110, RR2), 60-18 (110, RR2/YGPL), 60-19 (110, RR2/YGCB), 61-22 (111, RR2), 61-45 (111, RR2/YGCB) 63-74 (113, RR2/YGPL), 64-77 (114, YGPL); Pioneer 33N11 (114, HX1).

†† Asgrow RX756 (112); DeKalb: 60-18 (110, RR2/YGPL), 63-74 (113, RR2/YGPL), 57-79 (107, RR2/YGPL).

‡‡ Agrigold: A6457 (110, VT3), A6639 (115, VT3); Asgrow RX785 (113, RR2/YGPL); Becks: 5387 (110, RR2), 6733 (114, HXX); DeKalb: 61-19 (111, VT3), 61-69 (111, VT3), 62-29 (112, VT3), 64-24 (114, VT3), 65-44 (115, VT3); Pioneer: 32B83 (115, RR2/HXX), 33D14 (113, RR2/HXX), 33F88 (114, RR2/HXX), 33H29 (115, RR2/HXX), 33W84 (111, RR2/HXX).

§§ DeKalb 62-54 (112, VT3).

[*O*-[2-(1,1-dimethylethyl)-5-pyrimidinyl] *O*-ethyl *O*-(1-methylethyl) phosphorothioate] and cyfluthrin [cyano(4-fluoro-3-phenoxyphenyl)methyl 3-(2,2-dichloroethenyl)-2,2-dimethylcyclopropanecarboxylate]) was applied at planting (at 3.4 kg ha^{-1}) for corn rootworm and other early insect control. Notable rootworm damage was not encountered during the course of the study.

Specific information about the experimental treatments can be found in Table 1. For 2005 through 2008, the treatments consisted of rotation, N fertilizer rate, and hybrid. Nitrogen was applied as granular $(NH_4)_2SO_4$ at the V3 growth stage (Abendroth et al., 2011) in a diffuse band in the center of the row and incorporated. The types and number of hybrids tested varied from year to year; for each year, 2005 to 2008, 22, 12, 4, and 15 commercial hybrids, respectively, were tested. The hybrid effect was nonsignificant in all years ($P > 0.3$) and no hybrid interactions were significant so all data were averaged across this variable. In 2009, treatments consisted of rotation, N fertilizer application rate, N source, and N fertilizer application timing (spring and fall application). The N source treatment compared $(NH_4)_2SO_4$, urea, and two controlled-release N fertilizers, ESN (a polymer-coated urea) and SuperU (a urea-based fertilizer containing urease and a nitrification inhibitor). There were no significant effects for N source ($P = 0.83$), N timing ($P = 0.84$), or related interactions, so the data were averaged across these treatments. In 2010, treatments consisted of rotation, N fertilizer application rate, and N source. Nitrogen source treatments for this year consisted of urea, ESN, and SuperU. There were no treatment effects for N source ($P = 0.37$) or related interactions, so all data were averaged across N source.

Planting dates were 18 Apr. 2005, 26 Apr. 2006, 20 Apr. 2007, 20 May 2008, 12 May 2009, and 1 June 2010. Plant population density was 79,040 plants ha^{-1}. Seeds were overplanted in 2005 and 2006 and plots were thinned to achieve the correct population density. In all other years, plots were planted with a precision Almaco plot planter and plant populations were confirmed with stand counts recorded at the R1 and R6 plant growth stages (Abendroth et al., 2011). For grain yield determination at physiological maturity, plots were harvested by hand in 2006 and with a two-row combine all other years (the middle two rows were harvested). Ears were shelled, measured for moisture, and weighed to determine plot yields; grain yields (reported in Mg ha^{-1}) were adjusted to 0% moisture.

Table 2. Analysis of variance for grain yield for year, previous crop, and N fertilizer rate.

