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Continuous Corn and Soybean Yield Penalties across Hundreds of Thousands of Fields

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ABSTRACT

The effects of crop rotations on yields have historically been assessed with field trials, but new datasets offer an opportunity to evaluate these effects using data from commercial farmers' fields. Here we develop a unique dataset of 748,374 joint observations of field-level yields, crop histories, and soil and weather conditions across the U.S. Midwest to empirically evaluate crop rotations. For rainfed fields, we found an average continuous corn (*Zea mays* L.) yield penalty (CCYP) of 4.3% and continuous soybean [*Glycine max* (L.) Merr.] yield penalty (CSYP) of 10.3% during the 2007 to 2012 growing seasons. The CCYP is greater in locations with low moisture, while the CSYP shows the opposite pattern. Relatedly, irrigation decreases the CCYP but not the CSYP. Both penalties increased with the number of years a field had been continuously cropped, and while the CCYP leveled off after 3 yr in corn, the CSYP showed significant increases out to the (very rare) 5-yr continuous soybean sequence. An analysis of weather, soil, and planting date interactions with the CCYP and CSYP suggests that timely planting, favorable soil-climate, and warm early and late-season minimum temperatures correlate with reductions in the CCYP, while dry conditions and less favorable soil-climate correlate with reductions in the CSYP. The results of this study not only help refine estimates of rotation effects in commercial fields, but also shed light on the relationships between rotation effects and other factors, thereby offering insight into potential causal mechanisms.

Core Ideas

- Analysis of 748,374 yield records showed a 4.3% yield penalty for continuous corn.
- Corn yield penalties were more severe in areas with low moisture and low yields.
- Continuous soybean showed a 10.3% yield penalty, worse in low-yielding years.
- Corn yield penalties grew with up to 3 yr of continuous cropping, but not more.
- Soybean penalties increased monotonically with number of years continuously cropped.

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In the United States, soybean is the most commonly rotated crop with corn and has been for decades. For corn, a yield benefit for rotation has been widely reported, with results from 28 field trial studies of crop rotation exhibiting, on average, a 7.8% increase in yield from the practice (Erickson, 2008) and a wide degree of variation across studies. The yield benefit of rotation may derive from improved soil structure (Barber, 1972), decreased disease pressure (Meese et al., 1991), decreased allelopathy between corn residue and growing plants (Martin et al., 1990) and increased N availability for corn in rotated systems (Stanger and Lauer, 2008). Nitrogen availability, however, is thought to be the primary driver behind this benefit (Gentry et al., 2013). Benefits for soybean also have a wide range, reported as 8 to 17% by Crookston et al. (1991), an average of 25% by Edwards et al. (1988), approximately 4% by Nafzinger (2007), and for no-till first-year soybean, 13% by Pedersen and Lauer (2002), with pest pressure from soybean cyst nematode historically cited as a major reason for this benefit (Dabney et al., 1988).

Several studies have also focused on the specific circumstances in which rotation provides the greatest increase in crop production. Based on previous year's moisture, Peterson et al. (1990) found large differences in rotation benefits in east-central Nebraska. Porter et al. (1997) performed a statistical analysis of environment-driven changes in rotation benefits, finding that for each Mg ha^{-1} of rainfed corn yield, the benefit of a corn–soybean rotation over continuous corn decreased by 4.1%, implying that more favorable growing conditions might counter the CCYP. Soybean may benefit more from rotation in stressed circumstances as well. Porter et al. (1997) found the yield advantage of rotated soybean decreased by 5.8% for every Mg ha^{-1} that continuous soybean yield increased.

Typically, analyses of yield drag from continuous cropping rely on split-plot field trials for data. Such trials have an advantage, in that the systematic testing of crop sequences they entail creates strong claims for causality (or lack thereof). However, they are subject to the weakness that the standard errors for such experiments are dependent on the weather, soil qualities, and management practices at the location(s) they took place. Given this, it can be difficult to generalize findings outside of specific experimental settings and circumstances. Another advantage of field trials is

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Abbreviations: CCYP, continuous corn yield penalty; CDL, cropland data layer; CLU, common land units; CRD, crop reporting district; CSYP, continuous soybean yield penalty; NCCPI, National Commodity Crop Productivity Index; RMA, Risk Management Agency; VPD, vapor pressure deficit.

that they often allow for the examination of crop responses to conditions rarely seen on farms (e.g., zero N fertilizer added to corn). A field trial focusing on such conditions, however, might not produce much insight relevant to economically realistic production decisions. These tradeoffs allow an opening for complementary, alternative approaches to estimate the effects of different crop sequences on corn and soybean yields.

