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The causes and unintended consequences of a paradigm shift in corn production practices

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ABSTRACT

Independent but simultaneously occurring changes in U.S. agricultural and energy policies in conjunction with advances in biotechnology converged to create an economic and regulatory environment that incentivized corn acreage expansion. Advancements in Bt seed and ethanol production technologies contributed to scale efficiency gains in corn and biofuel production. These advancements were accompanied by changes in market forces that altered the balance between corn and other agricultural crop production. The causal linkages among Bt adoption, ethanol production, and corn production are explored along with a discussion of how this shift toward corn production generated unexpected economic and environmental consequences. Alternative policy solutions to mitigate the negative consequences and enhance the resiliency of U.S. agriculture are discussed.

1. Trends in U.S. row crop production

The corn/soybean monoculture cropping system has become a dominant fixture in modern crop production in the U.S. Roughly 30% of total field crop acreage was devoted to corn in the past 5 years (NASS, 2014), which annually equates to 4.6% of the terrestrial land surface of the continental United States (U.S.) and represented 35% of total crop profits between 2010 and 2012 (NASS, 2014). Soybeans are the next most widely planted crop (24% of total field crop acreage), but soybeans produced only 19% of total U.S. crop value.

In the Midwest Corn Belt, crop production has shifted significantly toward corn and away from other crops over the last 15 years (Table 1; Fig. 1). This trend coincides with a significant decline in the diversity of agricultural production systems in the Midwest and the Northern Great Plains (Wallander et al., 2011; Larson et al., 2010). This shift toward greater homogeneity in agricultural production systems (landscape simplification) has also taken place in other regions of the U.S. and Canada (Wiens et al., 2011). Landscape simplification does not only imply a reduction in agricultural production system diversity, but also a decrease in ecosystem biodiversity (e.g., Purtauf et al., 2005; Meehan et al., 2011). The increases in corn production are due to a combination of yield productivity increases (Wallington et al., 2012), and regional land use changes (Johnston, 2014; Wright and Wimberly, 2013; Wallander et al., 2011; Larson et al., 2010). However, the future of corn yield productivity increases is uncertain. Recent increases in yield productivity attributed to GM corn varieties are partially due to improvements in non-GM germplasm (Shi et al., 2013). Shi et al. argues that due to patent laws, seed

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Table 1 – Changes in area planted to principal crops in the Corn-Belt (NASS, 2014).[a]

Crops (planted acres)	Pre-ethanol incentive policy (1996–2000)[c]	Post-ethanol mandates (2009–2013)[c]	Change in area planted by crop (%)
Corn	64380.0 (35.7)	73640.0 (41.5)	14.4
Soybeans	55596.0 (30.9)	58028.0 (32.7)	4.4
Barley	669.4 (0.4)	182.8 (0.1)	−73.0
Oats	2161.8 (1.2)	1166.4 (0.7)	−46.0
Wheat	23724.0 (13.2)	18663.4 (10.5)	−21.3
Hay[b]	24370.0 (13.5)	20462.0 (11.5)	−16.0
Other crops	9253.8 (5.1)	5423.0 (3.1)	−41.4
Total planted area	180155.0 (100)	177565.6 (100)	−1.4

[a] Data are from the following states: IA, IL, IN, KS, MI, MN, MO, NE, OH, SD, and WI.
[b] Harvested acres.
[c] Thousands of acres planted (% of area).

company research dollars have gone into GM technology and not germplasm productivity improvement. This has implications for the future of corn yield productivity increases.

These trends raise the following questions: (a) what are the factors that encouraged U.S. agricultural production to move toward monoculture cropping practices focused on corn, and (b) what have been the unintended consequences and the unforeseen future consequences associated with the current U.S. corn production system? To address the first question, the causal linkages between state-level Bt corn seed adoption rates, ethanol production capacity, and the proportion of crop acres planted to corn are empirically tested. The second question is addressed through a synthesis of the pertinent literature. Finally, potential long-run economic and environmental implications of the current system are discussed.

2. The convergence hypothesis

Over the last 20 years, the U.S. has experienced a shift in row crop production practices. Row crop producers have moved away from a rotational-based-multi-crop production system and toward a monoculture based (corn/soybean) production system. It is proposed here that the recent shifts in U.S. agriculture and energy policies provided the *opportunity* and the *motivation* for the rapid change toward a corn-dominated agricultural system.

2.1. *Opportunity*

The policy that provided the *opportunity* for corn expansion was the Federal Agriculture Improvement and Reform Act of 1996 (P.L. 104-127) (also known as The Freedom to Farm Act; FFA). The FFA made two fundamental changes to U.S. agricultural policy: (a) it removed the linkage between prices of agricultural products and income support payments, and (b) it removed acreage restrictions from cropping decisions (Claassen et al., 2011). Claassen et al. (2010) argue that the cropping patterns that occurred after implementation of FFA would not have been possible under the old policy regime because FFA "... allowed producers to respond more freely to market signals, policy incentives, and technology change."

