Microclimate effects of wind farms on local crop yields*

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Abstract

This paper considers a novel spillover effect of wind farms - microclimate impacts on neighboring crop yields. Using US county-level crop and wind capacity data, I examine the effects of wind energy development on crop yields, controlling for time-invariant county characteristics and state-level annual shocks. I find robust evidence that counties with increased wind power development have also experienced increased corn yields, such that an additional 100 megawatts of wind capacity increases county yields by roughly 1%. Evidence of similar effects are found for soy and hay yields; however no evidence of an effect on wheat yields is found. At recent prices, this suggests a \$5.45 per megawatt-hour local benefit associated with microclimate effects from wind power.

JEL Codes: Q12, Q42, Q48, Q51

1 Introduction

As the use of renewable energy sources has grown globally, there is increased academic interest and public debate regarding potential externalities associated with these various sources of renewable energy. One unique feature of wind power as a form of renewable electricity is that it is spatially diffuse and sited on properties with other land uses (often agriculture), raising the possibility of wind farm spillovers on co-located land uses. One potential externality that has been examined within the natural science literature (but overlooked in the

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economics literature) is the effect of wind farms on crop outcomes due to "microclimate" effects (Rajewski et al. 2013; Rajewski et al. 2014; Armstrong et al. 2014). The exact mechanisms underlying these microclimate effects are discussed in more detail below, but briefly they arise from changes in local temperature, moisture and CO_2 levels due to vertical mixing, turbulence, and wakes created by wind turbines. Given climate affects crop productivity (Schlenker et al. 2005; Schlenker et al. 2006; Deschênes and Greenstone 2007; Fisher et al. 2012; Deschênes and Greenstone 2012), and wind farms create microclimate effects, it stands to reason wind farms in turn may affect crop yields. As such, this paper asks: Does wind energy development affect local crop yields, and what is the direction and magnitude of the effect? Understanding the sign and magnitude of these microclimate effects on crops has important welfare and policy implications for renewable energy.

While the natural science literature has found evidence of microclimate changes due to wind farms, the net effect on crops is still an open question. In an ideal experiment, one would want to compare two otherwise identical areas, whereby one area has a wind farm installed. Comparing crop yields in both areas before and after the wind installation would yield the net effect on crop yields from microclimates created by the wind farm.[1] Panel econometric techniques are well-suited to approximating this thought experiment - by controlling for time-invariant county characteristics, state-level annual shocks, and annual weather fluctuations at the county level, the effect of wind farms on crop yields can be plausibly identified.[2]

[1] It is possible the substantial royalties associated with farmers leasing their airspace to wind developers (Brown et al. 2012; Rakitan 2017) could also impact yields via increased purchases of production inputs - this potential income channel is examined in the analysis to follow.

[2] The econometric approach in this paper is similar in spirit to that in Deschênes and Greenstone (2007), which exploits yearly weather variation to identify the effects of temperature and precipitation on farm profits and crop yields, controlling for time-invariant county characteristics and common state-by-year shocks.

The data for this analysis consists of a county-level annual panel of yield, production, acreage, wind capacity, and weather from 1997-2013 in the US for corn, soy, hay and wheat crops. These four crops are the largest in terms of total planted acreage and provide relatively broad geographical coverage (thousands of counties). Across a variety of specifications, I find robust evidence that increases in county-level wind capacity lead to increased county-level corn yields. Roughly speaking, the addition of a 100 megawatt (MW) wind farm increases county-level corn yields between 0.5% and 1.5% depending on the specification. I find similar, though less robust, evidence for increased soy and hay yields of a similar magnitude. By contrast, no effect is found on wheat yields. In a series of extensions, I examine how the wind capacity effect on yield varies with wind speeds, turbine hub height, terrain, wind farm distance to county border, and wind direction. Results are consistent with the underlying physical processes of microclimates and are difficult to reconcile with alternative mechanisms.

While these estimated microclimate effects may seem relatively small, at recent prices they amount to an annual local benefit of over $400 million dollars, with roughly 3/4 of that benefit derived from increased corn yields. On a per megawatthour (MWh) basis, this implies a local benefit of $5.45 dollars per MWh. While it may be tempting to consider this benefit as a positive externality to be potentially addressed by policy, the policy implications are slightly more nuanced. To the extent the microclimate benefits fall within the immediate footprint of the wind farm, these benefits should be internalized by the leasing and bargaining process between landowners and wind developers, and thus there is little rationale for policy interventions beyond providing information for the relevant parties. However, to the extent these benefits spillover to neighboring farms, then these benefits would constitute a positive externality that state lawmakers may wish to consider when crafting renewable policies pertaining to wind.

Given the recent growth of renewable energy sources, understanding their potential externalities is a pressing concern. U.S. electricity generation from wind has grown from less than 1% in 2007 to more than 5% in 2016 and growth is likely to continue. A proper accounting of spillover effects from these new and growing renewable technologies can aid policymakers in assessing whether policies that support that growth should be continued, curtailed or expanded.

This analysis contributes to a growing literature on the externalities of renewable energy, and wind energy in particular. Much of this initial literature has focused on the emission savings from these renewable technologies and the extent to which such savings justify policy interventions to support and expand renewable energy.[3] A number of papers have also examined how wind farm externalities such as noise impacts and visual disamenities are capitalized into housing prices and local property values (Heintzelman and Tuttle 2012; Lang et al. 2014; Jensen et al. 2014; Gibbons 2015; Dröes and Koster 2016). Furthermore, because wind farms can diminish wind speeds for significant distances downwind, upwind wind farms may impose a negative externality on neighboring wind farms in their wake (Kaffine and Worley 2010; Rule 2012). To my knowledge this is the first econometric analysis of microclimate effects from wind turbines and their impact on crop yields.