When adequate data are available, statistical analyses of observational data have been shown to be powerful tools for investigating agronomic questions, such as for assessing system-wide vulnerabilities to drought (Lobell et al., 2014). These sorts of analyses have an opposing set of strengths and weaknesses. Because management practices are not randomly assigned, latent variables can cause differences observed between groups. Thus, showing a correlation in an observational analysis does not prove causation. However, observational data has the strength that it can often capture outcomes across a wide set of conditions where experimentation may not be feasible. Furthermore, if economic models of farmer behavior can help bridge any difference between experimental outcomes and observational ones, it can build confidence in the causal mechanism underlying those differences. In this study, we take a large-scale statistical approach to examine the CCYP and CSYP at wide spatial scales to examine how much rotation decisions matter in practice across a range of weather and soil conditions.

METHODS

Data Processing

The data used in this study relied on a combination of five independent datasets. Geolocated yield reports provided to the USDA's Risk Management Agency (RMA) for insurance purposes serve as the basis for measuring production. These data were made available to the authors in connection with the project to examine the sensitivity of corn yields to drought. Although privacy issues prevent disclosure of the original data, the non-sensitive code associated with the analysis is available. The raw data contained 19,265,669 rows in total–3,629,677 of which were within the years studied.

To link the geolocated production reports to fields, the RMA data were spatially joined to shapefiles of common land units (CLUs) made available by Texas A&M. The CLU shapefiles were from 2008, the last year in which USDA released such data publicly. To ensure consistency in this matching process, the RMA data were filtered to include yield records that were for one CLU only, based on an hectareage match between the RMA and CLU data with a tolerance of ±0.4 ha. There were 806,516 rows that survived this filter.

Crop rotation data were added by joining the CLU/RMA join result with the cropland data layer (CDL) data provided by the National Agricultural Statistics Service (Boryan et al., 2011). The CDL has been used in previous studies to establish trends in crop rotation both in Iowa (Stern et al., 2012) and regionally over the central United States (Plourde et al., 2013). To ensure that the crop in the RMA data matched the crop in that particular CLU in that year, CLUs that were classified as any other crop or land cover type in more than 25% of their land area were dropped from the data at this step. This threshold ensured that CLUs that had potentially been sown to multiple crops, and thus where the sequence of crop rotations was ambiguous, were excluded. Most CLUs had either close to 100% in a single crop (often slightly less due to infrequent classification errors in the CDL) or well below 75%, thus 75% was chosen as a reasonable threshold to distinguish these two cases.

Table 1. Number of samples and proportion of samples in each crop rotation (C for corn, S for soybean) by length of cropping history for rainfed corn. The leftmost letter in any sequence is the most recent crop grown before corn, and right most letter corresponds to the earliest crop in the sequence.

Previous year	C	S						
304,858 samples	0.235	0.765						
Previous 2 yr	CC	CS	SC	SS				
252,526 samples	0.138	0.082	0.741	0.039				
Previous 3 yr	CCC	CCS	CSC	CSS	SCC	SCS	SSC	SSS
206,220 samples	0.095	0.039	0.080	0.003	0.078	0.669	0.025	0.012
	CCCC	CCCS	CCSC	CCSS	CSCC	CSCS	CSSC	CSSS
Previous 4 yr	0.072	0.021	0.039	0.001	0.029	0.051	0.002	0.001
172,400 samples	SCCC	SCCS	SCSC	SCSS	SSCC	SSCS	SSSC	SSSS
	0.033	0.039	0.659	0.020	0.002	0.020	0.007	0.003

Table 2. Number of samples and proportion of samples in each crop rotation (C for corn, S for soybean) by length of cropping history for rainfed soybean. The leftmost letter in any sequence is the most recent crop grown before soybean, and rightmost letter corresponds to the earliest crop in the sequence.

Previous year	C	S						
280,310 samples	0.932	0.067						
Previous 2 yr	CC	CS	SC	SS				
224,269 samples	0.118	0.826	0.031	0.0247				
Previous 3 yr	CCC	CCS	CSC	CSS	SCC	SCS	SSC	SSS
191,744 samples	0.049	0.059	0.810	0.034	0.003	0.024	0.009	0.011
	CCCC	CCCS	CCSC	CCSS	CSCC	CSCS	CSSC	CSSS
Previous 4 yr	0.025	0.022	0.058	0.002	0.062	0.760	0.021	0.010
150,224 samples	SCCC	SCCS	SCSC	SCSS	SSCC	SSCS	SSSC	SSSS
	0.001	0.002	0.015	0.006	0.001	0.008	0.003	0.006

Indeed, only 7.2% of the data did not have a pure enough classification, leaving 748,374 rows. As a final step, weather data from the PRISM data group (Daly et al., 2008) and soil data from SSURGO (Soil Survey Staff, 2014) were joined with these RMA/CLU/CDL data.