2.2. *Motivation*

Key biofuel policy initiatives occurred shortly after the introduction of GM seed technology for corn and soybeans in the late 1990s. These biofuel policies provided the *motivation* for the expansion of corn-based ethanol. The biotech crop revolution then opened the door for producers to adopt a corn/soybean monoculture production system when biofuel production expansion resulted in a surge in derived demand for corn (Fig. 1). These independent but simultaneous events provided the mechanism for the expansion of corn production that in turn supported a further expansion in ethanol

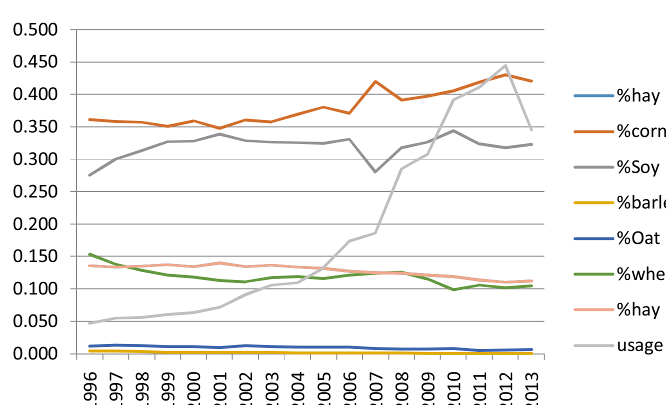

Fig. 1 – Changes in the Midwest Corn-Belt cropping system (proportion of total acres planted) and Ethanol Production Usage of Annual U.S. Corn Crop.
Source: USDA NASS (2014), USDA (2014), RFA (2014).

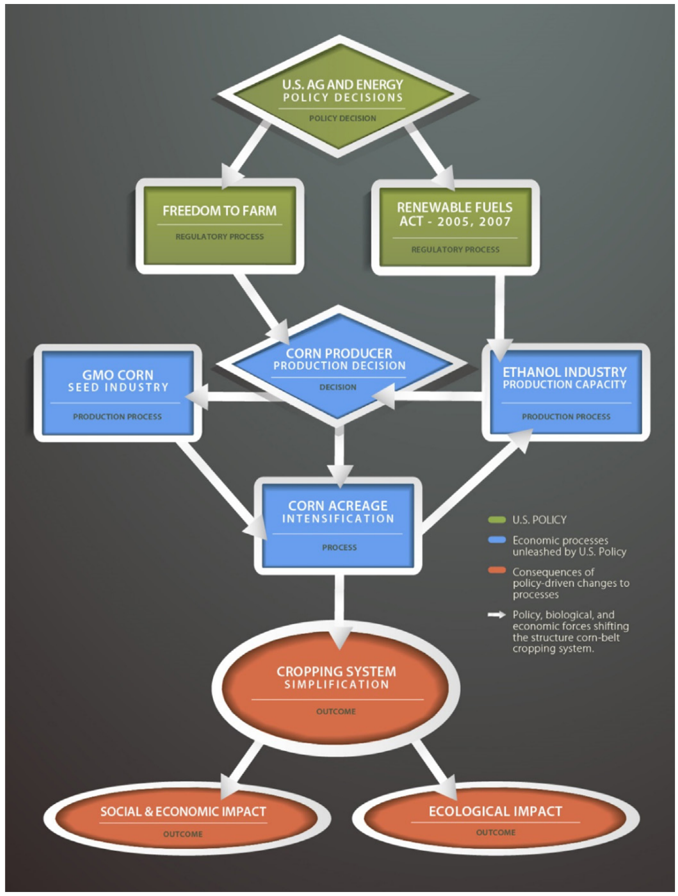

Fig. 2 – U.S. corn cropping systems and the role of Ag and bio-fuel policy. The empirical results reported in Table 3 support the causal relationships depicted by the economic processes section. The economic process section (center) hypothesizes the presence of an ethanol and corn production linkage and a feedback mechanism. Granger Causality test provides statistical support for the existence of these linkages. The establishment of ethanol plants incentivized corn producers to expand production by adopting Bt seed varieties. Bt technology allowed producers to expand corn acreage. Increased corn production incentivized ethanol companies to expand capacity. Rising ethanol fuel mandates allowed the economic feedback mechanism to intensity. Cropping system simplification and its associated untended consequences accelerated as the feedback mechanism intensified.

production capacity. Thus, a feedback mechanism was established.