Source of variation	$P > F$
Year	–
Previous crop	<0.0001
N fertilizer rate	<0.0001
Year × previous crop	<0.0001
Year × N fertilizer rate	<0.0001
Previous crop × N fertilizer rate	<0.0001
Year × previous crop × N fertilizer rate	0.0347

An analysis of variance was conducted on the grain yield data (Table 2). For this analysis, year and replicate were declared random effects and the previous crop (corn or soybean) and N rate were declared fixed effects. A significance level of 0.10 was used throughout our statistical analysis, except where indicated for model development.

An N rate by yield response function was fitted to the data using the PROC REG and PROC NLIN procedures in SAS (SAS Institute, 2008). We evaluated response models for best fit in the following order: linear, quadratic, and linear-plateau. Best fit was determined by testing the significance of the increase in the coefficients of determination between models. Agreement between the fitted function and data was generally good, as measured by the coefficient of determination (average $R^2 = 0.63$, median $R^2 = 0.70$, range = 0.36–0.82). The agronomically optimum N rate (AONR) was determined by identifying the "hinge point" in linear-plateau models (2005) and by taking the first derivative of the quadratic equation in the quadratic functions (2006, 2007, and 2008). In the linear models (2009 and 2010), we set the maximum N rate as the AONR to evaluate the CCYP. The CCYP was calculated by subtracting the yield at the AONR for CC from that for SC treatments (Eq. [1]):

$$\text{CCYP} = \text{Yield}_{\text{AONR(SC)}} - \text{Yield}_{\text{AONR(CC)}} \qquad [1]$$

Because the CCYP was calculated from values obtained from regression equations (AONR is a value determined by regressing N rates on corn grain yield), there is no issue with differing N rates among years of the study.

We constructed a model that identified significant predictors of the CCYP from among the following 11 factors (Table 3): CCYRS, CC AONR, SC AONR, yield of CC at the AONR, yield of SC at the AONR, 0NCCYD, SC yield without N fertilizer (0NSCYD), CC delta yield (maximum yield minus 0N yield), SC delta yield, the difference between CC delta yield and SC delta yield (DELTADIFF), and modified growing degree days (MGDD) accumulated from the planting date through 15 September for each year as calculated by Gilmore and Rogers (1958).

Forward and fully stepwise regressions were performed on the potential predictors with SAS (version 9.2) using the regression procedure. In the forward regression, the method calculates the *F* statistic of each potential independent variable (predictor) reflective of the variable's contribution to the model, if included (SAS Institute, 2008). To enter the model, *P* values for the *F* statistics are compared with the statistical criterion for entry (we set the value at 0.15); if no *F* statistic has a *P* value less than the criterion, the forward selection stops. Otherwise, the selection adds the variable with the smallest *P* value (equivalently, the largest *F* statistic) to the model (Fomby, 2005). The method then calculates the *F* statistics again for those variables not included in the model, and the evaluation process is repeated until no remaining potential predictors produce an eligible *F* statistic according to the statistical criterion.

In the fully stepwise regression, the process begins as in the forward regression, but with each addition of a predictor to the model, those variables already in the model are evaluated for removal. We again set the statistical criterion for entry to be $P < 0.15$ for the *F* value associated with addition of the variable into the model; we set the criterion for remaining in the model at $P < 0.15$ as well. Thus, if a variable is added to the model but, after addition of more variables, is found to be less predictive of the CCYP ($P < 0.15$), probably due to redundancy with the newly added variable, that variable is removed from the model. It can, however, be added back into the model at a later time if it is found to again produce a significant *F* statistic. The stepwise process ends when there are no remaining variables outside of the model with an *F* statistic that meets the statistical criterion for entry into the model (SAS Institute, 2008).

RESULTS AND DISCUSSION

Yearly seasonal weather patterns influenced corn yields (Table 4), response to the previous crop, and response to the N fertilizer application rate (Table 2). Corn yields were reduced in 2005 by drought conditions and mean temperatures in June and August that were almost 2°C greater than average, resulting in symptoms of water stress. The 2006 growing season was favorable despite below-average precipitation for May, June, August, and September; above-average rainfall amounts in July were timely and provided needed moisture during critical grain-fill periods. The 2007 growing season was also one of below-average precipitation with the exception of June; August and September were particularly hot and dry and resulted in stressful conditions for grain fill. In 2008, temperatures were near average and rainfall was above average for June, July, and September; August received below-average precipitation. The 2009 growing season had above-average rainfall and below-average temperatures, resulting in a poor growth environment and favorable conditions for NO_3 leaching and denitrification. In 2010, growing-season conditions were generally hot and dry with the exception of June, when precipitation levels were about 50% above average.

