Role of land quality in corn acreage response to price and policy changes: evidence from the Western Corn Belt

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Abstract
Land quality influences how farmers allocate croplands in response to market forces. Farmers in the Western Corn Belt (WCB) have historically utilized the highest quality lands for corn cultivation, putting lower quality lands to other uses. This paper questions whether high corn prices influenced expansion of corn cultivation on lower quality lands, and the role played by US biofuel policy in such land use change. Using three decades of data, I estimate that the proportional change in corn acreage to rising corn prices is nearly three times larger in counties with lowest land quality versus those with the highest land quality. This variable response, however, is driven by the changes in cropland use for corn cultivation after 2006, the period following the change in US biofuel policy, and punctuated by two crop price spikes. Marginal agricultural lands and other lower quality lands, such as grasslands used for range or pasture, are therefore prone to conversion into corn cropping disproportionately during high price periods. High price responsiveness of lower quality lands also suggests these lands may cycle in and out of corn cropping opportunistically. This has implications for marginal land availability for bioenergy crops, and poses environmental concerns to the extent lower quality lands are also more environmentally sensitive.

1. Introduction
Globally, corn prices rose between 2005 and 2008 from $2 per bushel to nearly $8 per bushel, with similar price increases observed for soy, wheat, and rice. Since most of the world food supply is connected to these staple grains, the higher crop prices meant higher food prices for many, with the burden falling disproportionately on the poor who spend a larger share of their income on food (Mitchell 2008). Between 2008 and 2010, high prices for food items led to protests across the world (Baker 2008, the UN 2011). The World Bank (2011) predicted high prices might have pushed as many as 44 million people into extreme poverty.

Biofuel mandates that had recently been introduced in the US and the EU contributed to the increase in crop and food prices (see the National Research Council 2011, Roberts and Schlenker 2013, Chen and Khanna 2013, and Condon et al 2015), and in the US, there was a sharp increase in the use of corn as the feedstock for ethanol production. The policy has transformed US corn production, impacted world food supply, and reshaped agricultural land use within and outside of the US (Khanna and Crago 2013 and Nuñez et al 2013), despite a subsequent restriction on the share of corn ethanol in total biofuels quota in 2007.

The US biofuel policy had been motivated by the desire to reduce dependence on fossil fuels and mitigate climate change, but the conversion of previously uncropped lands into the cultivation of corn may have been an unintended consequence of its implementation (Wright and Wimberly 2013, Lark et al 2015). Such land use/land cover change has adverse consequences for natural habitats (Meehan et al 2010), while also adding to the planet’s carbon debt by possibly reversing the environmental benefits of a switch to ethanol from gasoline (Searchinger et al 2008 and Fargione et al 2008).
One way to mitigate the negative land use effects of the ethanol industry is to use perennial bioenergy crops (miscanthus and switchgrass) grown on marginal, abandoned, or idled agricultural lands as feedstock rather than corn (Field et al. 2008, Somerville et al. 2010, Gelfand et al. 2011, Georgescu et al. 2011, and Wang et al. 2017). Earlier studies estimated the supply of such lands at the global and US-scales (Cai et al. 2010, Zumkehr and Campbell 2013). Yet, some of these newly added corn acres could also be encroaching on available marginal lands. Under current policy, about 90 million acres of corn is harvested every year in the US, compared to fewer than ten thousand acres dedicated to perennial bioenergy crops (NASS 2018).

Both previously uncropped lands and marginal or abandoned agricultural lands are likely to be of lower quality and more environmentally vulnerable. Such lands tend to have more sloped and erodible soils, experience more nutrient runoff, and may harbor more species of imperiled plants and animals than croplands that remain in cultivation (Lubowski et al. 2006a). The features that make these lands more susceptible to environmental degradation may be exacerbated by farming practices. For example, sloping lands are prone to erosion and difficult to farm, and their very erodibility may be worsened by farming (Pimentel 2006).

All else equal, farmers would not choose to cultivate on lower quality lands because of their poor productivity and higher upfront conversion costs, both of which translate into lower profitability. However, when crop prices are high it becomes easier to clear these hurdles. Thus, an interesting question is how corn cultivation has expanded on lower quality lands in response to high corn prices, and whether such response has varied before and after the change in US biofuel policy, which now routinely consumes over a third of US corn output. If the lands that move in and out of corn cultivation have lower productivity, are more environmentally vulnerable, and at the same time more sensitive to high prices, then high prices would generate larger environmental impacts while delivering limited economic (output) benefits (Lubowski et al. 2006a).

Earlier economic studies that considered land quality and acreage response did so in the context of conversion of non-croplands into croplands. For example, in a national study, Lubowski et al. (2006b) find the category least likely to convert into croplands are rangelands, which are of lowest quality. Claassen et al. (2011) report higher economic responsiveness for rangelands to transition to croplands when studying 77 counties in the Dakotas for a more recent time period. Miao et al. (2016) also estimate corn acreage response to price, but their analysis ends in 2007 and does not investigate the role of land quality. This paper considers the influence of land quality on acreage decisions involving a major crop (corn) in the WCB rather than broad categories of land use; it covers the post-biofuels period that has experienced not one but two crop price spikes; and combines high resolution spatial and high frequency time series data in its analysis. In addition, it revisits the 2007 change in US biofuel policy and examines the policy’s land use impacts on the use of marginal lands and grasslands over a longer timeframe in the economically and environmentally significant WCB region.

2. Data and methods

2.1. Study area

Consisting of Iowa, Minnesota, Nebraska, North Dakota and South Dakota, the WCB is an important US corn producing region. It represents 44% of corn acres planted and nearly 50% of corn production in the US (NASS 2018). The WCB is environmentally significant, as Nebraska, North Dakota and South Dakota contain almost all (99.5%) of the remaining tall and mixed grass prairie in the Corn Belt (Mac et al. 1998) and ecological hot spots such as the Prairie Pothole Region (PPR) are within its boundaries. The WCB also has a higher concentration of marginal agricultural lands suitable for bioenergy crop cultivation (Cai et al. 2010), a more sustainable alternative to corn for producing biofuels.