The Midwest is the epicenter of U.S. corn production and ethanol production capacity (Lambert et al., 2008; Stewart and Lambert, 2011). The causal linkages outlined in Fig. 2 hypothesizes that federal agricultural and energy policy initiatives independently influenced producer crop planting decisions and industrial corn-based-ethanol production decisions. The establishment of ethanol production capacity in corn production regions altered producers' crop production decisions to meet the anticipated increased demand for corn. In turn, producers adopted GM seed technology to facilitate the expansion of corn acres planted. Expansion of corn production resulted in the intensification of corn acreage planted relative to other crops. Increased corn production motivated the ethanol industry to increase plant capacity in corn producing areas to capture additional economic incentives associated with federal biofuel mandates. Thus, it is hypothesized that energy and agricultural policy actions implemented independently created a feedback mechanism that resulted in rapid expansion of U.S. corn and ethanol production from 2000 to 2013.

Fig. 2 also suggests a linkage between the unintended consequences associated with this feedback mechanism for ecological systems in corn production regions and world grain markets. These untended consequences have been widely documented in the academic literature and are discussed in Section 5.

3. Ethanol production, gm seed adoption, and market incentives

3.1. *Ethanol production*

California's 2003 decision to replace MTBE (methyl tertiary-butyl ether) with ethanol prompted refiners nationwide to make a rapid conversion from MTBE to ethanol (EPA, 2014). This shift in production was accelerated by the passage of the 2005 Energy Policy Act (EPAct) and the Energy Independence and Security

Act (EISA) of 2007. These policy initiatives established a goal of blending 36 billion gallons of renewable fuel (of which 15 billion gallons would come from corn) into gasoline by 2022. As a result of these policy initiatives, ethanol production expanded rapidly from 2.1 billion gallons in 2002 to 13.44 billion in 2013 (U.S. Energy Information Administration (EIA), 2015a,b). The number of corn-based ethanol refineries more than doubled since 2005 (95 and 210 refineries in 2005 and 2014, respectively), and 90% of these refineries are located in Corn Belt states (Renewable Fuels Association, 2014; Cai and Stiegert, 2014).

3.2. GM seed adoption

The increased flexibility provided by the biotechnology revolution enabled row crop producers to reduce labor input requirements for crop production during the planting season as a result of GM seed (Fernandez-Cornejo and McBride, 2002). To meet the ethanol-driven increased demand for corn, many farmers abandoned traditional crop rotation practices. This shift was only agronomically and economically feasible with the adoption of Bt corn hybrids. Crop rotations are traditionally used to mitigate yield reductions (rotation effect) from insect pests (e.g., the corn rootworm, *Diabrotica* spp.; Gray et al., 2009). Bt corn reduces the need for crop rotation for pest management in the short run, allowing corn-on-corn production practices to maximize short-term profitability of farms. By 2014, adoption of Bt corn increased to an average of 80% of acres planted in the Corn Belt, matching the rapid expansion of corn-ethanol production (Fig. 3). The proliferation of modern Bt technology and the linkage between grain markets and energy markets via ethanol (Cai and Stiegert, 2014; Wallander et al., 2011) facilitated the expansion that occurred in the U.S. corn production system.

3.3. Market incentives

The surge in U.S. corn-based ethanol production changed relative crop prices (Wallander et al., 2011). Producer cropping

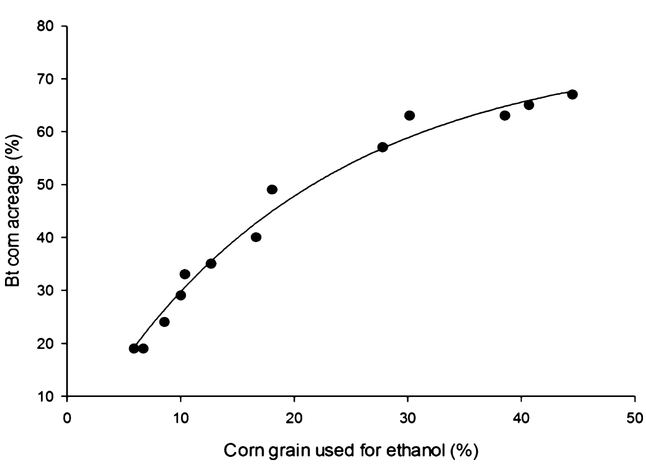

Fig. 3 – Annual data for acres planted to Bt corn and corn ethanol production since 2000. The nonlinear relationship between Bt and corn usage reveals that annual Bt corn acreage was highly predictive of grain devoted to corn ethanol ($y = 76.04 \times (1 - e^{(-0.050x)})$ ($F_{1,\,12} = 685$, $P < 0.001$; adjusted $R^2 = 0.98$).
Source: USDA (2014); RFA (2014); ERS (2014).

decision flexibility in the western Corn Belt increased and became more responsive to relative crop prices after FFA (Claassen et al., 2010). Conversion of grazing land to row crops in these states coincided with higher than expected return to crops relative to grazing. These states experienced a significant conversion of grassland, pasture, and wetlands to row crop production over the last decade (Johnston, 2014).