The final file contained yields, rotations, weather, and soil data for 370,420 rainfed and 41,388 irrigated corn and 319,815 rainfed and 16,751 irrigated soybean fields from 2007 to 2012 across Iowa, Illinois, Indiana, Minnesota, Nebraska, and South Dakota; the six states with the largest corn hectareage in the United States. Tables 1 and 2 illustrate the crop histories and number of samples for the rainfed fields.

The total number of samples declines with history length for two reasons; the filters applied to the data and limited history from the CDL–Minnesota and South Dakota do not have CDL data prior to 2006. The share of each crop grown without rotation varies, with 2-yr continuous corn being more than three times as common as 2-yr continuous soy and 5-yr continuous corn being more than 100 times more common than 5-yr continuous soy. Comparing the full dataset to USDA ARMS data for 2010 (USDA ERS and NASS, 2013), 16% of planted land area were in continuous corn as opposed to 18% of planted land area in our data for that year. This discrepancy may arise from sampling error.

Statistical Analyses

We used linear regression from the R programming language (Chambers and Hastie, 1993) to examine correlations between yield and a set of weather, practice, and soil covariates, in addition to rotation history. The model was as follows:

$$y = U\mathrm{a} + V\mathrm{b} + W\mathrm{g} + X\mathrm{d} + \mathrm{e} \quad [1]$$

where y is yield, U is crop history as a factor, V is a set of weather covariates, W is planting date, X is a set of soil covariates derived from the SSURGO data–National Commodity Crop Productivity Index Version 2 (NCCPI) (Dobos et al., 2012) for corn and soybean and rootzone available water storage, and e is the error term. The yield penalty as calculated can therefore be thought of as the difference in predicted yields between rotated fields and fields that have been continuously cropped for at least 1 yr, taking all other covariates into account.

The set of weather covariates for corn was as follows: average vapor pressure deficit (VPD) from 61 to 90 d after planting, maximum air temperature 91 to 120 d after sowing, maximum air temperature in the 30 d leading up to planting, and precipitation 31 to 60 d after planting. For soybean, the weather covariate set consisted of VPD 31 to 60 d and 91 to 120 d after sowing, and precipitation 61 to 90 d after sowing. These weather covariates were selected using multivariate adaptive regression splines fit to a superset of the data in Lobell et al. (2014) from the study period, that is, the full set of rows available rather than the restricted number examined in and released with the piece.

The model was fit to subsets of the data by irrigation status, by crop reporting district (CRD), by length of continuous cropping, and by state/year. To analyze interactions between rotation effect size and covariates, covariate quartiles were added as factors to the model and compared to the general model.

In addition, to account for spatial and temporal autocorrelation, robust clustered standard errors were estimated (Davison and Hinkley, 1997) using the "rms" package in R (Harrell and Pikounis, 2015) for the regressions performed to determine overall rotation effects, the effects by years of continuous cropping, and interaction effects. Specifically, this was done using a block bootstrap procedure with replacement using 1000 iterations with blocks representing state/year combinations. Block bootstrapping was conducted by year only for the regressions examining spatial variation in the CCYP and CSYP. General linearized hypothesis tests (Wald, 1943) using the "lmtest" package in R (Hothorn et al., 2015) were used to compare effect sizes, and where multiple comparisons were made, Bonferroni corrections (Dunn, 1961) were used.

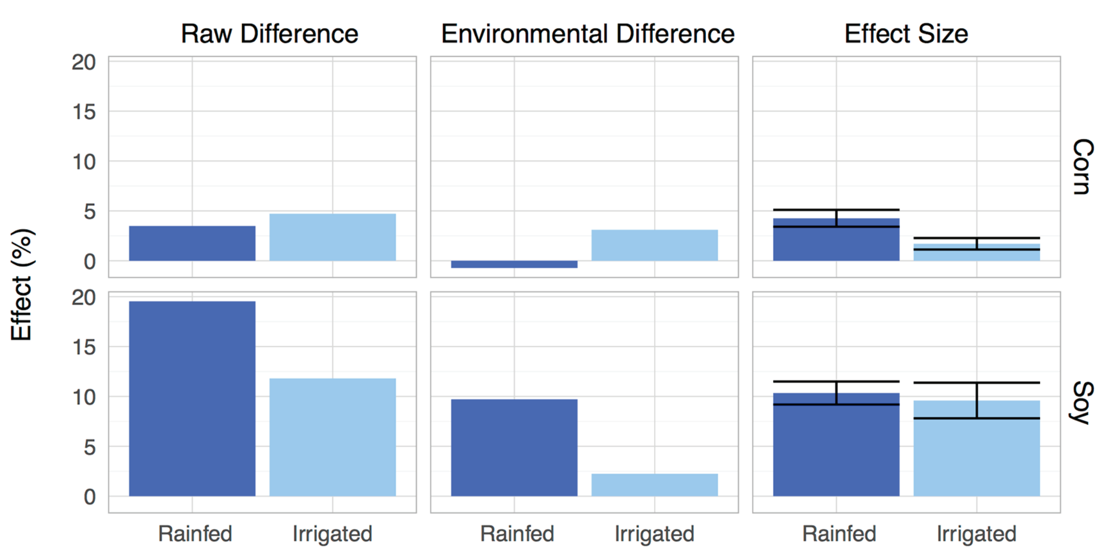

Fig. 1. Effects of corn and soybean rotations under rainfed and irrigated conditions (right two panels); predicted corn and soybean yield without rotation effects in the regression (center two panels) and the raw difference between rotated and continuous corn yields in the data (left two panels). Error bars represent one standard deviation in effect size.