2.2. Land quality metric and GIS analysis

There are several acceptable measures of land quality. Some previous studies use focused measures like topography (Muller and Zeller, 2002), soil water holding capacity (Lichtenberg 1989), or yield proxies like the NCCPI (Claassen et al. 2013). Here, I use the non-irrigated land capability classes (NICC) from the Natural Resources Conservation Service’s gridded 90 m soil data (gSSURGO) product (Soil Survey Staff 2016). The NICC is a broad-based measure of land suitability for agriculture that captures soil and climate characteristics along with land management considerations. It has been used widely in the economic analysis of land use change literature (Hardie and Parks 1997, Lubowski et al. 2006a, 2006b, 2008, Lewis and Plantinga 2007, Claassen et al. 2011 and Radloff et al. 2012). It is a categorical measure that ranges from 1 to 8, where 1 indicates the highest land quality (most suitable for cropping), and 8 indicates the lowest (least suitable). Classes 4 and below are arable lands, although classes 3–4 are considered to have severe to very severe limitations for cropping. Best use for classes 5 and above is pasture/range.

Here the terms NICC score, average NICC score or mean NICC score are used interchangeably. They all correspond to land capability classes either at the 90 m spatial resolution or an area-weighted average computed
at coarser scale (e.g. county). To assess the distribution of land quality in the WCB, I perform a frequency analysis of NICC scores at the 90 m resolution for the entire region. The NICC scores are then aggregated to the county scale on an area-weighted basis for econometric analysis.

GIS analysis of the land quality by land use utilizes fine spatial scale satellite data from the National Agricultural Statistics Service (NASS) Cropland Data Layer (NASS 2017a) and coarser scale county-level data on corn acreage (NASS 2018) with a longer history. For consistency, I use the CDL product from 2010 to 2016, resampled from 30 m to 90 m to match the resolution of gSSURGO. (Prior year CDL products had different specifications, and comparisons across products were not recommended (Kline et al. 2013). In 2017, CDL for 2008 and 2009 were reissued at 30 m. As this extension does not cover the pre-biofuel period, the analysis is limited to post-2010).

Because the CDL contains over 100 distinct land use categories, land uses are first reclassified into groups: corn (including doublecroppings); soy or wheat; other field crops (e.g. oats); all other crops (e.g. vegetables); cultivated hay (including alfalfa); idle/fallowed croplands; grass/pasture; and non-cropland uses (e.g. urban). Then, the area-weighted average NICC scores is calculated for each combination of crop group and year for the entire study area and at the county level.

2.3. Price response of corn acreage under variable land quality

Price elasticity measures percent change in the supply of a product in response to percent change in its own price. Because the supply of a crop—here corn—is the product of its acreage and yield, one can estimate the price elasticity of acreage by substituting acreage for total supply.

If higher corn prices result in an increase in area under corn cultivation (positive price elasticity of acreage), does such response vary with land quality? The hypothesis is that the acreage response to higher corn prices would be greater in areas with lower and more heterogeneous land quality compared to those with uniformly high land quality. In an area where land is relatively homogeneous and high quality, farmers would already have cropped most of the land, and there might not be much additional acreage for expanding corn cultivation. While more land might be available for corn cropping in areas of heterogeneous land quality, these would be of lower average quality. When corn prices rise, however, farmers can justify using these lower quality lands that might have been unprofitable corn cropping before.

To test this, I develop a multivariate model of price response that relates corn acreage and corn prices. My sample includes 396 counties in the WCB (out of 398, as two reported no corn acreage for the sample period) and covers 1986 to 2015. All price and acreage data used in the model is from NASS (2018) unless specified otherwise.

The dependent variable is planted (not harvested) corn acreage because it is more representative of the farmers’ planting decision. During the sample period, planted corn acres in the WCB rose by 6.9 million acres (23%). At the county level, there is considerable variation in planted acres. The top quartile of counties plant corn, on average, five times more than the bottom quartile, though the gap has narrowed since 2006 (figure 1 (A)).

The main explanatory variable is the state-year average of received corn prices. Comparable price series for major crops grown as alternatives to corn are control variables. Based on the average planted acreage over 1986–2015, these alternative crops are soy, oats and hay (Iowa) and soy, wheat and hay (Minnesota, Nebraska, North Dakota, and South Dakota). Prices for corn and these major alternative crops follow similar trends during 1986–2015 (figure 1 (B)).

I use one-year lagged prices to capture farmers’ expectations of current prices, which are formed prior to planting season. Use of lagged prices also helps control for the simultaneous causal relationship between current year supply (acreage) and price. If there are unobserved supply shifts in the current year—e.g. a reduction in corn harvest due to an unanticipated drought—these would affect the current price. Using current prices in the model would thus cause price and the error term to be correlated, creating a biased price elasticity estimate. However, a shift in supply in the current period could not have influenced past prices.

The fertilizer price index is used as a proxy for changing input costs. Corn is a fertilizer intensive crop, making this index an appropriate measure of input costs (figure 1(C)).

All price variables are in 2015 dollars obtained by deflating nominal prices by the consumer price index (Bureau of Labor Statistics 2016).

In the US, federal policy plays an important role in shaping farmers’ land use decisions. I consider three relevant policy events. Acreage reduction programs compensated farmers to idle otherwise productive croplands during periods of low prices. The latest incarnation, known as ‘set asides’, was eliminated in the 1996 farm bill (FAIR Act). This is represented by a dummy variable that takes on the value of 0 before 1996, and 1 after.

The Conservation Reserve Program (CRP) is also a type of acreage reduction program. Under CRP, farmers are paid to temporarily remove cropland from production, though the program’s main goal is environmental, and limiting surplus crop production and providing income to farmers are secondary (Goodwin and Smith 2003). I include the county average CRP rental payments (FSA 2018) in the model. These payments are customized to each
contract’s environmental benefits index (EBI) score, but pegged to past three-year’s non-irrigated cropland rental rates in the county (figure 1(D)).

Another dummy variable captures any non-price related effects of the Energy Policy Act of 2005 (EPAct), which created an annual quantity mandate for biofuels, mainly ethanol, to be blended with gasoline. In the US, the primary feedstock for ethanol continues to be corn.

I control for pre-planting (April average) precipitation, since excess moisture adversely affects the decision to plant corn. The spatially interpolated, gridded daily precipitation data (2.5-mile cell size) is from Schlenker and Roberts (2009), updated through 2015.