Claassen et al. (2011) estimate that Federal Crop Programs (commodity support, crop insurance, and disaster payments) added 8.5% to annual crop revenues from 1998 to 2007 and reduced the financial risk associated with converting grasslands to crops in North and South Dakota. The decoupling of USDA commodity programs from crop production decisions after the passage of FFA provided producers an additional economic incentive to expand row crop production.

U.S. agriculture and energy policy changes facilitated private sector activities, including the expansion of ethanol production capacity; and the technological advancement in Ht, Bt, and stacked GM corn seed varieties. Advancements in these areas of biotechnology evolved independently but then converged to alter crop production practices in the Midwest and the Northern Great Plains.

4. Empirical evidence in support of the convergence hypothesis: a test for statistical causality

The concept of causality within a time series framework was introduced by Granger (1969). Essentially, a "Granger Causal Relationship" exists if past values of X_t can be used to better predict current values of Y_t. If this is true, then this relationship is expressed as X_t "Granger Causes" Y_t. Thus, Granger Causality is a statistical concept of causality that is based on prediction.

There are several caveats that influence the degree of statistical robustness when using Granger's empirical technique. First, for bilateral causality, both random variables must be stationary or cointegrated. Next, the selection of the lag length for the sampling period needs to be carefully considered. Finally, relevant variables which influence both X_t and Y_t may be the source of the causal relationship between X_t and Y_t.

Formally, Fig. 2 hypothesizes a causal linkage between ethanol production capacity, the proportion of corn acres planted, and Bt corn seed adoption rates. To test the robustness of this proposition, a statistically based test for evidence of statistical causality is conducted. There are four possible Granger Causality outcomes between X_t and Y_t: (a) bidirectional (coinciding) causality, (b) Granger non-causality, and (c) unidirectional causality ($\mathbf{X_t} \rightarrow Y_t$ or $X_t \leftarrow Y_t$).

Statistical analyses were conducted on the data reported in Table 1, using SAS (2009). Given that the data span 11 states over 14 years, a panel Granger Causality test was conducted using a modified version of a SAS pooled panel data program for Granger Causality developed by J. Morrison (2015). Significant modifications to Morrison's SAS program were made to overcome the econometric issues associated with the statistical analysis associated with this project. Modifications include unit root tests, adding an individual equation lag selection process, an endogeneity test, and a test for serial correlation.

For clarity of mathematical presentation, the dependent variable is defined as Y_t, and the independent variable is defined as X_t. The potential relationship between Y_t and X_t is defined in Eqs. (1) and (2). The direction of Granger Causality is not assumed. Toward that end, a Vector Autoregressive (VAR (*n*)) model is utilized that allows for varying lag lengths (Y_{t-j}, X_{t-k}) for Y_t and X_t:

$$Y_t = \sum_{j=1}^{n} C_j Y_{t-j} + \sum_{k=1}^{n} B_k X_{t-k} + e_{1t} \tag{1}$$

$$X_t = \sum_{k=1}^{n} B_k X_{t-k} + \sum_{j=1}^{n} C_j Y_{t-j} + e_{2t} \tag{2}$$

The null hypothesis of X_t does not Granger cause Y_t can be specified as

$$H_0^1 : B_1 = B_2 = \ldots = B_n = 0 \tag{3}$$

and the null hypothesis of Y_t does not Granger cause X_t can be specified as

$$H_0^2 : C_1 = C_2 = \ldots = C_n = 0 \tag{4}$$

Summary statistics for the data used in the Granger Causality analysis are provided in Table 2. The sensitivity caveat of the Granger test for lag length is addressed by adopting an optimal VAR lag length selection criteria rule based on the AIC "goodness of fit" statistic. The optimal lag length for the dependent variable was selected first and then the independent variable lag length was determined. The adoption of an optimal VAR lag length rule is consistent with the basic economic principle of maximization of an objective function. Residual white noise was confirmed using the Wald–Wolfowitz run test for serial correlation (http://support.sas.com/kb/33/092.html). An endogeneity test was conducted by examining the correlation between the independent covariates and the residual. The null hypothesis of Corr(X, ε) = 0 was confirmed for all VAR models presented.