It should be noted the primary limitation of this analysis is that, due to data availability, the unit of observation is at the county level while the actual microclimate effect on yields is likely at the sub-county local and varies spatially (and potentially spills across county

[3] For example, estimates of emission savings from wind power have typically found substantial reductions in CO_2 and other pollutants (Kaffine et al. 2013; Cullen 2013; Novan 2015). By contrast, estimates of emission savings from biofuels have varied considerably and have generally suggested modest CO_2 reductions from corn ethanol (Farrell et al. 2006).

borders). Nonetheless, the county-level estimates provided by this analysis are a useful measure of the microclimate externalities generated by wind farms.[4]

2 Wind power and microclimates

This section reviews the existing scientific literature on microclimate effects from wind turbines. The basic mechanism underlying microclimate effects is that wind turbines alter the surface meteorology through decreased wind speeds and turbulent mixing (Lissaman 1979; Keith et al. 2004; Armstrong et al. 2014). Furthermore, these changes in local conditions extend well beyond (on the order of 10 kilometers) the small footprint of the wind turbine itself (Fitch et al. 2012; Rajewski et al. 2013; Fitch et al. 2013). Through these physical mechanisms, local temperatures, CO_2 levels, and moisture levels are in turn affected.[5] The existence of these microclimate effects has been confirmed via simulation (Roy and Traiteur 2010; Fitch et al. 2012; Fitch et al. 2013; Fitch et al. 2013; Vautard et al. 2014), remote sensing (Zhou et al. 2012), and in-situ field experiments (Rajewski et al. 2013; Smith et al. 2013; Rajewski et al. 2014). Operating via similar mechanisms, "frost fans" are a standard technology utilized by vineyards to create mixing and prevent frosts from damaging their crops (Snyder and Melo-Abreu 2005).

Based on the above, the general consensus in the literature is that microclimate effects

[4] For example, Lost Lakes wind farm in the center of Dickinson County, Iowa is a 100 MW wind farm with a direct footprint of roughly 25 square miles. But given wake effects from wind turbines can extend on the order of 10 kilometers, more than half of the 400 square mile county is potentially affected by the wind farm. Of course, farm-level data would be ideal, but USDA only provides county-level crop data. This is essentially a form of measurement error, and will tend to bias estimates towards zero. I return to this issue below.

[5] Atmospheric conditions near the surface (the "boundary layer") can be quite different from those at the altitude of wind turbines, and the rotation by the wind turbine blades can create vertical mixing. For example, during nighttime hours, warmer air is brought towards the surface. The effects during the daytime are generally weaker, due to the fact the boundary layer is unstable and already mixing itself.

from wind turbines exist, and that some of these effects may be beneficial and some may be harmful for crops. For example, Rajewski et al. (2013) note they find enhanced CO_2 levels in crop canopies during daytime hours, which would be beneficial to crops. On the other hand, they also find higher nighttime temperatures, increasing plant respiration and therefore possibly harming crop growth.[6] Nonetheless, to the best of my knowledge, there are no existing studies that have conclusively determined the direction and magnitude of the net effect of wind farm microclimates on crop yields.

The studies in Rajewski et al. (2013) and Rajewski et al. (2014) are part of a larger project known as the Crop Wind Energy Experiment (CWEX), which attempts to better understand the scientific links between wind turbines, local climate, and crops through field experiments at a large wind farm in Iowa. However, as the authors note in Rajewski et al. (2013), "...variability within and between fields due to cultivar, soil texture and moisture content, and management techniques creates large uncertainties for attributing season-long biophysical changes, and much less yield, to turbines alone." As a complement to these natural science field experiments, I consider an alternative approach to examining the effects of wind farms on crop yields. Rather than examine crop yields at a single site, I take advantage of annual crop yield reporting across thousands of U.S. counties, of which more than three hundred have experienced wind development from 1997 through 2013.[7]

An advantage of this reduced-form, econometric approach is that the large number of observations will help resolve the "signal-to-noise" issue raised in Rajewski et al. (2013), while controlling for time-invariant county characteristics and state-level annual shocks to

[6] Further illustrating the complexity of understanding crop effects, higher nighttime temperatures may also be good for crops, if they prevent the growth of harmful fungi.

[7] This is a similar logic to the strategy in Li (2017) whereby counties with and without policy-driven tree-plantings are compared to examine the microclimate impacts of windbreak trees on agricultural productivity.

yields. However, as noted in the introduction, it has the disadvantage of using county-level yields, despite the fact microclimate effects are likely at the sub-county level.[8] Nonetheless, uncovering a plausibly causal and significant relationship between wind farms and crop yields at the county level provides evidence of the net effect of wind farm microclimates. Estimates can also provide insight into the aggregate external benefits or costs associated with these effects, as well as potential policy implications.

Finally, a quick note about anticipated effect sizes. The microclimate effects on temperature, moisture, and CO_2 levels discussed above are relatively modest in size and are likely imperceptible to local landowners - in fact, despite the scientific evidence, landowner survey respondents in Mills (2015) generally disagreed with the statement that wind energy disrupts local weather patterns. In other words, the context is temperature changes on the order of a degree or smaller (Zhou et al. 2012), not extremes like blizzards in July. Similarly, the anticipated effects of wind farms on crop yields are likely modest, though hopefully statistically detectable given the large sample size.