RESULTS

Overall Effects

Based on a comparison of the mean yields of rotated and continuous crops, the results of which are shown in the left two panels of Fig. 1, raw yields for rotated corn were 0.34 Mg ha^{-1} (5.4 bu acre^{-1}), or 3.5% higher than yields for continuous corn in rainfed environments. For irrigated corn, the raw difference was 0.54 Mg ha^{-1} (8.6 bu acre^{-1}), or 4.7% of mean irrigated corn yields. For soybean, raw differences were more severe. On rainfed fields, rotated soybean was more productive than continuous soybean by 0.60 Mg ha^{-1} (8.9 bu acre^{-1}) or 19.5%, while on irrigated soybean fields, the raw difference was 0.45 Mg ha^{-1} (6.7 bu acre^{-1}) or 11.8%.

The center two panels of Fig. 1 compare predictions from a version of the regression model that contains only environmental covariates and no rotation history. The results indicate that some of the difference in raw yield outcomes could be attributed to differences in the environments in which rotated vs. continuous corn and soybean are grown, assuming there are no systematic differences in management across these environments. Given this assumption, we found that rainfed continuous corn is grown in fields that are slightly more environmentally favorable than rainfed rotated corn, while irrigated continuous corn, as well as both rainfed and irrigated continuous soybean were grown in fields with less favorable soil/weather conditions.

The estimated effects of crop rotation, conditional on environmental covariates, are presented in the right two panels of Fig. 1. Rainfed corn showed an estimated CCYP of 0.42 Mg ha^{-1} (6.7 bu acre^{-1}), or 4.3% (top right panel). For irrigated corn, the effect was 0.20 Mg ha^{-1} (3.1 bu acre^{-1}), or 1.7% of mean irrigated corn yields, as less favorable environments accounted for most of the unconditional difference in yield. For soybean, the modeled effect– 0.32 Mg ha^{-1} (4.7 bu acre^{-1}) or 10.3%– is just over half the raw difference. For irrigated soybean, the estimated effect was 0.36 Mg ha^{-1} (5.4 bu acre^{-1}) or 9.6% of the mean irrigated soybean yield, which accounts for most of the unconditional difference in yield. Parameters for all linear regressions performed in this analysis can be found in Table 3.

Analysis of Spatial and Spatiotemporal Variation in the CCYP and CSYP

To evaluate heterogeneity in the rotation effect, CCYP and CSYP were estimated for each CRD in our sample, using separate block-bootstrapped regressions with the controls outlined in the methods section. A CCYP of >0% was found in all but three districts, however, effects were only significant at $P < 0.05$ in 34 out of the 47 districts examined (regardless of sign), as mapped in the top left panel of Fig. 2. For soybean, a CSYP > 0 was found in all districts, however, effects were significant in 41 out of the 46 districts examined. Nonsignificant penalties may be the result of low sample sizes (see Supplemental Fig. S3). Average effects across significant districts were 0.48 Mg ha^{-1} (7.6 bu acre^{-1}) or 5.6% for corn and 0.30 Mg ha^{-1} (4.4 bu acre^{-1}) or 9.8% for soybean with average district-level standard errors of 0.19 Mg ha^{-1} (3.1 bu acre^{-1}) or 2.27% and 0.029 Mg ha^{-1} (0.42 bu acre^{-1}) or 0.95%, respectively.

For corn, western districts had a higher dryland CCYP, indicating a greater penalty in drier and typically irrigated conditions. Consistent with this, the irrigated CCYP averaged 48% less than its dryland counterpart for CRDs with significant irrigated and dryland CCYPs. For soybean, drier districts tended to have less of a penalty, with Nebraska CRDs seeing the lowest coefficients. For CRDs with significant irrigated and dryland CSYPs, the irrigated CSYP averaged 175% higher than its dryland counterpart.

The middle set of panels in Fig. 2 shows how penalties for continuous cropping varied with expected yield, calculated as the average yield over the study period in each district. Corn

Table 3. Parameters for regressions used to create Fig. 1. For all weather covariates, the time applicable is listed in days after sowing. Standard errors are in parenthesis.