The analysis of variance (Table 2) demonstrated that all treatments and treatment interactions were highly significant. Response to the N fertilizer application rate varied from year to year as a result of seasonal weather patterns and consequent crop growth potential (Table 2). Crop growth was limited in 2005 due to heat and drought stress, resulting in a linear-plateau response to N fertilizer (Fig. 1). A strong quadratic response to fertilizer in 2006 resulted from favorable weather conditions that supported high yields. The 2006 growing season was the only year in which the CC treatment effectively overcame the CCYP at greater N fertilizer application rates. The 2007 and 2008 response curves were similar in their quadratic responses to N fertilizer application. Wessel et al. (2007) conducted a study in the same location as the present experiment, demonstrating that N fertilizer application to corn was susceptible to losses when spring rainfall was above average. We speculate that NO_3 loss via leaching or denitrification was the result of above-average spring precipitation in 2009;

Table 3. Yield measurements, agronomic optimum N rate (AONR), and potential yield predictors for corn grown as continuous corn (CC) or in a soybean–corn (SC) rotation. For CC treatments, the number of years of continuously grown corn (CCYRS) is indicated. Also included are the continuous corn yield penalty (CCYP), Δ yield (maximum yield – unfertilized N yield), the difference between SC Δ yield and CC Δ yield (DELTADIFF), modified growing degree days (MGDD) accumulated from planting through 15 September each year, and the single-factor coefficient of determination (R^2) with CCYP.

Year	CCYRS	AONR		Yield at AONR			Yield without N		Δ Yield			
		CC	SC	CC	SC	CCYP	CC	SC	CC	SC	DELTADIFF	MGDD
	yr	kg ha^{-1}		Mg ha^{-1}								
2005	3	111.0	95.0	5.89	6.90	1.01	4.57	5.86	1.36	1.20	0.16	3546
2006	3	252.2	219.5	11.60	12.07	0.47	6.48	7.38	5.12	4.58	0.54	3135
2007	5	217.2	245.8	10.33	11.59	1.26	5.30	8.59	4.89	3.11	1.78	3795
2008	5	280.0	223.8	9.21	10.70	1.49	4.50	6.77	4.91	3.91	0.99	2915
2009	7	224.0	224.0	8.96	10.68	1.72	4.13	6.42	4.77	4.22	0.55	2766
2010	7	224.0	224.0	7.04	9.27	2.23	3.53	8.08	3.15	1.08	2.07	3403
R^2	0.834	0.017	0.081	0.232	0.046	1.000	0.845	0.036	0.123	0.168	0.372	0.025

Table 4. Average monthly temperature and precipitation for the 2005 to 2010 growing seasons. Values were obtained from the NOAA National Weather Service forecast office for the Urbana, IL, Weather Station 118740 (40.05 latitude, –88.14 longitude, elevation 220 m asl).