The common variable caveat was addressed by: (a) incorporating the soybean/corn price ratio as a variable (*PBCR*) to capture market forces affecting the possible causal relationships, (b) including state dummy variables to account for unique characteristics of states affecting causal relationships (controlling for fixed effects), (c) including a biofuel policy dummy variable that equals one for the year 2007 or later and zero otherwise, and (d) including the selected common variables in the lag length selection process. The policy variable (*ethdum*) definition is based on Akinfenwa and Qasmi (2014) who demonstrate that a structural break occurred in U.S. ethanol production time series in 2007.

The last issue is stationarity and it is addressed by conducting unit root tests (Phillips–Perron). Unit root tests indicated the presence of unit roots in all three variables of interest and PBCR. Therefore, Granger Causality tests were conducted using first differences of these variables. The three variables of interest are; the change in the ratio of corn acres to total acres planted (ΔCorn), the change in the ratio of Bt corn acres planted to total corn acres planted (ΔBt), the change in ethanol plant capacity (ΔEth), and the change in the soybean/corn price ratio (ΔPBCR). Unit root analysis was conducted using SAS Auto-Reg procedure in SAS/ETS Version 9.2 (SAS, 2009).

The empirical results provide statistical evidence to support the hypotheses graphically depicted in Fig. 2 of a causal relationship connecting the increase in the proportion of corn acreage planted relative to total acres, the share of corn acres planted with Bt seed, and ethanol production capacity in the Corn Belt region (Table 3).

Granger tests (Table 3) provide statistical evidence indicating that changes in ethanol production capacity were influenced by changes in the proportion of corn acres planted (*P*-value = 0.009). This suggests that changes in ethanol production capacity occurred in areas where corn production was increasing. The bi-directional statistical relationship between ΔCorn and ΔBt (*P*-value < 0.01) indicates a feedback mechanism resulting from producers simultaneously making decisions on how many acres of corn to plant and what type of seed to plant. Finally, there is statistical evidence that the change in ethanol production capacity influenced the producers' Bt adoption rate decision (*P*-value < 0.001). The Granger results indicate a production system feedback mechanism operating in Midwest corn production areas: $\Delta Corn \rightarrow \Delta Eth \rightarrow \Delta Bt \leftrightarrow \Delta Corn$.

The VAR parameter estimates for potential confounding variables (state dummies, ethdum, and ΔPBCR) are provided in Table 4. The state dummy variables (MI base) were included to capture fixed effects due to heterogeneity in agricultural production among states. Given that dependent variables were expressed as first differences, the empirical evidence indicates that state heterogeneity did not influence ΔCorn. The same is true for the ΔEth equations (except for IA and NE). However, with respect to the Bt equations, there are 8 of 11 states with significant coefficients (positive or negative), suggesting that states varied in how quickly they adopted Bt

Table 2 – State level summary statistics for 2000 to 2013.

Variable	No. obs.	Mean	Standard dev.	State level min	State level max
% Corn acres planted[a]	154	38.41742	12.03083	12.4801	58.04749
% BT adoption rate[b]	154	45.25974	21.39477	6	84
Ethanol production capacity (1000 U.S. BBL)[c]	154	14088.39	17166.82	0	87811.0
PBCR[a]	154	2.490437	0.292475	2.076412	3.060729

[a] Data collected from the National Agricultural Statistics Service (2014).
[b] ERS (2014).
[c] RFA (2014) and EIA (2015b,c). Production capacity for 2013 calculated using Nebraska Energy Office (December 2013 report) data. Note EIA date collected using EIA individual state data.

Table 3 – VAR (optimal) model: direction of Granger Causality.

Y[a]	X[a]	No. of obs.[b]	X Granger causes Y	Y lag length	X lag length	P-value of Wald χ^2 test[c]
ΔCorn	Δ*Bt*	143	Yes	1	1	0.001
Δ*Bt*	ΔCorn	88	Yes	6	4	0.001
Δ*Corn*	ΔEth	143	no	1	1	0.194
ΔEth[d]	ΔCorn	88	Yes	6	5	0.009
ΔEth[d]	ΔBt	88	No	6	1	0.26
ΔBT	ΔEth	88	Yes	6	4	0.001

[a] Delta (Δ) denotes first difference of variable ($X_t - X_{t-1}$).
[b] Data set contained 11 states and 14 time periods for a total of 154 observations.
[c] Granger asymptotic equivalency *F* test.
[d] Ethanol production VAR equation had to be corrected for heteroscedasticity using an ARCH (1) correction. Normality test accepted at the 5% level.

seed over time. The reported statistical evidence of heterogeneity is consistent with the ERS report on GM adoption rates (ERS, 2014).