3 Methods

3.1 Data

In order to construct the annual panel dataset for the regression analysis, county-level data on wind capacity is combined with county-level agricultural data. This county-level data is then matched with station-level meteorological data. Sources and details are provided

[8] In other words, the field experiment approach can examine crop yields at the locations where microclimate effects are likely to be most prominent, at the expense of a small sample size. The approach in this paper is able to look at tens of thousands of observed crop outcomes, however the sub-county microclimate effects are "averaged in" to the reported crop yields at the county level.

below, as well as a discussion of summary statistics.

3.1.1 Crop and wind capacity data

County-level crop yield (bushels or tons per acre) is the primary outcome variable of interest and is obtained from the USDA annual NASS Survey for 1997-2013 for each of the four crops of interest.[9] Productivity (bushels or tons) and acreage harvested are also obtained from the NASS Survey for all years. Additional data on capital (number of tractors), labor (hired labor expenditures) and fertilizer (expenditures) is also collected, but is only available for Census of Agriculture years (1997, 2002, 2007, 2012).

The crop data is then merged with wind capacity data from EIA-860 Form for 1997-2013. EIA-860 provides information for all wind generators in the US, including capacity (MW), year-built, and county, which provides the necessary information to construct a panel of wind capacity for each county by year. Finally, wind capacity in each county is divided by county (land) area, to generate the primary explanatory variable of wind capacity density (MW/square mile). Dividing by county land area provides a normalized measure of the prevalence of wind development for counties of differing sizes, where county land area (square miles) is obtained from the US Census.

3.1.2 Meteorological variables

The prior literature has identified precipitation and temperature as two key determinants of crop yields. Daily precipitation (inches), temperature (Fahrenheit), and surface wind

[9] Crop yield is reported in bushels/acre for corn, soy and wheat, and tons/acre for hay. Yield is not reported for every year for every county, resulting in an unbalanced panel. The NASS Survey provides breakdowns for many different varietals, particularly for hay and wheat. Alfalfa is the most prominent form of hay and winter wheat is the most prominent form of wheat, and as such the estimates below are for those specific varietals.

speed data is collected from NOAA NCDC covering the years 1997-2013 for roughly 500 Automated Surface Observing System (ASOS) stations with complete readings over this time period. Following the previous literature, growing-season precipitation is calculated as the cumulative inches of rain from April 1 to September 30 for each station. Similarly, growing-season growing degree days (GDD) are calculated for each station as follows:

$$\sum_{d=Apr1}^{Sept30} [\frac{T_{max,d} + T_{min,d}}{2} - 50], \tag{1}$$

such that if $T_{max,d} > 86$, then $T_{max,d} = 86$ and if $T_{min,d} < 50$, then $T_{min,d} = 50$. The temperatures of 86 and 50 have been identified as important temperature thresholds in terms of crop growth.[10] To illustrate, if the max daily temperature was 82 degrees and the min daily temperature was 54 degrees, then this counts as 18 growing degree days (average temperature of 68 minus 50 degrees). However, if the max temperature was 92 degrees with a min of 54, then $T_{max,d}$ is set to 86, resulting in 20 growing degree days. The effect of "Extreme degree days" (XDD) - degree days with temperatures in excess of 86 degrees - are also examined below. The above calculations are performed for each weather station, and then a simple nearest-neighbor match is conducted between stations and county centroids based on latitude-longitude.[11]

[10] There are a number of alternative cutoffs and additional refinements in the literature, but the above formulation is used for corn, soy and hay. Importantly, winter wheat is on a different growing season (October 1st of the previous fall to March 31st of the harvesting spring) and has a different min temp cutoff (32 degrees), and the above calculation is modified appropriately for winter wheat analysis. Alternative formulations were examined and yielded nearly identical estimates to those presented below.

[11] In Iowa for example, this procedure assigns the 99 counties to 12 different stations, with an average distance between county centroids and stations of 60 kilometers.

3.1.3 Summary statistics

The variables above are summarized in Table 1 for select years, with the top panel summary reflecting all counties in the sample, and the bottom panel summarizing only those counties that have experienced some wind development as of 2013 (315 in total, across 39 states). The rows summarizing wind capacity and density illustrate the remarkable growth of wind power from 1997 to 2013, particularly from 2005 to 2013. Over that same period, yields (and acreage) have also grown considerably, particularly for corn and soy. Clearly any attempt to estimate the effect of wind development on crop yields will need to address the fact both variables are trending upward.

Comparing between all counties in the sample and just those counties that ultimately experience wind development, counties with eventual wind development plant more acreage and have greater yields of corn, soy, and wheat. Importantly, these differences exist even in the early portion of the sample (pre-2005), at a time when only a small subset of eventual wind counties had experienced any wind development. Again, the presence of such differences suggests any analysis of the effect of wind development on crop yields will need to control for underlying differences between counties that do and do not experience wind development.