Year	April	May	June	July	August	September
			Temperature, °C			
2005	12.6 (2.0)†	16.3 (–0.6)	23.9 (1.9)	24.5 (0.7)	24.3 (1.7)	21.6 (2.7)
2006	13.6 (3.0)	16.7 (–0.2)	21.9 (–0.1)	24.8 (1.1)	23.3 (0.7)	17.7 (–1.2)
2007	10.2 (–0.4)	20.1 (3.2)	23.1 (1.1)	22.7 (–1.1)	25.7 (3.0)	21.6 (2.7)
2008	10.7 (0.1)	14.7 (–2.2)	22.9 (0.9)	23.2 (–0.6)	22.3 (–0.4)	19.7 (0.8)
2009	10.7 (0.1)	17.4 (0.5)	23.7 (1.7)	21.1 (–2.7)	21.4 (–1.3)	19.3 (0.4)
2010	14.5 (3.9)	18.1 (1.2)	23.8 (1.8)	25.0 (1.2)	25.1 (2.4)	19.7 (0.8)
			Precipitation, mm			
2005	101 (8)	25 (–97)	61 (–45)	109 (–9)	57 (–54)	144 (62)
2006	112 (19)	78 (–44)	42 (–65)	199 (81)	76 (–35)	34 (–48)
2007	62 (–31)	41 (–81)	144 (37)	87 (–31)	38 (–73)	52 (–29)
2008	76 (–16)	154 (32)	163 (56)	200 (82)	20 (–91)	207 (125)
2009	176 (84)	145 (23)	112 (5)	160 (41)	143 (32)	20 (–61)
2010	53 (–40)	87 (–35)	212 (105)	95 (–23)	42 (–69)	81 (–1)

† Values in parentheses are the deviation from the 30-yr monthly average (1981–2010).

the N-limiting conditions resulting from fertilizer N loss produced the strong yield responses to N fertilizer application (Fig. 1), evidenced by linear yield responses with steep slopes, demonstrated similarly by both CC and SC. The linear model was again the best fit for the N fertilizer response data in 2010 as a result of poor growth conditions due to drought stress.

Continuous corn produced less grain at the AONR than SC for every year of the study, resulting in a yield penalty for CC every year (Table 3). Averaged across all 6 yr, yield at the AONR for CC was 8.84 Mg ha^{-1} and for SC was 10.20 Mg ha^{-1}, resulting in a CCYP of 1.36 Mg ha^{-1} (25.6 bu acre^{-1}); CCYP values ranged yearly from 0.47 to 2.23 Mg ha^{-1} (8.9–42.0 bu acre^{-1}). In all years except 2007, the AONR was greater for CC than SC despite the lower yield of CC at the AONR (Table 3). It is widely recognized that corn grown in rotation with legume crops requires less fertilizer N than CC systems to reach maximum yields (Shrader et al., 1966; Peterson and Varvel, 1989; Meese et al., 1991; Varvel and Wilhelm, 2003). There is some disagreement among researchers regarding whether the CCYP is a simple function of N availability (Shrader et al., 1966; Baldock and Musgrave, 1980; Stanger and Lauer, 2008) or the product of a number of interacting factors (Baldock et al., 1981; Hesterman et al., 1987; Bergerou et al., 2004). Our data support the latter argument, demonstrating that although N availability is a critical factor for determining the magnitude of the CCYP in a given year, factors related to weather and crop residue accumulation (independent of the effect of residue on N availability) also contribute to the yield difference between CC and SC systems.

Potential predictors of the CCYP selected to test in this study are shown in Table 3 along with single-factor coefficients of determination (R^2). The best single predictors of CCYP were 0NCCYD ($R^2 = 0.84$) and CCYRS ($R^2 = 0.83$). The two next-best predictors of CCYP were DELTADIFF ($R^2 = 0.37$) and CC yield at the AONR ($R^2 = 0.23$).

To investigate the agents of the CCYP, we performed forward and stepwise regressions of the potential predictors of the CCYP. Both analyses produced the same model, selecting three variables to predict CCYP: 0NCCYD, CCYRS, and DELTADIFF (Table 5). With these three variables, the model R^2 was 0.9966 and the model was (Eq. [2]):