	Environmental model only		Model with rotation	
Parameter	Irrigated corn	Dryland corn	Irrigated corn	Dryland corn
Intercept	384 (79)	237 (35)	380.0(80.0)	231 (35)
Planting date	−1.21 (.36)	0.059 (0.19)	−1.18 (0.36)	0.0665 (0.19)
Mean daily VPD† 61–90	−1.49 (5.0)	−53.3 (6.2)	−1.28 (4.7)	−53.0 (6.4)
Mean daily Tmax 91–120	−2.60 (1.5)	0.212 (0.97)	−2.58 (1.5)	0.143 (1.0)
Mean daily Tmax −30–0	−0.393 (0.69)	−2.05 (0.50)	−0.412 (0.70)	−2.04 (0.50)
Mean daily precipitation 31–60	−0.789 (0.56)	−0.765 (0.66)	−0.752 (0.53)	−0.774 (0.68)
Water holding capacity	0.117 0(0.02)	0.0419 (0.027)	0.117 (0.020)	0.045 (0.026)
NCCPI	13.0 (8.8)	68.6 (6.6)	11.6 (8.9)	69.1 (6.3)
Rotation	na	na	3.12 (1.1)	6.66 (1.3)
	Irriated soybean	Dryland soybean	Irrigated soybean	Dryland soybean
Intercept	98.2 (16)	69.2 (7.9)	98.3 (16)	68.8 (7.5)
Planting date	−0.417 (0.09)	−0.192 (0.04)	−0.415 0(.086)	−0.180 (0.036)
Mean daily VPD 31–60	2.64 (3.1)	−3.36 (1.6)	2.53 (2.8)	−3.42 (1.6)
Mean daily VPD 91–120	−1.97 (3.8)	−4.13 (2.3)	−1.93 (3.6)	−4.06 (2.3)
Mean daily precipitation 61–90	0.549 (0.41)	0.909 (0.30)	0.546 (0.40)	0.895 (0.30)
Water holding capacity	0.052 (0.0073)	0.0045 (0.0087)	0.051 (0.0072)	0.0031 (0.0087)
NCCPI	−3.51 (3.2)	22.2 (2.4)	−3.52 (3.0)	21.3 (2.5)
Rotation	na	na	5.44 (1.0)	4.74 (0.54)

† VPD, vapor pressure deficit, NCCPI, National Commodity Crop Productivity Index; na, not applicable.