3.2 Econometric Strategy

This section details the econometric strategy used to estimate the effect of wind farms on crops. Similar to Deschênes and Greenstone (2007), the following panel regression model is estimated:

$$y_{ct}^{j} = \alpha_{c}^{j} + \beta^{j} W_{ct} + \sum_{i} \theta_{i}^{j} f_{i}(X_{ict}) + \eta_{sy}^{j} + \epsilon_{ct}^{j} \tag{2}$$

where y_{ct}^{j} is yield (bushels or tons per acre) of crop j in county c in year t, W_{ct} is wind capacity density (megawatts of wind capacity per square mile), and X_{ict} is a set of control variables discussed below. Fixed-effects for county (α_c^j) and state-year (η_{sy}^j) respectively control for time-invariant county characteristics and common yield shocks within a state over time. The inclusion of fixed-effects for counties controls for persistent differences across counties that affect yield and may be correlated with wind capacity density.[12] State-year fixed effects control for time-varying differences in yield at the state level that may be correlated with wind capacity density.[13] As previous research has indicated, weather variables are an important county-specific, time-varying determinant of yield, and as such X_{ict} represents growing season growing degree days and precipitation. In the preferred specification, these enter quadratically, with robustness checks considering linear and cubic specifications, as well as specifications allowing the effects of the weather variables to vary with irrigation status and by state. Standard errors for all results are clustered at the state level.

From the above, β^j is the coefficient of interest, and represents the change in yield with respect to a change in wind capacity density, identified off of within-county variation with respect to common state-year variation. As such, potential threats to identification will arise from county-specific time-varying shocks. One concern may be counties that eventually experience wind development were on a different yield trend prior to wind development. Examining pre-trends finds no evidence that counties that eventually develop wind power were consistently on a different trend (see further discussion below). One might also be

[12] For example, the overlap between the "Farm Belt" and the "Wind Belt" would suggest counties that experience wind development likely have higher yields irrespective of wind development. This is confirmed in part by the summary statistics in Table 1 and raw correlations bear this out as well.

[13] One would be concerned, for example, that states that enacted policies to promote wind development also enacted policies to support biofuels. Failure to control for state-year effects would erroneously attribute changes in yield due to biofuel policies to the presence of wind development.

concerned about selection effects. Fortunately, selection of wind sites is primarily based on long-run, time-invariant characteristics such as topography, long-run meteorology, and grid access, which will be absorbed by county fixed-effects. Furthermore, many time-varying selection factors such as electricity prices or renewable subsidies will be swept out by state-by-year fixed-effects.[14]

Finally, while the discussion above has focused on the microclimate effects of wind farms, there may be other potential mechanisms by which wind capacity density may hypothetically affect yields. For example, while the amount of land actually taken out of production by wind turbines is very small (on the order of an acre per MW), this decline in acreage may hypothetically affect yields. Alternatively, if farmers use the royalties from wind development to plant more acres, or to purchase additional inputs (land, labor, capital, fertilizer), then β^j may still identify the effect of wind development on crop yields, but the mechanism would not be microclimate effects (exclusively). Analysis below examines and controls for acreage (available for all years) and other input decisions (available only for Ag Census years 1997, 2002, 2007, 2012).

4 Results

This section begins by presenting baseline results from estimating equation 2 for corn yields. The initial focus is on corn due to the fact it is grown in the most counties, has the most

[14] One potential concern is farmers may base their decision to lease to wind developers in part on (unobservable) yield expectations. In particular, farmers may be more inclined to lease and thus gain royalty payments if yields are expected to decline. If these expectations are based on factors that vary at the state-level, the state-by-year fixed effects will control for them. To the extent there is any remaining county-specific time-varying selection concerns, the likely direction is a minor negative bias of the estimated effect of wind development on yield, running counter to the direction of estimates below. As such, the estimate below may be slight underestimates of the effect of wind development on yield.

overlap with wind development counties, and is the most valuable crop in the U.S. in terms of total output. Next, robustness checks for corn explore alternative specifications, control for input choices, and replace yield with production as the outcome variable of interest. Having established robust results for corn, analysis of soy, hay and wheat follows. Finally, this section concludes with a discussion of additional specifications and extensions that were considered.

4.1 Central estimates for corn

Table 2 reports the baseline estimates of the effect of wind capacity density on corn yields.[15] Note the coefficient on wind density is difficult to directly interpret due to the units. Evaluated at the means, a coefficient of 12 can be interpreted as implying a 100 MW wind farm increases county-level corn yields by roughly 1%. Column I reports estimates from a specification with state-year fixed effects and quadratic controls for weather variables. The coefficient on wind density is significant at the 1% level and can be interpreted as implying a 100 MW wind farm increases yield by a little over 2%.

While the estimation in column I controls for the fact states with large wind developments are also states with inherently higher yields, there may still be important within-state differences. As such, column II adds county fixed-effects to control for time-invariant characteristics at the county level. The coefficient on wind density decreases relative to column

[15] Observations for Benton County, Indiana from 2010-2013 are removed for all results that follow. These are the highest leverage observations in the dataset (by far), and inspection of reported yields raises concerns about the data validity. In particular, although yields in the county generally track neighboring counties closely, reported yields declined by nearly 30% in 2012, despite "normal" yields in the neighboring counties. While the results presented below are only slightly changed by excluding this county, given the extraordinary leverage of these observations (wind density levels that are more than 30 standard deviations above the mean) and evidence of data error, it has been removed.

I, suggesting such within-state differences are important, but nonetheless the coefficient remains statistically significant at the 1% level. The interpretation of the coefficient is that a 100 MW wind farm increases county-level corn yields by roughly 0.6%. Note the coefficients on the weather variables exhibit the expected concave relationship, with maximum points for GDD and precipitation that align very closely with previous research, particularly Schlenker et al. (2006).