The policy-induced structural shift in the rate of increase in ethanol production and capacity after 2006 was found to have a statistically significant and positive effect on ΔCorn and ΔBt. The magnitudes of these changes are surprising. Relative to the pre-2007 period, the policy induced estimated range for the change in ΔCorn is between 0.69 and 0.88% (P-value <0.04 and <0.02, respectively) based on the two ΔCorn VAR equation estimates (Table 4). However, for ΔBt, the policy induced estimated change in corn acres planted with Bt is between 6.8 and 9.01% (*P*-value <0.02 and <0.01, respectively). This suggests the acceleration in ethanol production capacity induced by U.S. energy policy had a much greater effect on Bt adoption rates than ΔCorn. This finding supports the supposition posed earlier that GM seed technology and biofuel technology may have begun as independent technological forces in U.S. agriculture, but U.S. policy initiatives provided an economic environment that created a feedback mechanism that linked these two technologies. Thus, the empirical evidence suggests that U.S. biofuel energy policy is a key contributing factor in the rapid adoption of Bt corn seed technology in the U.S. corn production system.

The last issue to be addressed is whether microeconomic forces exerted through the marketplace influenced a producer's decision to plant corn. The soybean/corn price ratio was included to address the caveats associated with conducting Granger Causality tests. Market prices send economic signals to producers on market demand and supply conditions. Soybeans and corn are complementary members in the mono-cropping system currently gaining popularity among U.S. row crop producers. Historically, the long run average of the soybean/corn price ratio has been 2.52 as reported by Zulauf (2013). Ratios exceeding the historical level signal to producers to plant more soybeans and less corn.

Table 4 – VAR analysis results for Granger Causality models.

Models (Y/X)[a]	ΔCorn/ΔBt	ΔBt/ΔCorn	ΔCorn/ΔEth	ΔEth/ΔCorn	ΔEth/ΔBt	ΔBt/ΔEth
AICC stat	614	515	621	1674	1676	520
Rsq.	0.44	0.61	0.42	0.58	0.51	0.60
No. of OBS	143	88	143	88	88	88
Variables[b]						
ΔPBCR	−1.01*	NS	−1.23**	NS	NS	NS
Ethdum	0.69**	6.79**	0.88**	NS	NS	9.01***
IA	NS	S	NS	S	S	S
IL	NS	NS	NS	NS	NS	NS
IN	NS	S	NS	NS	NS	S
KS	NS	S	NS	NS	NS	NS
MI-Base	NA	NA	NA	NA	NA	NA
MN	NS	S	NS	NS	NS	NS
MO	NS	S	NS	NS	NS	S
NE	NS	S	NS	NS	S	NS
OH	NS	NS	NS	NS	NS	NS
SD	NS	S	NS	NS	NS	S
WI	NS	S	NS	NS	NS	NS
ARCH 0	NA	NA	NA	***	***	NA
ARCH 1–3	NA	NA	NA	NS	NS	NA
Runs test P-V[c]	0.21	0.93	0.21	0.74	0.44	0.93

Note: S, NS, and NA denote; statistically significant at the 10% level, not statistically significant at the 10% level, and not applicable, respectively.
[a] Delta (Δ) denotes first difference of variable ($X_t - X_{t-1}$).
[b] Statistical significance levels of 0.1, 0.05, and 0.01 are denoted by the following asterisks, *, **, and ***, respectively. Values reported are estimated VAR coefficients.
[c] Wald–Wolfowitz run test for serial correlation. Ho: white noise. *P*-V denotes *P*-values.

The ΔPBCR coefficient signs estimated in the ΔCorn/ΔBt and ΔCorn/ΔEth VAR equations are negative and statistically significant (P-value <0.09 and <0.04, respectively), as theory predicts. Furthermore, the price ratio was statistically insignificant for the Bt and ethanol production capacity VAR equations (Table 4), which is not surprising for the ethanol VAR equations. However, for the Bt VAR equations, this suggest that the relative market valuation of soybeans to corn did not play a role in Bt seed adoption, and further indicates that Bt seed cost did not play a significant role in the decision to plant corn relative soybeans. Given that both GM soybeans and GM corn have technology fees, it appears that seed cost is not the primary factor affecting the decision to plant corn or soybeans, rather relative price plays the primary role.

5. Consequences of the corn-ethanol feedback mechanism

The rapid increase in the derived demand for corn, as a result of expanding ethanol production, has shifted corn usage (Fig. 4) away from its traditional role as a food source for (1) animal production, and (2) human consumption (Anderson et al., 2008; Wiens et al., 2011). Ethanol expansion has had widespread effects on the world economy and price volatility in the grain markets, and continued reliance on corn-based ethanol will likely result in (1) higher and more volatile food prices, and (2) a further intensification of corn production in the U.S.

The economic and social consequences of the corn-ethanol feedback mechanism have been discussed in the economics literature. Wright (2014) estimates that corn-based ethanol expansion has caused an $800 billion increase in agricultural land prices and a transfer of wealth from consumers to land owners. Bellemare (2015) empirically links the recent spikes in commodity grain prices to increased social unrest in the developing world.