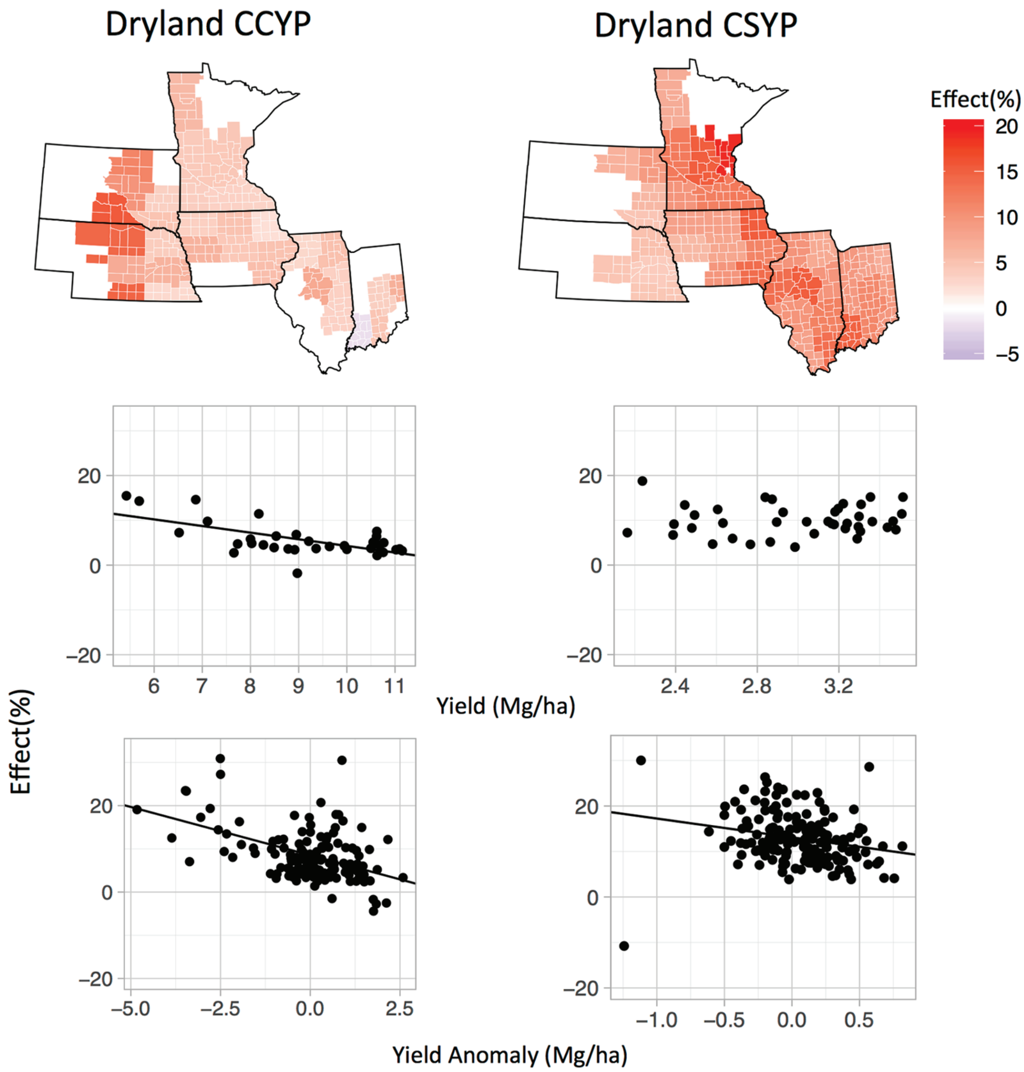

Fig. 2. Spatial and spatiotemporal variation in the (left) continuous corn yield penalty and (right) continuous soybean yield penalty. Only crop reporting districts with effects that are significant ($P < 0.05$) are displayed in the maps in the top two panels. Lines of best fit are only displayed on bottom four panels when significant. One point represents one district in the center two panels and one district-year combination in the bottom two panels.

penalties increased with decreasing expected yield ($P < .01$), while soybean penalties did not.

Finally, the bottom set of panels in Fig. 2 illustrates the CCYPs and CSYPs in each district-year and their correlation with the yield anomaly in that district-year. The results show significant ($P < 0.05$) increases in the CCYP and CSYP with decreasing realized yield relative to normal, a result consistent with Porter et al. (1997). The continuous crop penalty for soybean showed a smaller association with yield anomalies than does the effect for corn, a finding consistent with those of Wilhelm and Wortmann (2004).

Effects by Years of Continuous Cropping

Regressions were also used to analyze how yield penalty varied with the number of years a field was continuously cropped. Penalties increased with duration of continuous cropping for both dryland corn and soybean (Fig. 3), but the progression differed somewhat between the two crops. Penalties for corn tripled from 1.9 to 5.7% between 1 and 2 yr of continuous cropping but then leveled off. Dryland soybean exhibited monotonic increases in effect size with number of years continuously cropped.

The CCYP exhibited a significant difference between the 1-yr only effect and the effects for longer durations of continuous cropping lengths but no significant differences for effects for 2-yr or more continuous cropping. This result was consistent with findings by Crookston et al.(1991), but not with Gentry et al. (2013) who found that CCYP increased with the number of years of continuous cropping. For soybean, the penalty increased with duration of continuous cropping, with differences between 1- and 3-yr, 1-yr and 4-plus yr, and 2-yr and 4-plus yr all being significant, a finding that is also consistent with Crookston et al. (1991).

Analysis of Soil, Weather and Yield Interactions

As a final analysis, interactions between the CCYP and CSYP and other variables were examined. Two hypotheses were tested first; that better soil-climate can ameliorate the CCYP (Vyn, 2006), and that the CCYP may interact with planting date, as soil temperature is critical to timely corn emergence (Schneider and Gupta, 1985) and increased crop residue often decreases soil temperature (Kaspar et al., 1990). The two left panels of Fig. 4 show how penalties differ across soil and climate, as measured by the NCCPI. Here, the CCYP shows a decrease at higher NCCPI,