As previous research has indicated irrigation status is an important determinant of yields, column III allows the effect of weather to vary by irrigation status.[16] The coefficient on wind density remains unchanged. The response of yield to the weather variables is as expected - non-irrigated counties respond to variation in precipitation, while irrigated counties do not. Next, column IV estimates a trimmed sample, where the 5% of observations with the greatest wind capacity densities (within the subset of county-year observations with positive wind capacity levels) are dropped from the sample (64 observations in total).[17] The coefficient on wind density is larger, such that a 100 MW wind farm increases county-level corn yields by approximately 1%. Finally, columns V and VI are log-linear estimates of the models from columns III and IV. The coefficient on wind capacity density in column V can be interpreted as a 0.6% increase in corn yield due to a 100 MW wind farm, which is consistent with the linear specification. Similarly, the coefficient in column VI with the trimmed sample implies a 100 MW wind farm increases county corn yields by 0.9%.

[16] Specifically, a county is considered a "dry" or irrigated county if rainfall was less than 15 inches. Alternative indicators of whether or not a county is irrigated, such as alternative rainfall cutoffs and fraction of irrigated acres, were explored and yielded nearly identical results. See below for further discussion

[17] Due to their high leverage, these observations (0.2% of the overall sample) may impart substantial influence on estimates.

4.2 Alternative Specifications

While the estimates in Table 2 provide strong evidence of a positive impact of wind farms on corn yields, the additional robustness checks to follow consider alternative specifications, control for other margins of adjustment by farms, and estimate a model of production. Table 3, column I includes a quadratic term in wind density to allow for potential non-linear effects on crop yields. The coefficient on the quadratic term is marginally insignificant ($p = 0.11$), suggesting a potential concave relationship between wind density and crop yields. However, the lack of data support at the higher levels of wind densities is problematic, and for the remainder of the specifications a simple linear form will be considered.[18]

The remaining columns in Table 3 consider alternative weather specifications. Column II considers cubic specifications for the weather variables, while column III fully interacts quadratic specifications between GDD and precipitation. Estimates of the effect of wind capacity density on corn yields are similar to those in Table 2. Column IV interacts the quadratic weather terms with state fixed effects, to allow for differential responses to climate variability by state, and Column V and VI interacts quadratic weather with irrigation status and with state effects for the untrimmed and trimmed samples, respectively. The coefficient on wind density is consistent with previous estimates.

One concern about attributing the increase in crop yields to microclimate effects is there may be other margins of adjustment that farmers undertake in response to wind development that may affect crop yields. For example, wind development is typically coupled with leasing or royalty payments to farmers, and one might imagine that farmers may use those payments

[18] Note the marginal effect evaluated at the mean is roughly equivalent to the estimates in the "trimmed" specifications in columns IV and VI in Table 2. As wind capacity continues to grow and densities increase, returning to this issue of a concave relationship would be beneficial.

to plant more acreage or purchase more production inputs (capital, labor, fertilizer).[19] Table 4 examines the effect of wind density on corn yields, holding acres planted and other inputs constant (specifically tractors, labor expenditure and fertilizer expenditure). The primary challenge with this exercise is that inputs other than acreage are only available during Census years of 1997, 2002, 2007, 2012, substantially reducing the sample size.

Column I of Table 4 includes harvested acreage per square mile as a control variable for the full sample (all years 1997-2013) and the coefficient on wind capacity density remains statistically significant and of a similar magnitude to the previous estimates. To examine the power implications of reducing the sample to only Census years, column II repeats the specification in column I, but only over Census years. The coefficient on wind capacity density is nearly identical, but as expected, precision is lost due to the reduced sample size. With this sample size effect in mind, columns III and IV add tractors per square mile, labor expenditure per square mile, and fertilizer expenditure per square mile as controls for the Census years sample, with column IV considering the trimmed sample per above. Estimated effects of wind capacity density on crop yields are similar in magnitude to those previously reported, though insignificant ($p = 0.148$ for column IV). Column V and VI repeat the specifications in columns III and IV with a log-linear specification, with significant wind density coefficient estimates of similar magnitude to previous estimates. Taken together, the results in Table 4 suggest the estimated changes in crop yield due to wind development are not due to changes in acreage or other inputs.[20]

[19] While U.S. farmers may not be particularly credit constrained, it is plausible input decisions may be influenced given payments are often on the order of thousands of dollars per turbine annually (see for example, "Wind Energy Easements and Leases: Compensation Packages" http://windlibrary.org/items/show/451 and Rakitan (2017)).

[20] Regressions of wind capacity density on input choice are also examined in Appendix Table A.1. Only fertilizer per square mile responded significantly to changes in wind capacity density; however, per Table 4,

While the above regressions examined outcomes for corn yields, the effect of wind development on corn production (bushels) is also examined as a final alternative specification. Column I of Table 5 replaces yield with production as the dependent variable and controls for acreage and quadratic weather variables. Coefficient estimates on wind capacity density are positive and significant. The coefficient remains positive and significant in columns II and III which interact weather with irrigation status with and without the trimmed sample. Columns IV-VI normalize production and acreage by square mile, with columns IV and V replicating the specifications in columns II and III, while column VI interacts acres per square mile with state. All specifications support the finding that wind development provides a positive benefit to corn crops.[21]

4.3 Other crops

The preceding results establish robust evidence of a positive effect of wind capacity on corn yields. This section examines the effect of wind capacity on other crop yields, specifically soy, hay (alfalfa) and wheat (winter). Table 6 reports linear and log-linear estimates for these crops for the trimmed sample with quadratic weather variables interacted with irrigation

changes in fertilizer expenditure do not lead to a statistically significant increase in yields, and taking the point estimates at face-value implies a tiny fraction of a percent increase in yields. This is consistent with survey respondents in Mills (2015), where only 3 of 198 respondents linked wind farm income to on-farm investments. One respondent noted wind income had "Very little effect as it is a small percentage of income compared to the gross farm income," while another noted that wind income was "Very little but what we receive does help a lot with property taxes."