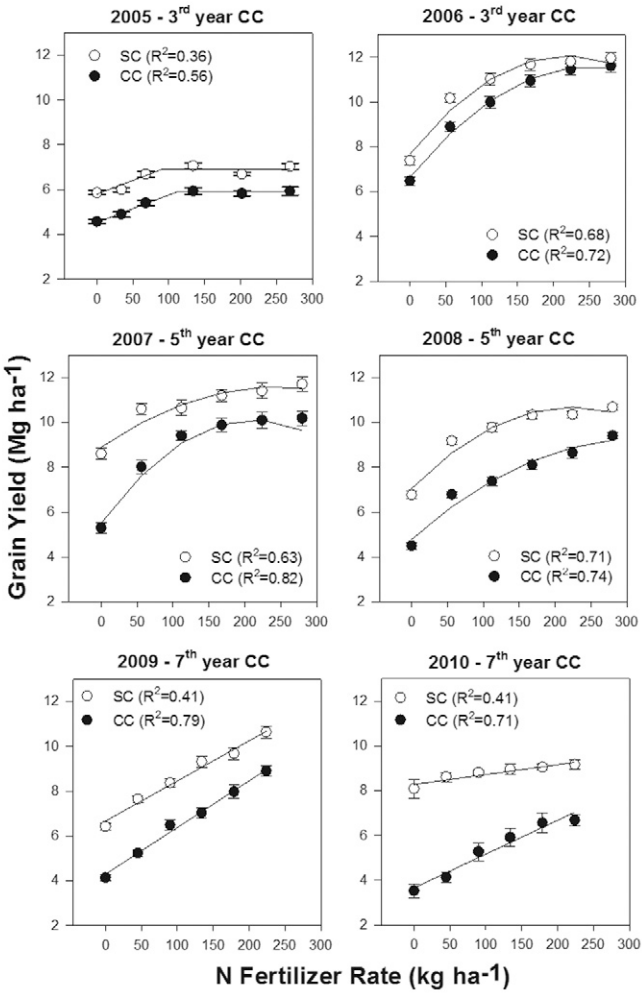

Fig. 1. Corn yield response to N fertilizer application rate for each year, 2005 to 2010, for continuous corn (CC) and a soybean–corn rotation (SC). Quadratic, linear, or linear-plateau regressions to response curves were fitted to yield data. Treatments were in the third, fifth, and seventh years of CC production for 2005 and 2006, 2007 and 2008, and 2009 and 2010, respectively. Bars indicate ±1 SE.

$$\begin{aligned}\mathrm{CCYP} = 2.2206 &+ 0.1209(\mathrm{CCYRS}) \\ &- 0.3448(\mathrm{0NCCYD}) \\ &+ 0.1736(\mathrm{DELTADIFF})\end{aligned} \qquad [2]$$

Nonsignificant predictors of the CCYP are not discussed. Continuous corn yield without N fertilizer application (0NCCYD) was the strongest predictor of CCYP in this model (partial $R^2 = 0.84$) and the inverse relationship demonstrates that in years when unfertilized CC yields are relatively low, the CCYP is expected to be greater and vice versa. Unfertilized corn yield is primarily determined by weather and N supplied by the soil. In turn, N supplied by the soil is controlled by the quality and quantity of previous crop residues, soil organic matter content, residual N from previous N applications, atmospheric N_2 fixed by legumes and free-living N_2–fixing bacteria, and atmospheric deposition (Legg and Meisinger, 1982). In this study, we maintained low residual fertilizer N levels (by applying relatively low maintenance levels of N in setup years before the study year) and accounted for leguminous N inputs with the crop rotation treatment; N inputs from sources other than those related to the rotation treatment should be the same across the study. In our model, 0NCCYD is an indicator of net soil N mineralization in CC systems, a conclusion supported by the findings of Gentry et al. (2001). Net soil N mineralization is significantly reduced in CC relative to SC systems (Gentry et al., 2001; Álvarez et al., 2008) and in years when 0NCCYD is especially low, as seen when weather was unfavorable or after more years in CC, the CCYP can be expected to increase. Enhanced net soil N mineralization in SC relative to CC systems may be the result of a soil microbial community that enhances soil N mineralization (Vanotti and Bundy, 1995). Similarly, Wilhelm and Wortmann (2004) suggested that the CCYP may be associated with lower soil temperatures in CC vs. SC, resulting in reduced activity of N-mineralizing bacteria. In a notable study, Trinsoutrot et al. (2000) tested 47 different crop residues during a 168-d incubation study and found that corn residue had the lowest net N mineralization (–28 kg N kg^{-1} C), demonstrating the slow decomposition rate and potential for N immobilization presented by incorporation of corn residue. No research that we are aware of has indicated that differing N mineralization kinetics from corn residue resulted in greater N loss to the environment than N released from other crop residues and, as such, corn residues may be viewed as N reservoirs, releasing N at a reduced rate relative to other cropping systems.