The model is a multivariate panel regression of county-year corn acreage data on corn prices and these control variables, estimated using ordinary least squares (1).

\[
A_{jt} = \beta_1 \text{corn}_{jt-1} + \beta_2 \text{soy}_{jt-1} + \beta_3 \text{wheat/oat}_{jt-1} + \beta_4 \text{hay}_{jt-1} + \beta_5 \text{fert}_{jt-1}
+ \beta_6 \text{CRP}_{jt-1} + \psi \text{ppt}_{jt} + \beta_7 D1996 + \beta_8 D2006 + \varphi j + f(t) + \epsilon_{jt}
\]

The dependent variable is the natural log of planted acres of corn, \(A_{jt}\), in county \(j\) and year \(t\). The explanators are \(\text{corn}_{jt-1}\), the log of lagged received state-level corn prices; and \(\text{soy}_{jt-1}\), \(\text{wheat/oat}_{jt-1}\), \(\text{hay}_{jt-1}\), the similar price series for alternative crops; and \(\text{fert}_{jt}\), the fertilizer price index. The CRP variable is the log of county-level CRP rental payments. The log-log specification allows us to estimate percentage changes linearly. Average April precipitation is represented by \(\text{ppt}_{jt}\). The dummy variable for the FAIR Act is labeled \(D1996\) and \(D2006\) marks the pre/post-biofuels period. Finally, \(f(t)\) is the linear time trend and \(\epsilon_{jt}\) is the error term. The coefficient on corn price (\(\beta_1\)) is the measure of price elasticity, which predicts percentage change (increase) in acreage given percentage change (increase) in crop prices.

Land quality variables are not included in the model directly. Instead, the model is estimated for sub-samples of counties based on quartiles of county-average NICC scores. The quartile breakpoints reflect the benchmark NICC scores by land use derived from the 2010–2016 CDL data. The breakpoint between the 1st and 2nd quartiles (2.65) is comparable to the average NICC score for corn-planted areas. Moving from the 2nd to the 3rd quartile, the breakpoint (3.05) is indicative of the transition from active to idled/fallowed croplands and hay. The NICC scores for counties in the 4th quartile (3.97 and above) signal shift into grass/pasture. Also, the county...
average corn yield declines with each quartile. The yield differences between quartiles are statistically significant (pairwise comparison of means, \( p < 0.01 \)), indicating each quartile is distinct in terms of land productivity.

The county-level fixed effects (\( \varphi \)) control for average differences across counties in (observable or unobservable) predictors that are not explicitly included in the model. This insures against a type of omitted variables bias in case there are fixed parameters common to the sample counties. Analyzing a large sample of counties (99 for each land quality quartile) increases statistical power of the model and generates an ‘average effect’ for the sample.

3. Results and discussion

3.1. Analysis of land quality

Land quality in WCB is, on average, suited to cropping. The area-weighted average NICC score for the entire region is 3.75 with 72% of all lands belonging to class 4 or lower (figure 2(A)). The higher quality lands are concentrated between the rivers Upper Mississippi and the Missouri, and lie in Iowa, southwestern Minnesota, and the eastern portions of South Dakota, North Dakota, and Nebraska.

Satellite data from the CDL for 2010–2016 permits a high-resolution assessment of how land use and land quality interact. The mean NICC score for corn planted areas during any of these 7 years is 2.45: lower and statistically different from the mean score for the entire WCB. The lower standard deviation of NICC scores for corn cultivation indicates the activity is concentrated in high land quality areas (figure 2(B)). Ninety-six percent of all corn cultivation in the WCB takes place on arable lands (NICC score \( \leq 4 \)). The majority of the remaining 4% occurs on lower quality lands in Nebraska. There, farmers can irrigate crops using groundwater from the Ogallala Aquifer, offsetting the effect of lower land quality (Lichtenberg 1989).

Over a third of WCB was planted to corn at least one year between 2010–2016. Most often, farmers planted corn in the same fields 3–5 years out of the 7 analyzed here. Opportunistic cultivation of corn (1–2 years out of 7) is less prevalent, and so is near-continuous cultivation of corn (6–7 years out of 7). Corn is still likely planted in rotation with other crops. Moreover, a substantial portion of arable lands were never planted to corn (34%) (figure 2(B)).

Benchmark NICC scores by different agricultural land uses in the WCB indicate corn cultivated areas to have the highest land quality and grass/pasture the lowest (mean NICC scores of 2.45 versus 4.75). The average NICC score for the other two main cash crops, soy and wheat, is slightly higher at 2.49, followed by other field crops, croplands left idle or fallowed, and cultivated hay (figure 3(A)). Each pair of means are statistically different from each other at 1% based on t-tests. Non-parametric ranksum test also indicates corn is different from all other land use categories in terms of land quality (at \( p < 0.01 \)), except for the soy/wheat planted areas.

Clearly, farmers consider land quality when choosing land use, and allocate the highest quality lands to primary cash crops. If farmers have been allocating increasingly poorer quality lands into corn cultivation over the years, using a more recent (post-2010) estimate of average land quality would tend to raise the average NICC scores. However, the relative positions of different land uses with respect to land quality would remain comparable.

Since satellite-based cropland data does not go as far back as survey-based, county-level land use data, I pair the high-resolution data on soil quality with high temporal resolution county crop acreage data from the USDA for the econometric analysis. Due to aggregation and within-county variation in land quality, the mean NICC scores by land use are slightly different at the county level (2.66 for corn and 3.80 for grass/pasture as bookends). Of the 396 WCB counties in the sample, 103 have average land quality scores at or below 2.66. Most are in Iowa (46) and Minnesota (34). Another 110 have an average NICC score \( > 3.80 \), the benchmark score for grass/pasture, majority of which are in Nebraska (40) and South Dakota (23). Nearly half of them (183) have average NICC scores that fall in between (see histograms in figure 2(A)).

County-level data confirms the link between higher land quality and corn cultivation. Between 1986–2015, the better the average land quality in a county, the more acres have been planted to corn. This pattern is not driven by cropland size, since the relationship holds for the share of corn cultivated areas in total cropland by county (figure 3(B)).