The disproportionate increase in corn production relative to other crops has created unintended ecological consequences as a result of landscape simplification and increased environmental pollution (Hill et al., 2006). High crop prices

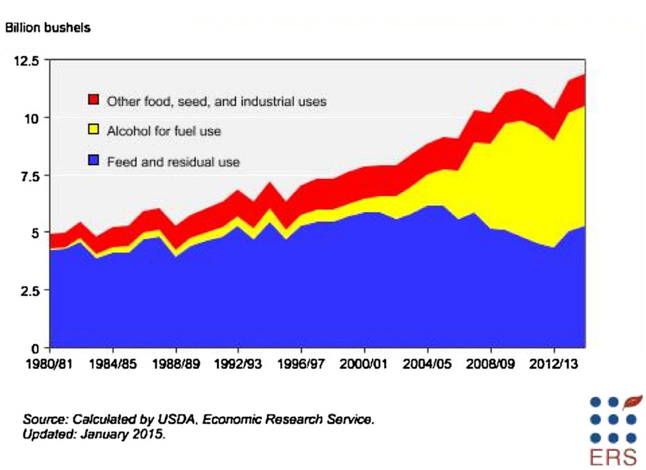

Fig. 4 – U.S. Corn Crop Usages. Source: ERS (2015).

(driven by the corn-ethanol feedback mechanism) have incentivized the replacement of natural areas (wetlands and grasslands) in highly cropped regions (Johnston, 2014; Wright and Wimberly, 2013). Reductions in biodiversity associated with corn intensification reduce the ecosystem services provided by healthy biological communities (Landis et al., 2008), and challenge wildlife conservation (Meehan et al., 2010).

Science has also established that pollution (fertilizers and pesticide use) associated with corn production has important environmental consequences. Several studies have linked the increased nitrogen levels in the lower Mississippi to changes in corn and soy production practices in the Midwest (Donner and Kucharik, 2008). Increased nitrogen levels have been linked to hypoxia and a dead zone in the Gulf of Mexico (Turner et al., 2007). Larson et al. (2010) provides evidence from a simulation analysis predicting an increase in fertilizer and chemical use, and a decrease in soil carbon stocks as a result of increased corn production. Fausti et al. (2012) provide evidence of a positive association between increased per acre insecticide usage and increased corn acreage planted at the county level in South Dakota.

When land-clearing is considered, greenhouse gas emissions associated with corn-based ethanol production are often greater than those created by burning fossil fuels, creating a net carbon debt that will take generations to repay (Fargione et al., 2008). Finally, long-term projections indicate that cellulosic ethanol production based on corn stalks or plant-based feedstock alternatives will not cure this problem (Liska et al., 2014; Searchinger et al., 2008; Pimentel and Patzek, 2005).

Furthermore, studies on alternative energy using biofuel feed-stocks have demonstrated that crops such as sugarcane and palm oil have more favorable conversion ratios with respect to net energy; e.g. Wiens et al. (2011). However, U.S. trade policy with respect to the import quota on sugar, U.S. ethanol subsidies, and the high production cost of commercial cellulosic ethanol preclude the current commercial viability of these feedstock alternatives to corn-based ethanol production in the U.S. Specifically, enzymes required for cellulosic ethanol have a relative production cost basis 20–40 times that of corn based ethanol (Sainz, 2011). While cellulosic ethanol has a smaller carbon footprint than corn based ethanol, it is not economically competitive without additional technological advances.

6. Cracks in the ice: the brittleness of corn dominated agriculture?

The current corn-based ethanol production system is dependent on the three economic forces: (a) U.S. agricultural policy, (b) U.S. energy policy, and (c) technology innovation in the areas of biofuel production and GM seed development. If any one of these three support mechanisms begins to falter, the system will begin to break down.

Consequences to food production will be dependent on which support mechanism becomes unstable. Recent developments in public sentiment, federal biofuel policy, and vulnerabilities to current technologies may forewarn of impending challenges for corn production. For instance, concern continues to be raised about the efficacy and the long run sustainability of the GM seed technology to mitigate pest damage and sustain advancements in yield productivity. In the U.S., widespread adoption of Bt corn technology and abandonment of crop rotations (Claassen et al., 2011; Wallander et al., 2011) and traditional non-Bt corn refuges (Onstad et al., 2011) have helped to select for Bt-resistance in the western corn rootworm (Gassmann et al., 2014). Pest resistance, if not overcome with new technological advancements in GM seed technology, will force producers to return to a traditional rotational cropping system. In turn, this will increase economic stress on grain markets due to a reduction in land suitable for growing corn in any given year. If yield productivity gains fail to materialize, then increasing total U.S. production capability will require extensive growth in planting areas. In turn, extensive expansion of corn acres will lead to further simplification of rural landscapes.