The second variable added to the forward and stepwise regression models was CCYRS (partial $R^2 = 0.1204$, Table 5). Years in CC exhibited a positive relationship with CCYP, demonstrating that the yield penalty increased with time through the seventh year of CC culture. This finding is counter to common thought about CC yields in the U.S. Corn Belt, where farmers often claim that yields in CC systems improve with time, eventually reaching the same yield level as SC after the fourth or fifth year. Other researchers have reported that corn yields decreased with additional years of CC (Meese et al., 1991; Dam et al., 2005) or that there was little evidence that CC benefited from more years of corn growing in the same field (Nafziger, 2007). Some studies, however, did not determine significant yield losses from 2, 3, 4, or 5 yr of CC relative to the first year of corn following corn (Crookston et al., 1991; Porter et al., 1997; note: these reports were based on different years of the same study). In the present study, a clear escalation of the CCYP was observed from 3 to 7 yr of CC (Fig. 2). On average, the CCYP increased by 186% (0.64 Mg ha^{-1}, 12.0 bu acre^{-1}) from the third year of CC to the fifth year of CC and 268% (1.24 Mg ha^{-1}, 23.4 bu acre^{-1}) from the third year of CC to the seventh year of CC. We speculate that the primary agent of CCYP represented by CCYRS is accumulated corn biomass. Accumulation of large quantities of high C/N ratio residue under CC with time can exert negative effects on nutrient cycling (Stanford and Epstein, 1974; Westermann and Crothers, 1980; Green and Blackmer, 1995; Nicolardot et al., 2001), soil temperature and moisture (Burrows and Larson, 1962; Grundmann et al., 1995), disease pressure (de Nazareno et al., 1993; Jirak-Peterson and Esker, 2011), and other crop growth factors (Dam et al., 2005). By comparison, the relatively low C/N ratio residue deposited in much smaller quantities under SC decomposes quickly and, consequently, cycles bound nutrients into plant-available forms more rapidly (Green and Blackmer 1995; Gentry et al., 2001) and eliminates issues associated with maintaining large quantities of residue on the soil surface (Álvarez et al., 2008).

The final predictor of CCYP in the model was the difference between CC and SC delta yields (DELTADIFF), contributing a partial factor R^2 of 0.0311. The relationship between DELTADIFF and CCYP was positive, i.e., in years when the CC delta yield was close to the SC delta yield (i.e., DELTADIFF was small), the CCYP was correspondingly small and vice versa. In some instances, as in 2005, CCYP and DELTADIFF were both small because of weather conditions that severely limited grain production for CC and

Table 5. Model summary for stepwise regression analysis predicting the continuous corn yield penalty (CCYP). Eleven potential predictor variables were added to the model. Forward and stepwise regressions produced the same model, therefore only stepwise model results are shown. Default criteria in SAS were used for adding and removing potential predictors from the stepwise regression (*P* = 0.15 for both entry and removal from the model). Because there was little redundancy among the added predictors, no variables were removed from the model.

	Summary of stepwise selection				Summary of model parameters				
Variable†	Partial R^2	Model R^2	*F*	*P*	Parameter estimate	SE	Type II sum of squares	F	P
0NCCYD	0.8451	0.8451	21.82	0.0095	–0.34477	0.03688	0.27411	87.39	0.0113
CCYRS	0.1204	0.9655	10.46	0.0480	0.12088	0.02429	0.07767	24.76	0.0381
DELTADIFF	0.0311	0.9966	18.11	0.0510	0.17358	0.04079	0.05682	18.11	0.0510
Intercept					2.22064	0.26524	0.21986	70.09	0.0140

† 0NCCYD, unfertilized continuous corn yield; CCYRS, years in continuous corn; DELTADIFF, the difference between SC delta yield and CC delta yield, where delta yield is maximum yield minus unfertilized N yield.