[21] While using wind capacity per square-mile as the regressor of interest is preferable due to the ability to exploit variation in wind farm size, Appendix Table A.2 considers a differences-in-differences-style estimation using an indicator $1(A_{it})$ for whether or not there is any wind energy development in the county in a given year ($1(A_{it}) = 1$ if $W_{it} > 0$). Point estimates from this exercise are statistically significant and of a consistent magnitude with results from the main specification. Furthermore, this exercise confirms the results are not solely being driven by a few large wind farms.

status (column IV Table 2).[22] The estimates provide some evidence soy yields increase by roughly a half a percent and hay yields increase by one percent per 100 MW of wind capacity, with no significant effect on wheat yields. Additional robustness testing similar to that undertaken for corn in Tables 2-5 was also undertaken for soy, hay, and wheat. Results were generally consistent with those in Table 6 - positive and often significant wind effects on soy and hay, and insignificant effects on winter wheat.[23]

Because of confidentiality rules and planting decisions by farmers, yields for a particular crop for a particularly county-year are often unreported, leading to an unbalanced panel. Table 7 estimates the effect of wind capacity density on crop yields for a balanced panel for each crop for both the linear and log-linear specifications. While the balanced panel has fewer observations, restricting the analysis to those counties with reported yields for all 17 years of the sample has the advantage that the sample may consist of more "alike" counties. The general pattern of results is consistent with the prior unbalanced panel estimates, with significant coefficients on wind capacity density for corn, soy and hay yields, and insignificant estimates for wheat. Interpretations of the coefficients are in line with the prior estimates as well, with a 100 MW wind farm leading to a roughly 1% increase in yields for corn and soy.[24]

[22] The trimmed specification is used due to the fact that, relative to corn, there are fewer counties with reported yields and wind development, and as such concerns about exceedingly high leverage observations are even greater.

[23] Note a few alternative specifications resulted in a statistically significant negative coefficient on wheat.

[24] The estimate for hay is quite a bit larger than prior estimates, though the estimate is noisy and not statistically distinguishable from the corresponding estimate in Table 6.

4.4 Pre-trends

A key assumption underlying the analysis above is that counties that experience wind farm development are not on a different yield trend prior to adoption. To examine this assumption in more detail, let A_c represent an indicator variable for each county that equals one if the county ever experiences wind farm development in the sample, and T_c represent the first year of wind farm development (the first year t when $W_{ct} > 0$). Then the following regression is estimated on the balanced panel for corn yields (Table 7 Panel A):

$$y_{ct} = \alpha_c + \sum_{l=-6}^{l=4} \beta_l I_{ct}(t - T_c = l) A_c + \sum_i \theta_i f_i(X_{ict}) + \eta_{sy} + \epsilon_{ct}, \tag{3}$$

where $I_{ct}(t - T_c = l)$ takes the value of one for observations l years before/after initial wind development. For $l < 0$, the coefficients β_l can be thought of as the "effect" of eventual wind development at time T_c on yields l years prior to T_c; in the absence of a pre-trend, these should be near zero. For $l \geq 0$, β_l can be interpreted as the effect of wind development at time T_c on yields l years in the future; based on the above results, these coefficient estimates should be positive.[25] A range of 6 years prior and 4 years post was chosen to give a "reasonable" number of observations on either side of the year of first wind development.[26]

Figure 1 plots the coefficient estimates $\hat{\beta}_l$ and corresponding confidence intervals based on the balanced panel for corn yields (Table 7). Estimates are near zero and statistically insignificant in the years prior to first wind development, and then become positive and roughly significant in the years following first wind development. This provides reasonable

[25] Note that this approach collapses the variation in size of the wind farm into a simple indicator for its existence. Thus these coefficients can be interpreted similar to those in the differences-in-differences specification in Appendix Table A.2.

[26] There is more wind development later in the sample, so more pre-adoption years are observable than post-adoptions years (and pre-adoption years are a more pressing issue given the importance of pre-trend concerns). Alternative ranges yield similar coefficient estimates.

assurance that the main estimates above are not driven by some pre-trend in yields for counties that eventually develop wind.[27]

4.5 Additional robustness checks and extensions

Several additional variations on the model discussed above were also considered. First, while county fixed effects aid in the identification of microclimate effects, they are fairly restrictive and absorb much of the variation in yields (roughly 60%). An alternative approach to county fixed effects would be to explicitly control for the primary omitted variable concern: counties with good conditions for crop growth may also have good conditions for wind development. Appendix Table A.4 drops county fixed effects in favor of county-level controls for wind speed and nine soil characteristics from Deschênes and Greenstone (2012).[28] Estimates are consistent with the above findings with county fixed effects, though somewhat larger for corn and soy. Second, the dummy variable measure of irrigation-status used above relies on observed rainfall, which is a useful but imperfect proxy. As an alternative, share of irrigated land is available for Ag Census years and Appendix Table A.5 replicates Table 2 with this new variable. Despite the smaller sample, point estimates on wind capacity are positive and significant, and again similar though slightly larger than in Table 2. Finally, following Schlenker and Roberts (2009), extreme degree days (XDD) are calculated

[27] To further explore this issue, a cohort-style analysis was conducted in Appendix Table A.3 to assess whether yields were trending prior to wind development for counties that had their first development in different sub-periods (e.g. early developers vs late developers). Trend coefficients are typically near zero and insignificant, though there may be some positive yield trend for counties that first develop wind between 2005-2010. To further verify that there are no pre-trend issues here, different cohorts (early 1997-2003, mid 2004-2010, and late 2011-2013 adopters) were dropped from the analysis. Estimates are similar to those above, suggesting that results are not being driven by pre-trends for a specific cohort, and more generally that the estimated microclimates effects are positive and significant regardless of the time period considered.