3.2. Analysis of price response

The response of corn acreage to higher corn prices—the coefficient estimate on corn price—is positive and significant in the full sample as well as for the four quartiles of county-average NICC scores (table 1). The positive sign and the magnitude of the coefficient is consistent with the literature for the supply of crops, and specifically, acreage (Chavas and Holt 1990, Chembezi and Womack 1992, Lin and Dismukes 2007 and Miao et al 2016). A positive price elasticity indicates farmers’ ability to expand corn acreage in response to rising corn prices. Additionally, the higher the price elasticity, the more flexibility farmers have in expanding acreage.
Moreover, the price elasticity estimates are decreasing in land quality, indicated by the higher coefficient on corn price for successive quartiles. This aligns with the prediction that counties with more heterogeneous and thus lower average land quality would be more flexible in adding corn acreage when corn prices rise (table 1, quartile columns). The log-log specification of the empirical model allows the interpretation of the coefficients as percentage changes. So, when corn prices double (in real terms), the planted acreage of corn can be expected to increase by 52% in counties that are in the bottom quartile for land quality. However, the comparable response would be only 18% for the counties in the top quartile. Evaluated at the means, these translate to an expansion of corn acreage by approximately 18,900 acres for the counties in the bottom quartile, compared to 24,700 acres for those in the top quartile. Thus, the magnitude of impacts are closer in terms of levels than in percentage terms. This is because, on average, the planted corn acreage in the bottom quartile counties is much lower than the top quartile (36,500 versus 140,800 acres; see the last row in table 1 for the mean planted acres of corn by land quality quartile).

Corn acreage generally responds negatively when the prices of alternative crops (except for soy) and CRP rental payments are higher (table 1, full sample). This suggests wheat, hay and oats, and enrolling croplands into the CRP program are substitute land uses to corn cultivation in the WCB.

Figure 2. Land quality and corn cultivation in the WCB. (A) Land quality in the WCB based on the non-irrigated crop capability (NICC) score (90 m resolution). The rivers Missouri and Mississippi, and boundaries for the Ogallala Aquifer and the Prairie Pothole Region (PPR) are denoted. (B) Areas planted to corn in the WCB from CDL (2010–2016) grouped by frequency of planting and overlaid with NICC scores high (<4) or low (≥4). The right-hand side histograms in both (A) and (B) depict the distribution of county-average NICC scores by state with reference lines that correspond to (i) areas planted to corn and (ii) lands identified as grass/pasture (CDL 2010–2016), respectively.
The coefficients on soy prices are positive for the full sample and the land quality quartiles (and significant except for the first quartile). Over the sample period, the dominant relationship of corn and soy with respect to land use appears to be one of complementarity. This is consistent with agronomic (Edwards et al 1988 and Crookston et al 1991) and field (Wallander 2013) evidence that corn-soy rotations improve yields and control pests, and continuous (at least three years in a row) cropping of either has been uncommon.

The generally expected relationship between prices of inputs, like fertilizer, and supply is negative. Higher input prices may cause farmers to switch away from corn to save on costs, especially in areas with low corn yields, to less fertilizer-dependent crops. Indeed, higher fertilizer prices have a statistically significant and negative impact on corn acreage across all quartiles.

Table 1. Price responsiveness of planted acres of corn, full sample and by land quality quartiles. The full sample includes 396 counties in the WCB. Model estimated with county-year data 1986–2015. T-statistics are reported below coefficients and significance levels of coefficients are reported as (‘’) 10%, (‘’’) 5%, and (‘’’) 1% level. (i) For counties in Iowa, the third major alternative crop is oat and not wheat, therefore oat prices are used in lieu of wheat prices.

| Variable: Full sample Quartile I Quartile II Quartile III Quartile IV |
|---------------------------------------------------------------|
| Lagged corn (‘own’) price 2015 $/bu 0.291*** 0.176*** 0.216*** 0.289*** 0.519*** |
| 16.71 5.66 6.26 7.47 10.42 |
| Lagged soy price 2015 $/bu 0.144*** 0.050 0.235*** 0.247*** 0.165*** |
| 5.61 1.06 4.12 4.63 3.33 |
| Lagged hay price 2015 $/ton −0.034* −0.117*** −0.072* 0.023 0.088* |
| −1.69 −4.2 −1.96 0.62 1.93 |
| Lagged wheat/oat prices 2015 $/bu −0.126*** −0.010 −0.129*** −0.139*** −0.365*** |
| −6.34 −0.46 −3.01 −2.57 −6.11 |
| Lagged county average CRP rental payments, 2015 $/acre −0.584*** −0.736*** −1.088*** −0.859*** −0.490*** |
| −8.77 −3.92 −5.29 −7.29 −4.55 |
| Fertilizer price index −0.294*** −0.261*** −0.317*** −0.365*** −0.221*** |
| −10.86 −9.03 −5.94 −6.75 −3.46 |
| April precipitation (mm) −0.0007*** −0.0003*** −0.0012*** −0.0010*** −0.0003 |
| −9.64 −4.03 −7.26 −6.27 −1.33 |
| Time trend 0.0147*** 0.0162*** 0.0210*** 0.0162*** −0.0007 |
| 13.78 11.22 9.55 7.96 −0.24 |
| Dummy for FAIR Act (1996) −0.0574*** −0.0675*** −0.1562*** −0.1488*** 0.0735* |
| −4.13 −3.45 −5.62 −4.98 1.83 |
| Dummy for EPAct (2006) 0.1150*** 0.0780*** 0.0872*** 0.1394*** 0.1210*** |
| 10.25 5.6 4.53 6.1 4.61 |
| Constant 14.09*** 16.31*** 16.98*** 15.01*** 11.77*** |
| 47.84 18.21 18.03 28.34 22.97 |
| No. of observations 10 734 2841 2818 2750 2325 |

Mean acres of corn planted (1986–2015) 89,810 140,774 102,906 72,826 36,453
Excessive precipitation during the planting season has a discouraging effect on corn planting in the WCB as suggested by the negative coefficient on average April precipitation for the full sample as well as the counties in quartiles I–III.

The 1996 dummy measures the impact of the passage of the FAIR Act in 1996, which eliminated the acreage set aside. In the mid 1980s, as many as 80 million acres of cropland were idled under this program nationwide (Glauber and Effland 2016). The model suggests, overall, the FAIR Act led to lower corn acreage in the WCB based on the negative and significant coefficients (for all but the 4th quartile counties). Initially, farmers welcomed the elimination of acreage controls and the planting flexibility afforded by the act, and corn acreage expanded nationwide. This expansion, however, led to lower crop prices and a subsequent adjustment in acreage and output.

The 2006 dummy for EPAct is positive and significant for the full sample as well as the land quality quartiles. Thus, the change in the US biofuel policy led to an increase in corn acreage beyond its influence on crop prices. Also, the coefficients are larger in magnitude for quartiles III and IV, suggesting this effect has been more pronounced for counties with lower land quality.

The coefficients of the linear trend component for all counties but those in quartile IV are positive and significant. Thus, even if prices and CRP payments had been constant, and there had been no policy changes, the corn acreage in the WCB would have risen over this period for counties in the first three quartiles. For the counties in quartile IV there is no discernible time trend to corn cultivation; a possible sign of opportunistic cultivation of corn in these counties. Lastly, the constant term confirms the baseline amount of corn planted declines with land quality since the estimates are smaller for the third and fourth quartile.