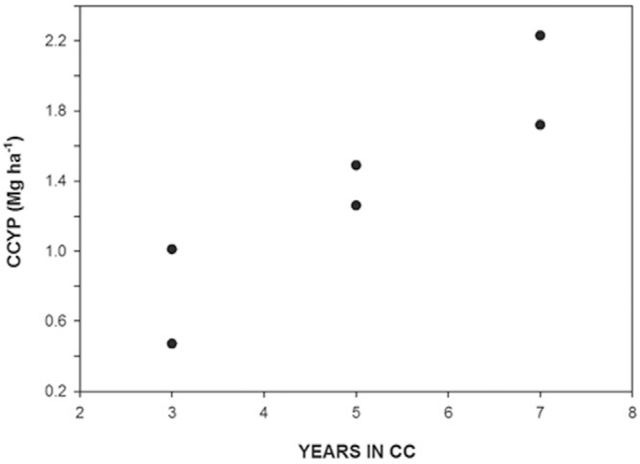

Fig. 2. The continuous corn yield penalty (CCYP), measuring the yield difference between continuous corn and a soybean–corn rotation, plotted as a function of years in continuous corn (CC) from 2005 to 2010. The experimental design, requiring two sites for the study, afforded duplication of Years 3, 5, and 7.

SC systems alike. In other cases, as in 2006, both CCYP and DELTADIFF were small due to favorable weather conditions that allowed the CC system to take full advantage of the greater N rates, producing yields comparable to those of the SC system. In years when DELTADIFF was large, as in 2007 and 2010, it appears that weather patterns (specifically, suboptimal moisture and above-average temperatures) more negatively affected grain production for CC systems than SC systems, resulting in relatively large CCYP values. Other studies have reported that water stress (Varvel, 1994; Wilhelm and Wortmann, 2004) and temperature stress (Wilhelm and Wortmann, 2004) are more detrimental in CC than SC systems.

In 2007, strong net soil N mineralization was indicated by the relatively high unfertilized SC yield value, probably due to favorable rainfall in June (as per Kay et al., 2006); however, the muted yield response across the N fertilizer range in the SC system in 2007 was probably the result of hot, dry conditions in July and August, which prevented the crop from achieving potential yields by increasing ovule abortion or reducing grain weight (data not shown). The CC N fertilizer response was strong in 2007, indicating that (i) there was less N available for uptake in the unfertilized CC system relative to the unfertilized SC system, creating a low unfertilized CC yield, and (ii) N fertilizer was taken up early by the crop and probably used to develop ear shoots with large row number and ovule potential counts. The hot, dry conditions in July and August 2007 appeared to be more detrimental to CC than SC treatments, resulting in a substantial reduction of yield in CC relative to SC treatments.

In 2010, as in 2007, the CC system was more responsive to N fertilizer application than the SC system; however, the 0 N yield for CC was much less than in other years, probably due to a large accumulation of corn residue (reflected by CCYRS), which limited net N mineralization. Unfortunately, the response to N at the high end of the fertilizer rate range in 2010 is not completely understood because the maximum N fertilizer rate was reduced to 224 from 280 kg N ha^{-1} in previous years, preventing determination of the point at which the crop response to N began to decline. The hot, dry conditions of the 2010 growing season, however, make it likely that the yields at higher N rates would have been similar to or less than those observed in 2007.

The difference between delta yields for CC and SC treatments in this study appears to be a function of weather conditions, particularly during critical growth periods, such as ovule determination in June and grain fill in July and August, which can disproportionately reduce yields of the CC system relative to the SC system. We conclude that DELTADIFF is primarily a weather-driven value reflecting the degree to which weather limits or promotes N availability to the CC crop relative to the SC crop. The inclusion of an indicator of weather in the model highlights the importance of weather for a number of growth and development factors (e.g., germination, ovule determination, pollination, grain fill, and kernel abortion) and demonstrates that CC systems are often more strongly affected by negative weather conditions than SC systems. If data are unavailable to calculate DELTADIFF, however, this factor can be removed from Eq. [2] and the model still maintains a strong explanatory ability ($R^2 = 0.97$).