The 2012 drought in the Midwest revealed a serious risk to markets dependent upon U.S. corn production. The current U.S. renewable fuel standard mandates that 15 billion gallons of ethanol (roughly 5.4 billion bushels of corn annually) be blended into fuel in 2015 and then remain constant through 2022. Recent U.S. annual corn production ranged from 10.8 to 13.9 billion bushels per year. Given the current ethanol mandate and recent U.S. corn production history; this implies that approximately 38–50% of the U.S. crop will be devoted to ethanol on an annual basis into the future. In 2012, drought reduced U.S. corn production to 10.8 billion bushels, and the resulting limited corn supply (exacerbated by the mandate to blend minimum levels of corn-based ethanol in gasoline) increased corn prices to record highs ($7.63 per bu.) in August of 2012. Sudden spikes in U.S. grain prices increase volatility in world grain markets, resulting in economic and social instability around the globe (Wright, 2014).

The recent dramatic decline in crude oil prices, the elimination of the ethanol export subsidy and low corn prices will likely result is downward pressure on both ethanol and corn production in the short run. This will result in producers shifting production toward soybeans, wheat, and other crops throughout the region. However, it is unlikely that world petroleum prices will remain depressed. Thus, the implication of the ethanol mandate is continued increased price volatility in world grain markets. Combining market issues associated with the current corn/ethanol production system with the recent challenges associated with extreme weather events, public sentiment, and pest resistance arguably reveal the brittleness of U.S. row crop production practices.

7. Potential solutions to the problem

The rapidity and outcome of the shift away from current corn-dominated crop production patterns could have important perturbations for agricultural markets if the latter are not prepared to adapt. As shown in Fig. 2, the current status of corn-dominated agriculture was created largely by U.S. policy, and thus the solution to the problem will likely have to be at this level.

Solution 1. Restrategize the ethanol mandate. A first potential solution to reducing agriculture's reliance on corn is to link the ethanol mandate to crop production levels by mandating that a maximum percentage of the corn crop (rather than a mandated fixed ethanol production level) be devoted to ethanol production. In addition to reducing the perturbations that ethanol consumption has on corn prices in years of low production, this would provide incentives to ethanol producers to increase their efficiency in extracting ethanol from corn grain. In years of below average corn production, a ceiling on corn usage for ethanol will reduce price volatility by reducing uncertainty surrounding the level of residual corn supply that will be available for human and animal consumption.

Solution 2. Grow more corn on less land. Grain-price-driven high land prices restrict the size of farms, so higher yields are needed to continue increasing ethanol feedstock. Germplasm development (not biotechnology) has historically been the source of increasing corn yields. But investment in corn germplasm research has been supplanted by biotechnology, which has led to a diminishing rate of yield increases and could lead to a trough in grain yield advancements (Shi et al., 2013). Also, crop production is inherently tied to soil health, and prolonged overuse of tillage and a lack of biodiversity in farming operations have reduced soil nutrient status and its capacity for supporting optimal yields (Lehman et al., 2015). Investment in germplasm development and soil health and conservation should be prioritized.

Solution 3. Incentivize innovation in crop and ethanol production. Even if the 15 billion gallon ceiling is lifted, corn will not produce sufficient ethanol to meet future EISA mandate of 36 billion gallons. Thus, major research initiatives into developing other cellulosic feedstock, and increasing the efficiency of ethanol production from these feedstock alternatives is needed to reduce our reliance on corn-based ethanol and increase the resiliency of our biofuel production system. Finally, as crop production is intensified to produce fuel in addition to food and fiber, the implications for these societal and economic changes on species conservation on and around farms becomes imperative. There are numerous ways to alter our current crop production systems in ways that conserve biodiversity (e.g., reduce soil disturbance, diversify in-field plant communities through rotations and ground covers, strategize uncropped areas of the field to promote biodiversity, etc.). Thus, promoting research to make these agronomic strategies scalable, transferable, and predictable will help alter farmer behavior.

8. Summary

The convergence hypothesis suggests that U.S. agricultural and energy policy induced a causal relationship running between ethanol production capacity decisions in high corn production states, to the Bt adoption decision by row crop producers, to the producer's decision on how many acres of corn acres to plant in the Midwest Corn Belt and Northern Great Plains region (2000–2013). Empirical evidence supporting the hypothesis is provided in the form of a Granger Causality test. VAR analysis also provides empirical evidence that U.S. biofuel energy policy has been a contributing factor of the rapid adoption of Bt corn seed technology by the U.S. corn production system.

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