Next, I investigate whether the acreage response varies before and after the change in biofuel policy using a break point at 2006. The biofuel mandate introduced by EPAct started at 4 billion gallons in 2006, which rose to nearly 17 billion gallons by 2015. Assuming 2.7 bushels of corn is needed to produce one gallon of ethanol (Rajagopal et al 2007), the 2015 mandate accounted for 46% of that year’s US corn output. More than a third of US corn crop is now consistently used for ethanol (average is 36% for 2007–2015), compared to 8% in the decade prior (ERS 2018).

The rapid ascent in corn prices around 2006 can be attributed partly to this policy change (Roberts and Schlenker 2013). Prior to 2006, received corn prices by farmers in the WCB averaged $2.1/bushel, which jumped to $4.4/bushel 2006–2015. Also, over 65% of the regional expansion in corn acreage in the WCB occurred post-2006.

Splitting the sample at 2006 reveals that the full (30-year) sample results (table 1) are driven by the price response post-2006 (table 2, A versus B). The price response is much higher in magnitude post-2016 (0.48 versus 0.19) for the complete set of counties. Additionally, the inverse relationship between land quality and price response is not apparent in the pre-2006 period, with the top quartile emerging as most price responsive. Estimates of the post-2006 period, on the other hand, strongly exhibit the relationship we observed in the full sample estimates, where price responsiveness rises with diminishing land quality.

There are two plausible, non-mutually exclusive explanations: first, the use of lower quality lands for corn cropping responds non-linearly to price. In other words, prices need to be above a certain threshold for farmers to utilize the lower quality lands for corn cultivation. The second is associated with declining availability of higher quality lands in the WCB over time for corn cultivation.

With respect to other control variables, the sign on soy price flips from positive before 2006 to negative after 2006. This suggests corn and soy have become substitutes in land use in the biofuel era.

The influence of CRP payments on corn acreage also appears to have diminished pre/post 2006. CRP enrolments peaked in 2007 at 36.8 million acres, about 10 million of which were in the WCB, and have steadily declined since then. In 2007, many CRP contracts were not renewed nationwide. Nearly 1.1 million CRP acres returned to cropping in the WCB. Several hundred thousand acres exited the program early in 2008, despite facing payback of past rents plus penalties (Heimlich 2010). Since 2005, CRP rental payments have not been able to keep up with high prices and lure farmers away from cropping. While cropland rents have adjusted to reflect high crop prices, CRP rental payments have trailed behind (figure 1C). Between 2004–2008, oil prices nearly tripled, resulting in higher fertilizer prices (figure 1C). Despite this, the impact of high fertilizer (and, generally, input) prices on corn acreage in the post-2006 period has been more muted than the pre-2006 period (for the full sample, −0.31 versus −0.23). It is possible that after 2006, rather than switching to alternative crops, some corn farmers have chosen to substitute land for inputs. This is a more meaningful strategy in the higher quality counties, and those in quartiles I and II have lower or not significant coefficient estimates for fertilizer price index post-2006. Strikingly, for the bottom quartile of counties (lowest quality), the sensitivity to input prices is substantially higher post-2006 than pre-2006. That may be due to the low productivity of these lands and high fertilizer use may be necessary to extract satisfactory yields (Cassman 1999).

Overall, the results indicate a different pattern of farmer choices with respect to corn cultivation based on land quality. Based on a joint Wald test of coefficients (after estimating pooled model of all quartiles) I reject the
Table 2. Price responsiveness of planted acres of corn, pre- / post-biofuels period, full sample and by land quality quartiles. The full sample includes 396 counties in the WCB. Sub-model (A) estimated with county-year data over 1986–2005 and (B) over 2006–2015. T-statistics are reported below coefficients and significance levels of coefficients are reported as (*) 10%, (**) 5%, and (***) 1% level. The 1996 dummy is omitted from (B) because it falls outside of the period covered in the sub-model, and the 2006 dummy is omitted from both (A) and (B) since the sample is divided at 2006. (i) For counties in Iowa, the third major alternative crop is oat and not wheat, and therefore oat prices are used in lieu of wheat prices.

| Variable: | Full sample | Quartile I | Quartile II | Quartile III | Quartile IV | Full sample | Quartile I | Quartile II | Quartile III | Quartile IV |
|-----------|-------------|------------|-------------|--------------|-------------|-------------|------------|-------------|--------------|-------------|
|           | (A) 1986–2005 |           |             |              |             | (B) 2006–2015 |           |             |              |             |
|           |             |           |             |              |             |             |           |             |              |             |
| Lagged corn (“own”) price 2015 $/bu | 0.191*** | 0.272*** | 0.157*** | 0.184*** | 0.223*** | 0.480*** | 0.268*** | 0.471*** | 0.577*** | 0.777*** |
| Lagged soy price 2015 $/bu | 0.161*** | 0.037 | 0.208*** | 0.263*** | 0.145*** | -0.359*** | -0.369*** | -0.423*** | -0.442*** | -0.212*** |
| Lagged hay price 2015 $/ton | 0.018 | -0.088*** | -0.039 | 0.079* | 0.136*** | -0.001 | 0.050 | -0.008 | -0.005 | -0.150* |
| Lagged wheat/oat pricesi 2015 $/bu | -0.171*** | -0.018 | -0.170*** | -0.224*** | -0.341*** | -0.174* | -0.157 | -0.280 | -0.288*** | 0.001 |
| Lagged county average CRP rental payments, 2015 $/acre | -0.314*** | -0.314*** | -0.725*** | -0.735*** | -0.331*** | -0.174** | -0.157 | -0.280 | -0.288*** | 0.001 |
| Fertilizer price index | -0.514 | -3.09 | -3.71 | -6.67 | -2.89 | -2.55 | -1.14 | -1.37 | -2.78 | 0.01 |
| April precipitation (mm) | -0.307*** | -0.292*** | -0.296*** | -0.347*** | -0.268*** | -0.234*** | 0.076 | -0.230* | -0.363*** | -0.850*** |
| Time trend | -0.005*** | -0.0001 | -0.0008*** | -0.0009*** | -0.0003 | -0.0003*** | -0.0003* | -0.0004** | -0.0004** | 0.0002 |
| Dummy for FAIR Act (1996) | 0.0113*** | 0.0191*** | 0.0119*** | 0.0059* | -0.0114** | 0.0279*** | 0.0091* | 0.0332*** | 0.0412*** | 0.0432*** |
| Dummy for EPAct (2006) | 0.0055 | -0.0386*** | -0.0418*** | -0.0491** | 0.1546*** | - | - | - | - | - |
| Constant | 12.87*** | 14.07*** | 15.36*** | 14.44*** | 11.48*** | 12.41*** | 12.27*** | 13.13*** | 12.88*** | 12.75*** |
| No. of observations | 7230 | 1863 | 1866 | 1845 | 1656 | 3504 | 978 | 952 | 905 | 669 |
hypothesis that the counties in different quartiles respond to corn price changes identically (F value significant at \( p < 0.01 \)).