Pairwise correlation coefficients for the three variables in the model ranged from 0.09 to 0.57 and tests for linear relationships among variables were nonsignificant ($P > 0.24$), indicating that there was no multicollinearity; thus the variables in the model act independently. There are obvious hidden factors, however, that we either cannot adequately quantify (e.g., weather) or did not measure (e.g., residue accumulation). Weather heavily influenced 0NCCYD and DELTADIFF; similarly, 0NCCYD and CCYRS were influenced by residue accumulation. The model presented here is not intended to be used to predict the CCYP because not all of the parameters in the model can be determined before the present crop year. Rather, the value of the model is to facilitate our understanding of the physical, chemical, biological, and, especially, management factors contributing to the CCYP.

Peterson and Varvel (1989) cited several studies observing the CCYP to be greatest in "dry" or "stress" years; they also noted greater whole-plant moisture content at maturity in CC systems, suggesting that crop development lags behind that of rotational systems. Similarly, Porter et al. (1997) concluded that the CCYP is reduced in "high yielding environments," characterized by high but not excessive rainfall, temperatures, and solar radiation during the growing season. Alternatively, Nafziger (2007) did not determine that the CCYP was correlated with soil productivity or environment. We believe that the concepts of 0NCCYD, CCYRS, and DELTADIFF are more reliable and quantifiable parameters of the CCYP than describing how "favorable" a year was or how "high yielding" an environment was. As seen in 2005, a very poor weather year does not necessarily result in a high CCYP (Tables 2 and 4). Similarly, a relatively good weather year, like 2008, can result in a fairly large CCYP. Residue decomposition rates and corresponding degrees of N mineralization and N immobilization are directly controlled by the interaction of seasonal weather, N fertilization, and residue amount, quality, and management. These three factors—N availability, residue, and weather—and their interactions appear to be the primary determinants of the CCYP.

CONCLUSIONS

In general, CC treatments required more N fertilizer and produced lower yields than SC treatments, as demonstrated by a greater AONR in all years except one and lower corn yields at the AONR for CC in every year of the study. Averaged across all years of the study, the CCYP was 1.36 Mg ha^{-1} (25.6 bu acre^{-1}); values ranged yearly from 0.47 to 2.23 Mg ha^{-1} (8.9–42.0 bu acre^{-1}). During favorable growing seasons early in the CC cycle, the CCYP was overcome by increasing the N fertilizer rate; however, greater N rates did not eliminate the CCYP when season-long weather was average or poor. This study suggests that the CCYP persists for at least 7 yr. Unfertilized CC yield (0NCCYD), CCYRS, and DELTADIFF were significant predictors of the CCYP. These three predictors used together in a regression model explained >99% of variability in the CCYP data set. The strongest predictor, 0NCCYD, indicates net soil N mineralization and reflects reduced mineralization or increased immobilization of plant-available soil N in CC relative to SC systems. Furthermore, CCYRS was strongly and positively correlated with CCYP, indicating that the CCYP became greater with more time in CC culture, a conclusion that is counter to the generally accepted position of many farmers in the U.S. Corn Belt. We believe that CCYRS is a measure of the negative effects of accumulated corn residue in CC systems. Finally, DELTADIFF reflects the season-long growth environment of the cropping system and, especially, indicates yearly weather patterns that are disproportionately adverse for CC relative to SC systems. Examining the relationship of each predictor with the CCYP suggests that the primary causative agents of the CCYP are N availability, corn residue, weather, and their interactions. Given that weather cannot be controlled and the annual optimum N fertilizer rate can only be determined ex post facto, managing corn residue has the greatest potential for reducing the CCYP.

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