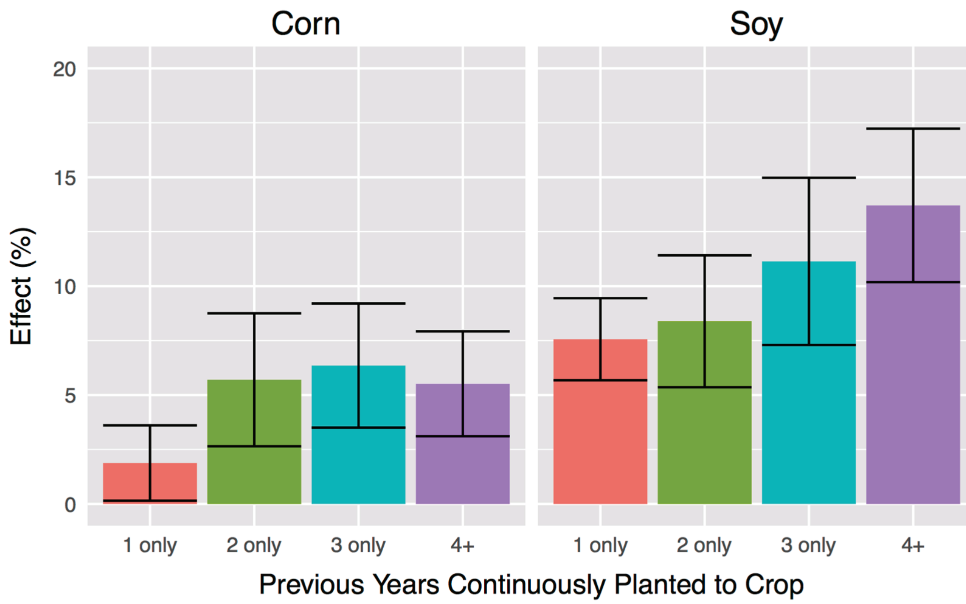

Fig. 3. Variation in continuous cropping penalty by years continuously in the same crop for (left) corn and (right) soybean. Error bars represent two standard deviations in effect size.

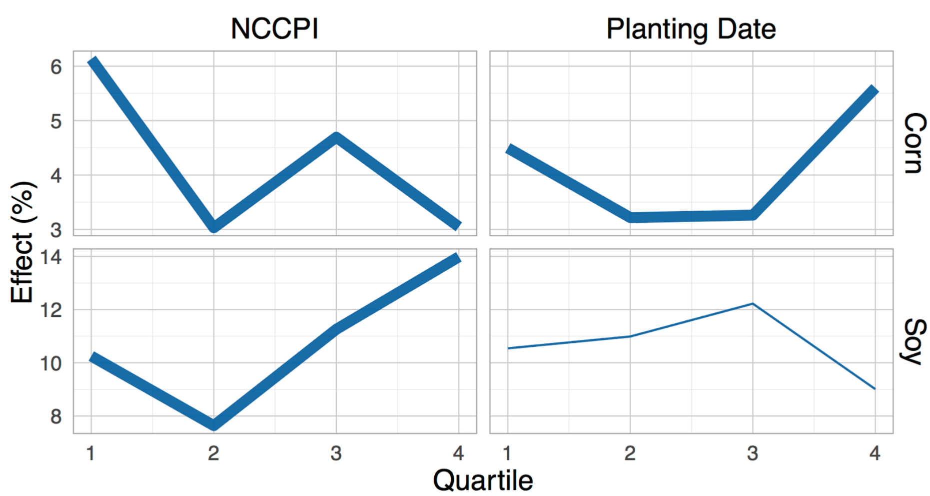

Fig. 4. Interactions between the continuous corn yield penalty and continuous soybean yield penalty and quartiles of soil-climate favorability and planting date. Thick lines indicate significant interaction at $P < 0.05$, thin lines indicate no significant interaction.

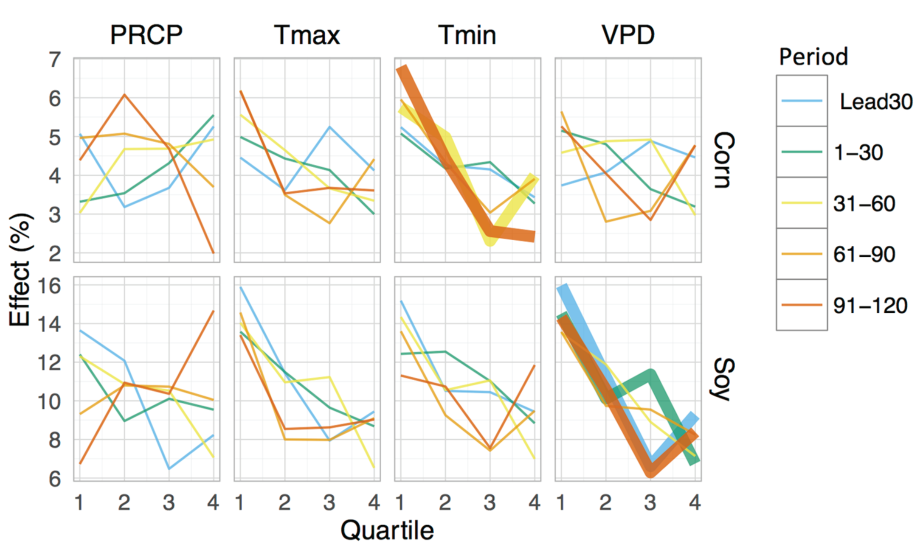

Fig. 5. Interactions between the continuous corn yield penalty and continuous soybean yield penalty and quartiles for weather features in the model. Thick lines indicate significant interaction at $P < 0.05$, thin lines indicate no significant interaction.

but the CSYP shows the opposite. The right two panels of Fig. 4 show how the penalty varies with planting date. Late planted corn suffers the biggest penalties ($P < 0.05$), and there is no significant planting date effect for the soybean penalty.