Clustering the standard errors by agricultural statistical districts (USDA groupings of 8–9 counties where similar crops are grown) to address potential spatial correlation in the dependent variable results in lower t-statistics and wider confidence intervals for some of the estimated coefficients. However, the price elasticity estimates remain robust (at \( p < 0.01 \)) and my conclusions do not change. Similarly, the results and their interpretation do not change materially if the NICC metric is derived from higher resolution (10 m) gridded SSURGO data instead of the 90 m (see supplemental information available online at stacks.iop.org/ERC/1/061004/mmedia).

3.3. Implications for marginal lands and grasslands in the WCB
About 41% of the WCB are marginal agricultural lands suitable for bioenergy crop cultivation based on assessment of Cai et al. (2010) conducted globally at 1 km scale. Higher resolution data from the NICC and CDL can be used to refine Cai et al. (2010) estimates for marginal lands for bioenergy crops in the WCB. Marginal land quality in the WCB is on average worse than the non-marginal portions based on NICC (mean scores of 3.8 versus 3.6, with the two groups statistically different at 1%). Using data from the CDL, it is observed that nearly a quarter of these marginal lands have already been planted to corn at least one year between 2010–2016, concentrated in portions with lower NICC scores (mean 1.87, figure 4). Also, on a county level, half of the counties in the WCB had 15% or more of their cropland described as marginal.

Based on this evidence, the highest quality marginal lands (NICC score \( \leq 2 \)) can be excluded from an assessment of available marginal lands, as these are likely to be used for conventional cropping. This shrinks available marginal land area in the WCB by almost 36%. Further excluding the lowest quality lands (NICC score \( \geq 7 \)) reduces the amount of available land for bioenergy crops by another 11% (figure 4). The remainder constitutes roughly one-fifth of the entire land area of WCB (about 48 million acres), still a sizeable land base for bioenergy crop cultivation.

Nonetheless, bioenergy crops might need to compete with corn even on this subset of lands in the event of another price spike. For example, between 2009–2012, corn prices increased again three years in a row (by 46%, 16%, and 9%), going from $3.8 to nearly $7/bushel (in real terms), reflecting the effects what became one of the worst droughts in the US history (Rippey 2015).

The analysis presented in this manuscript predicts this price increase would lead to a larger percentage expansion in planted corn acres for the WCB counties with lower land quality versus those with higher land quality. On an aggregate basis, total corn planted area expanded in the WCB by 5.52 million acres from 2010 to 2012, or by 15%. About 40% of this expansion, or 2.24 million acres, occurred in counties that fall within our refined marginal lands criteria, representing a growth rate of 29%. The comparable growth rate for the rest of
WCB counties over the same time frame was 6.6%. (Note acreage is responding to prices with a year’s delay). Thus, not only available marginal land area for bioenergy crops is smaller than estimated when refined using higher-resolution land use and land quality data, but this land is also more likely to be planted to corn during high crop price periods.

My results also speak to earlier work concerning the transition of grasslands to croplands in the WCB (Claassen et al 2011, Wright and Wimberly 2013). Based on recent satellite data, the grass/pasture land use category has the poorest land quality in the WCB (figure 3A). Also, the counties with the highest average NICC scores have a larger proportion of land use in grass/pasture. During 2010–2016, the proportion of grass/pasture in the fourth land quality quartile of counties averaged 58%, compared to 10% for those in the first land quality quartile. Based on the econometric predictions presented here, high prices will cause a larger relative expansion of corn cultivation in the counties with the largest grass/pasture land use.

Marginal agricultural lands and grass/pasture areas to some extent overlap in the WCB, but not all marginal lands are grass/pasture (and vice versa). However, during 2010–2012, the areas where most low quality marginal lands transitioned to corn also appear to be those that registered largest net losses of grass/pasture. Over one million acres of grass/pasture in 2010 appeared in corn cultivation in 2012. These hotspots for marginal land and grass/pasture losses also largely overlap with the fragile PPR wetlands (figure 5). The loss of grasslands to corn documented in the immediate aftermath of the change in US biofuel policy (Wright and Wimberly 2013) has apparently resumed with the next price spike. Since most of the CO₂ emissions from previously uncultivated grasslands versus managed range/pasture (Grandy and Robertson 2006), it is preferable to target bioenergy crop cultivation on these low quality marginal lands that have already been cropped. However, as this analysis demonstrates, these are precisely the areas farmers would choose to revert to cropping when economic conditions are favorable.

### 3.4. Data limitations and uncertainty

The work presented here has certain unavoidable limitations due to data availability. To utilize the three decades of yearly corn acreage data, the spatial scale of the econometric analysis is fixed at the county level. Hence, the NICC scores used to represent land quality are aggregated up from 90 m resolution to county average scores making the land quality metric less precise (mean county land area exceeds 0.5 million acres in the WCB). Using county-average land quality scores obscures precisely on what type of land within a county corn acreage would expand in response to high prices. This requires longitudinal land use data at the farm (or field) level. Also, the CDL data does not allow for identification of previously uncultivated grasslands versus managed range/pasture (Kline et al 2013). Therefore, there is uncertainty about the land quality of and the applicability of results to native grasslands.

The efficiency of the econometric estimation could be improved with a simultaneous equations approach where the acreage response for corn and the alternative crops/land uses would be estimated jointly. However, data coverage is substantially incomplete for the alternative crops, except for soy. Limiting the analysis to the subset of county-years with complete data could bias the representation of the variable land quality observed in the WCB and cause a loss of statistical power.
4. Conclusions

Land quality influences acreage response to prices through land availability. In the WCB, corn cultivation expanded by nearly seven million acres over 1986–2015. Most corn is still grown in counties with the highest quality lands that are physically well-suited to corn cropping. However, because there is a limited supply of such lands, when corn prices rise, there is a relatively small margin of land not already used for corn that can be shifted into corn production. On the other hand, in counties with a lower and more heterogeneous mix of land quality, there could be a significant margin of land not actively used to grow corn. In these counties, I find the proportional expansion in corn acreage in response to high crop prices to be more pronounced.