[28] The nine soil characteristics are: salinity, flood-prone, wetlands, "k-factor", slope, sand, clay, moisture, and permeability. These are mostly time-invariant so cross-sectional values from 2002 are used.

as $\sum_{d=Apr1}^{Sept30}(T_{max,d} - 86) * I(T_{max,d} > 86)$, with the growing season adjusted accordingly for winter wheat. Estimates for unbalanced and balanced panels in Appendix Table A.6 yield similar estimates to those above for all crops, with more extreme degree days reducing yields for corn, soy, and hay.[29]

Next, heterogeneity in the microclimate effects of wind farms on crop yields was also considered. First, Appendix Table A.8 estimates heterogenous effects of wind capacity by (surface) wind speed and hub height (above or below the median of 8 miles per hour and 235 feet, respectively).[30] While the estimates are somewhat inconclusive, they suggest crop effects may be larger for windier sites with taller turbines. Second, to the extent wind farm microclimates affect moisture levels, one concern may be that crop yield effects may be different for drier/irrigated counties (Higgins et al. 2015). Appendix Table A.9 interacts wind capacity density with the dummy indicator for irrigated counties and finds no evidence of a differential effect of wind capacity in drier counties. Third, the physical extent of the wake created by wind farms will cover a larger extent on flatter terrain. Appendix Table A.10 interacts wind capacity density with slope length (mean 210 feet) as a proxy for the ruggedness of the terrain, finding that, as expected, effects on corn yields diminish with increased ruggedness of terrain.

Returning to the main data limitation, the unit of observation is annual county-level yields, while the microclimate effects of the wind farms themselves may spillover county

[29] As additional robustness checks on the weather controls, Panel A of Appendix Table A.7 includes separate controls for GDD by month yielding similar estimates of microclimate effects on yield. One additional concern is that if wind farms affect local temperatures, this may be captured via changes in temperature at the weather stations themselves. In practice, there are not many wind farms directly near weather stations - weather stations are at airports, and wind farms are not cited close to airports due to obstruction and radar concerns. Nonetheless, Panel B removes all weather controls, yielding similar estimates.

[30] Hub height data is from EIA Form 860, and is capacity-weighted for counties with multiple wind farms.

boundaries. To examine this issue, an index is created for each county that calculates the distance between the wind farm and county centroid and then normalizes by the implied "radius" of the county. A value of 0 implies a wind farm at the dead-center of the county, such that microclimate effects should be fully subsumed within the county, while a value near 1 would indicate the wind farm is near the county boundary, whereby microclimate effects may spillover into neighboring counties.[31] Appendix Table A.11 replicates Table 2, but includes an interaction between wind capacity density and this normalized measure of distance to county centroid. Estimates are consistent with the intuition that the effect on county-level yield is greatest when the wind farm is centrally located (1-2% increased in yield per MW of wind capacity), and declines as the wind farm moves closer to the county border. Relative to estimates in Table 2, the marginal effect of wind capacity on crop yields when the distance index is zero is roughly double in magnitude (though not statistically distinct), suggesting the main results presented above are conservative given the potential attenuation issue per Appendix Table A.11.

To further examine the potential spillover issue, note that spillovers would be most likely to occur for counties with wind farms near the county boundary *and* a prevailing wind direction that would tend to push any microclimate effects over the county line. For each county and year, hourly wind direction station data from NOAA ISD-Lite is used to calculate the (wind speed-weighted) fraction of hours during the growing season that the wind blew in a direction that was conducive for out-of-county spillovers.[32] Appendix Table A.12

[31] The implied radius is found by taking the square mileage of the county and calculating the radius as if the county were a circle. For some irregularly shaped counties, this yields a value greater than 1; nonetheless this is still a useful proxy in the sense that microclimate effects are very likely to fall outside the county if a wind farm is at the tip of a long, skinny part of a county (e.g. Twin Falls County, ID). For counties with multiple wind farms, capacity weights are used in calculating the distance to the county centroid.

[32] For each county, the direction from the county centroid to the wind farm is first calculated to determine

replicates Table 2, but includes an interaction between wind capacity density and a spillover indictor for observations that fall in the top quartile of distance and the top quartile of spillover hours. Estimates for non-spillover observations are similar to those above, while the interaction coefficient is negative and often significant (though noisy due to the small number of spillover observations).[33]

Finally, Figure 2 plots the estimated marginal effect from a model that interacts wind capacity density with both distance and the fraction of spillover hours (for values of distance and spillover hours in the 25th-75th percentile range). Consistent with expectations, for counties with wind farms either near the county centroid or with winds that do not produce spillovers, the estimated marginal effect is similar in magnitude to estimates above. However, for counties with wind farms that are both near the border and have spillover-producing winds, the estimated marginal effect on yield tapers off to near zero.