Interactions between the rotation effect and specific covariates pertaining to weather in the model were also examined and illustrated in Fig. 5. Early and late season minimum temperatures showed significant interactions with the CCYP at $P < 0.05$ significance after Bonferroni corrections. For soybean, only VPD leading up to and after planting as well as late in the season affected the CSYP at $P < 0.05$ after corrections.

DISCUSSION

The results in this study provide potential insight into various aspects of the CCYP and CSYP, with important caveats being (i) that any empirical study cannot unambiguously identify causation, thus additional field trials may be needed to further test the effects shown; (ii) given available data, we could not control for important grower practices and decisions such as tillage, soil drainage, fertilization rate, or weed and pest management programs that differ by rotation; (iii) controls for certain variables for example, NCCPI for soil climate may be imperfect; (iv) that our results reflect historical varieties and practices, and new features such as improved soybean cyst nematode resistance in soybean could, for instance, change the CSYP going forward; and (v) that our aggregated effects do not take into account potential trends in crop rotation practices as seen from 2003 to 2010 by Plourde et al. (2013) and Iowa from 2001 to 2010 by Stern et al. (2012).

The first insight is that the CCYP and CSYP can be reproduced outside of field trials, based on statistical methods alone, as the CCYP found here is at the 25th percentile of the range of field trial values found by Erickson (2008) and well within one standard deviation of the mean of the estimates reported there. The CSYP found here is within estimates provided by the literature as well, with Pedersen and Lauer (2002) and Edwards et al. (1988) above it, while Nafzinger (2007) is below it. Given the frequency of continuous corn (28%) and the size of the penalty (4.3%), the penalty found amounts to approximately a 1.2% region-wide loss when expressed as average aggregate yield. While that overall loss may seem small, it amounts to about 8% of the difference between the contemporary crop yield gap in rainfed U.S Midwest corn systems and the "practical minimum" yield gap in those systems (Lobell et al., 2009).

While our estimated CCYP was broadly consistent with the range of penalties seen in the field-trial literature, it is notably on the low end. One explanation for this would be that our data observes the yield penalty after a grower optimizes practices for continuous cropping. For example, much of the advice given in the extension literature is to apply more inputs on continuous corn fields; Sawyer (2015) suggests an extra 32 to 51 kg ha^{-1} of N for continuous corn as economically optimal over the range of price ratios from U.S.$2.79 to 11.2 Mg^{-1} N: $ Mg^{-1} corn. In the extreme, using the relationship between N application and corn yield in continuous and rotated systems found by Livingston et al. (2015) and assuming zero weather uncertainty about yield outcome, there are even circumstances where N could be used to bring the CCYP to zero under economically optimal behavior (see Livingston-2015.R in the source code released with this paper).

Additionally, rotation effects vary widely but matter more for the CCYP in dry areas. If we are to assume that less N is typically used in dryland corn in the western Corn Belt given lower yield potentials and higher risks (Shapiro et al., 2001), then our results would support the Gentry et al. (2013) observation that N availability influences the CCYP more than any other variable. The decrease in the CCYP with higher early and late-season minimum temperatures is also supportive of this, as higher soil temperatures increase soil N mineralization. Contradicting Gentry et al. (2013), however, we do not find an increasing CCYP with the number of years continuously cropped. This may be due to differing corn residue management practices used in that study as compared with many commercial farms. For example, despite chisel plowing and lightly cultivating the study site, the Gentry et al. (2013) study notes neither the use of chopping corn heads at harvest nor any sort of residue removal. These latter practices may reduce the penalty and are common in farmers' fields, though data on specific practices were not available in this study.

For soybean, the continuous cropping penalty appears to have the opposite pattern, with greater penalties in cooler, wetter areas. Given that soybean sudden death syndrome prospers in cool, wet conditions (Leandro et al., 2013), soybean cyst nematode prospers in conditions that would otherwise promote high soybean yields (Niblack, 2005), and the two interact strongly (Westphal, 2008), this result is consistent with evidence that pest pressure is the major cause of the CSYP. The finding that VPD is the most important weather covariate with the CSYP is also consistent with effects related to pest pressure, given the finding that warmer, drier soils at planting are critical in reducing soybean sudden death syndrome's development (Scherm, 1996). Build up of pest pressure is also broadly consistent with the continuously higher penalty to more years continuously cropped in soybean.

Overall, our examination of the CCYP and CSYP on commercial farms supports many of the findings seen in field trials, with both types of analyses complementing one another in understanding these phenomena. Given recent volatility in the commodity markets, with high prices for corn relative to soybean during much of the ethanol boom encouraging more continuous corn (Hendricks et al., 2014), and higher prices for soybean relative to corn encouraging more rotation today, understanding effects on a region-wide level can help inform both farmer and policy decisions. Data such as those presented in this study can help to reach this understanding in a much more precise and cost-effective way than traditional approaches can achieve on their own.

ACKNOWLEDGMENTS

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