As corn cultivation creeps into lower-quality marginal agricultural lands, available land for bioenergy crops is further constrained. If lower quality lands are also more environmentally vulnerable, like the remnants of native prairie in the WCB, then their large sensitivity to corn prices is a concern, for this indicates such lands can easily cycle in and out of corn cultivation. Furthermore, any loss of native prairie is noteworthy because it can trigger indirect emissions of greenhouse gasses (Searchinger et al. 2008), and lead to habitat loss for native species (Mushet et al. 2014) and loss of biodiversity (Welting et al. 2014). When lower quality, environmentally sensitive lands are utilized for corn cultivation, there are further environmental concerns involving the heavy use of nitrogen fertilizers and attendant issues of runoff and leaching, as well as groundwater depletion in parts of the WCB overlying the Ogallala aquifer (Dennehy et al. 2002, Donner and Kucharik 2008, Langpap and Wu 2011, and Keeler and Polasky 2014).

Policies that may alter cropland use by creating financial incentives tied to the farming of specific crops, such as the US biofuel policy, needs to consider the policy-price feedback and higher price responsiveness of low quality lands. Although the higher price elasticity estimates signal farmer flexibility, suggesting land transitions to corn need not be irreversible, discouraging opportunistic farming on the most environmentally vulnerable areas might reduce stress on ecosystems.

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References

Baker J L 2008 Impacts of Financial, Food, and Fuel Crisis on the Urban Poor 45725 Directions in urban development (Dec) Washington, D.C. World Bank Retrieved from http://documents.worldbank.org/curated/en/319241468335932047/Impacts-of-financial-food-and-fuel-crisis-on-the-urban-poor

BP 2016 Statistical Review of World Energy [online data] Available from bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy/downloads.html

Bureau of Labor Statistics 2016 Consumer Price Index (CPI) Databases Series id CUUR0000SA0 [online data file] Available from https://www.bls.gov/cpi/cpi_data.htm

Cai X, Zhang X and Wang D 2010 Land availability for biofuel production Environmental Science & Technology 45 334–9

Cassman K G 1999 Ecological intensification of cereal production systems: yield potential, soil quality, and precision agriculture Proceedings of the National Academy of Sciences USA 96 5952–9

Chavas J P and Holt M 1990 Acreage decisions under risk: the case of corn and soybeans American Journal of Agricultural Economics 72 27–33

Chemberi D M and Womack A W 1992 Regional acreage response for US corn and wheat: the effects of government programs Southern Journal of Agricultural Economics 24 187–98

Chen X and Khanna M 2013 Food versus fuel: the effect of biofuel policies American Journal of Agricultural Economics 95 289–95

Claassen R, Carriazo F, Cooper J C, Hellerstein D and Ueda K 2011 Grassland to cropland conversion in the Northern Plains ERR 120 USDA Economic Research Service Retrieved from www.ers.usda.gov/webdocs/publications/44876/7477_err120.pdf?v=0

Claassen R, Hellerstein D and Kim S G 2013 Using mixed logit in land use models: can expectation-maximization (EM) algorithms facilitate estimation? American Journal of Agricultural Economics 95 419–25

Condon N, Klemick H and Wolverton A 2015 Impacts of ethanol policy on corn prices: a review and meta-analysis of recent evidence Food Policy 51 63–73

Crookston R K, Kurle J E, Copeland P J, Ford J H and Lueschen W E 1991 Rotational cropping sequence affects yield of corn and soybean Agronomy Journal 83 108–13

Dennehy K F, Little D W and McMahon P B 2002 The High Plains Aquifer, USA: Groundwater Development and Sustainability Geological Society London Special Publications 193 99–119

Donner S D and Kucharik C J 2008 Corn-based ethanol production compromises goal of reducing nitrogen export by the Mississippi River Proceedings of the National Academy of Sciences USA 105 4513–8
Edwards J H, Thurlow D L and Eason J T 1988 Influence of tillage and crop rotation on yields of corn, soybean, and wheat *Agronomy Journal* **80** 76–80

ERS 2018 U.S. Bioenergy Statistics Table 2 Fuel ethanol supply and disappearance calendar year (x10) [online data file] USDA Economic Research Service (ERS) Available from https://ers.usda.gov/data-products/us-bioenergy-statistics/

Fargione J, Hill J, Tilman D, Polasky S and Hawthorne P 2008 Land clearing and the biofuel carbon debt *Science* **319** 1235–8

Field C B, Campbell J E and Lobell D B 2008 Biomass energy: the scale of the potential resource *Trends in Ecology & Evolution* **23** 65–72

FSA 2018 Conservation Reserve Program Statistics CRP Enrollment and Rental Payments by County 1986–2018 (xls) [online data file] USDA Farm Service Agency (FSA) Available from https://fsa.usda.gov/programs-and-services/conservation-programs/reports-and-statistics/conservation-program-statistics/index

Gelfand I, Zenone T, Jasrotia P, Chen J, Hamilton S K and Robertson G P 2011 Carbon debt of conservation reserve program (CRP) grasslands converted to bioenergy production *Proceedings of the National Academy of Sciences* **108** 13864–9

Georgescu M, Lobell D B and Field C B 2011 Direct climate effects of perennial bioenergy crops in the United States *Proceedings of the National Academy of Sciences* **108** 4307–12

Glauber J W and Effland A 2016 *United States agricultural policy: its evolution and impact* IFPRI Discussion Paper 1543 Washington, D.C.

Goodwin B K and Smith V H 2003 An ex post evaluation of the conservation reserve, federal crop insurance, and other government program program participation and soil erosion *Journal of Agricultural and Resource Economics* **28** 201–16 http://purl.umn.edu/31090

Grandy A S and Robertson G P 2006 Initial cultivation of a temperate-region soil immediately accelerates aggregate turnover and CO2 and N2O fluxes Global Change Biology **2** 1507–20

Hardie I and Parks P 1997 Land use with heterogeneous land quality: an application of an area base model *American Journal of Agricultural Economics* **79** 299–310

Heimlich R 2010 USDA's conservation reserve program *Issues of the Day: 100 Commentaries on Climate, Energy, the Environment, Transportation, and Public Health Policy* ed I W Parry and F Day (New York: Routledge) 63–132–34

Keeler B L and Polasky S 2014 Land-use change and costs to rural households: a case study in groundwater nitrate contamination *Environmental Research Letters* **9** 074002

Khanna M and Crago C L 2013 Measuring indirect land use change with biofuels: implications for policy *Annual Review of Resource Economics* **5** 416–44

Kline K L, Singh N and Dale Y H 2013 Cultivated hay and fallow/ idle cropland confined analysis of grassland conversion in the Western Corn Belt *Proceedings of the National Academy of Sciences USA* **110** E2863–2863

Langpap C and Wu J 2011 Potential environmental impacts of increased reliance on corn-based bioenergy *Environmental & Resource Economics* **49** 147–71

Lark T J, Salmon J M and Gibbs H K 2013 Cropland expansion outpaces agricultural and biofuel policies in the United States *Environmental Research Letters* **10** 044003

Lewis D J and Plantinga A J 2007 Policies for habitat fragmentation: combining econometrics with GIS-based landscape simulations *Land Economics* **83** 109–27

Lichtenberg E 1989 Land quality, irrigation development, and cropping patterns in the northern high plains *American Journal of Agricultural Economics* **71** 187–94

Lin W and Dismukes R 2007 Supply response under risk: implications for counter-cyclical payments' production impact *Review of Agricultural Economics* **29** 64–86

Lubowski R N, Bucholtz S, Claassen R, Roberts M J, Cooper JC, Gueorguieva A and Johansson R 2006a Environmental effects of agricultural land-use change: the role of economics and policy *ERR 25 USDA Economic Research Service* Retrieved from www.ers.usda.gov/webdocs/publications/45609/17593_err25_1.pdf

Lubowski R N, Plantinga A J and Stavins R N 2006b 2006 Land-use change and carbon sinks: econometric estimation of the carbon sequestration

Miao R, Khanna M and Huang H 2016 Responsiveness of crop yield and acreage to prices and climate *American Journal of Agricultural Economics* **98** 191–211

Mitchell D 2008 A note on rising food prices *Policy Research Working Paper* WPS 4682 Washington, D.C. World Bank Retrieved from http://documents.worldbank.org/curated/en/729961468140943023/A-note-on-rising-food-prices

Muller D and Zeller M 2002 Land use dynamics in the central highlands of Vietnam: a spatial model combining village survey data with satellite imagery interpretation *Agricultural Economics* **27** 333–54

Mushet D M, Neau J L and Endress N H Jr 2014 Modeling effects of conservation grassland losses on amphibian habitat *Biological Conservation* **174** 93–100

NASS 2017b CropScape CDL Published crop-specific data layer for 2010–2016 [online data] USDA National Agricultural Statistics Service (NASS) Available from https://nassgeodata.gmu.edu/CropScape/

NASS 2017b Census of Agriculture for 1982, 1987, 1992, 1997, 2002, 2007 and 2012 [online data] USDA National Agricultural Statistics Service (NASS) Available from https://www.nass.usda.gov/AgCensus/

NASS 2018 Quick Stats U.S. Agricultural data by commodity, location, or time period [online database] USDA National Agricultural Statistics Service (NASS) Available from http://quickstats.nass.usda.gov/

National Research Council 2011 *Renewable Fuel Standard: Potential Economic and Environmental Effects of U.S. Biofuel Policy* (Washington, D.C.: The National Academies Press) (https://doi.org/10.17226/13105)

Nuñez H M, Oral H and Khanna M 2013 Land use and economic effects of alternative biofuel policies in Brazil and the United States *Agricultural Economics* **44** 487–99

Pimentel D 2006 Soil erosion: a food and environmental threat *Environment, Development and Sustainability* **8** 119–37

Radeloff V C et al 2012 Economic-based projections of future land use in the conterminous United States under alternative policy scenarios *Ecological Applications* **22** 1036–49
Rajagopal D, Sexton S E, Roland-Holst D and Zilberman D 2007 Challenge of biofuel: filling the tank without emptying the stomach? Environmental Research Letters 2 1–9
Rippey B R 2015 The US drought of 2012 Weather and Climate Extremes 10 57–64
Roberts M J and Schlenker W 2013 Identifying supply and demand elasticities of agricultural commodities: implications for the US ethanol mandate American Economic Review 103 2265–95
Schlenker W and Roberts M J 2009 Nonlinear temperature effects indicate severe damages to US crop yields under climate change Proceedings of the National Academy of Sciences USA 106 15594–8
Searchinger T D, Hentrich R, Houghton R A, Dong F, Elobeid A, Fabiosa J, Tokgoz S, Hayes D and Yu T 2008 Use of croplands for biofuels increases greenhouse gases through emissions from land use change Science 319 1238–40
Soil Survey Staff 2016 Gridded Soil Survey Geographic (gSSURGO) Database for the Conterminous United States [online data] USDA Natural Resources Conservation Service Available from https://gdg.sc.egov.usda.gov/ (FY2016 official release)
Somerville C, Youngs H, Taylor C, Davis S C and Long S P 2010 Feedstocks for lignocellulosic biofuels Science 329 790–2
UN 2011 The global social crisis: Report on the world social situation 2011 ST/ESA/334 Department of Economic and Social Affairs www.un.org/esa/socdev/rwss/docs/2011/rwss2011.pdf
Wallander S 2013 While crop rotations are common, cover crops remain rare Amber Waves (March) USDA Economic Research Service Retrieved from https://www.ers.usda.gov/amber-waves/2013/march/while-crop-rotations-are-common-cover-crops-remain-rare/
Wang M et al 2017 On the long-term hydroclimatic sustainability of perennial bioenergy crop expansion over the United States Journal of Climate 30 2535–57
Werling B P et al 2014 Perennial grasslands enhance biodiversity and multiple ecosystem services in bioenergy landscapes Proceedings of the National Academy of Sciences USA 111 1652–7
World Bank 2011 Food price watch 64361 (February) Washington, D.C. Retrieved from http://documents.worldbank.org/curated/en/24016146838505130/Food-price-watch
Wright C K and Wimberly M C 2013 Recent land use change in the Western Corn Belt threatens grasslands and wetlands Proceedings of the National Academy of Sciences USA 110 4134–9
Zumkehr A and Campbell J E 2013 Historical US cropland areas and the potential for bioenergy production on abandoned croplands Environmental Science & Technology 47 3840–7