5 Economic and policy implications

The results above provide robust evidence of a microclimate net benefit for corn yields, along with somewhat weaker evidence of a benefit for soy and hay yields. While these estimates provide useful information for natural scientists interested in understanding the net effect of microclimates from wind farms, there are also important economic and policy implications. Based on the estimates above, this section provides a back-of-the-envelope calculation of the

what wind direction would create spillovers, and then the fraction of spillover hours is determined based on a 90 degree arc around that direction. So for a wind farm located due east of the county centroid at 90 degrees, wind from 270 degrees would create spillovers. The fraction of spillover hours is thus the share of hours where wind blew from 225-315 degrees.

[33] Simply dropping the small number of spillover observations from the main regression specifications above yields similar though slightly larger marginal effects on yield.

external crop benefits generated by wind development.

Table 8 summarizes the key inputs and results from this exercise. "Preferred" coefficient estimates ($\hat{\beta}^j$) for each crop are taken from the unbalanced panel results above (column IV, Table 2 for corn, column I, Table 6 for soy, and column III, Table 6 for hay) with the exception of wheat, due to the fact no evidence of a significant microclimate effect, positive or negative, was found above. Recall these coefficients represent the change in yield (bu/acre or tons/acre) due to a change in wind capacity per square mile (MW/sqmi). For each crop, the number of counties with wind development is determined, and then average wind capacity and yields are calculated. Multiplying the estimate microclimate effect by average wind capacity density gives the average change in yield in the counties with wind development, and then multiplying that by average acreage yields the average change in crop production (in bushels or tons). These average changes in production per county are multiplied by the assumed prices in Table 8 and then by the number of counties to determine the aggregate microclimate crop benefits for 2013.[34]

Per Table 8, at the preferred coefficient estimates there was an aggregate microclimate benefit on the order of $400 million dollars, with approximately three-quarters of that benefit generated by changes in corn yields and one-quarter from changes in soybean yield. Assuming a capacity factor of 0.33 for wind, this translates into a $5.45/MWh benefit from microclimate effects.[35] To put this into context, Novan (2015) finds that at a social cost of carbon of $32 per ton, wind generation in Texas (ERCOT) results in average external benefits from CO_2

[34] Corn and soybean prices are 2013 calendar year averages for Iowa, http://www.extension.iastate.edu/agdm/crops/html/a2-11.html, while hay prices are 2013 US average prices from the Livestock Marketing Information Center. These assumed prices are similar to other reported values.

[35] Across alternative specifications, the external benefit per MWh ranges from $2.56/MWh to $9.76/MWh, and aggregate benefits range from $200-700 million. See Appendix Table A.13.

reduction of \$20-24 per MWh of wind. While the benefits to crops are less than the emission savings benefits, they do represent local as opposed to global benefits.

While the economic implications are fairly straightforward, the policy implications are more nuanced. As noted, while the analysis is at the county level, microclimate effects vary within a county. To the extent the microclimate benefits fall within the footprint of the leasing farmer, these benefits should be internalized by the leasing and bargaining process. This of course assumes farmers are aware of these benefits, and as such, beyond informing farmers of potential microclimate benefits, there would be little rationale for policy interventions in this case. On the other hand, to the extent these benefits spillover to neighboring farms, this would constitute a positive externality that state lawmakers may wish to consider when crafting renewable policies pertaining to wind. At present, it is unknown what exact fraction of the measured benefit spills beyond the local footprint of the leasing farmer, but ongoing research from the CWEX project (Rajewski et al. 2013; Lee and Lundquist 2017) may help resolve this issue to better inform policy responses.

6 Conclusions

While engineers in the 19th Century were no doubt impressed by the utility of burning coal to generate steam and electricity, it was only when billions of people began to rely on coal for heat and electricity that some of its downsides became apparent in terms of externalities from local air pollution and climate change. Given the global boom in renewable energy development, a proper accounting of their positive and negative spillovers can help policymakers assess the wisdom of further encouragement of renewable energy. In the context of wind power, a unique aspect relative to other electricity sources is that it is co-located with other land uses, often agriculture. In this paper, I examine a novel spillover of wind energy development - microclimate effects on local crop yields.

Using US county-level crop and wind capacity data I estimate the effect of wind energy development on crop yields, controlling for time-invariant county characteristics and state-level annual shocks. I find robust evidence that counties with increased wind power development have also experienced increased corn yields, such that an additional 100 megawatts of wind capacity increases county yields by roughly 1%. Examination of other possible channels linking wind development and yields (such as income) suggests microclimate effects are the likely mechanism. Some evidence of similar effects are found for soy and hay yields, but no evidence of an effect on wheat yields is found. At recent prices, these estimates suggest benefits of several hundreds of million dollars annually, corresponding to a $5.45 per megawatt-hour local benefit associated with microclimate effects from wind power.

Returning to the primary caveat of this analysis, as noted throughout the paper the mismatch between the spatial effects of wind farms (sub-county) and the spatial level of analysis (county) is less than ideal. Additional field work by the CWEX project (Rajewski et al. 2013; Rajewski et al. 2014) or others (Smith et al. 2013) could provide complementary evidence to the results presented here. Field work could also provide additional insight into the spatial scale of these effects, which would help clarify policy recommendations. Nonetheless, the results of this paper provide evidence that, in addition to any emission savings generated by wind power, there are also additional sizeable local benefits in terms of increased crop yields due to microclimate effects.

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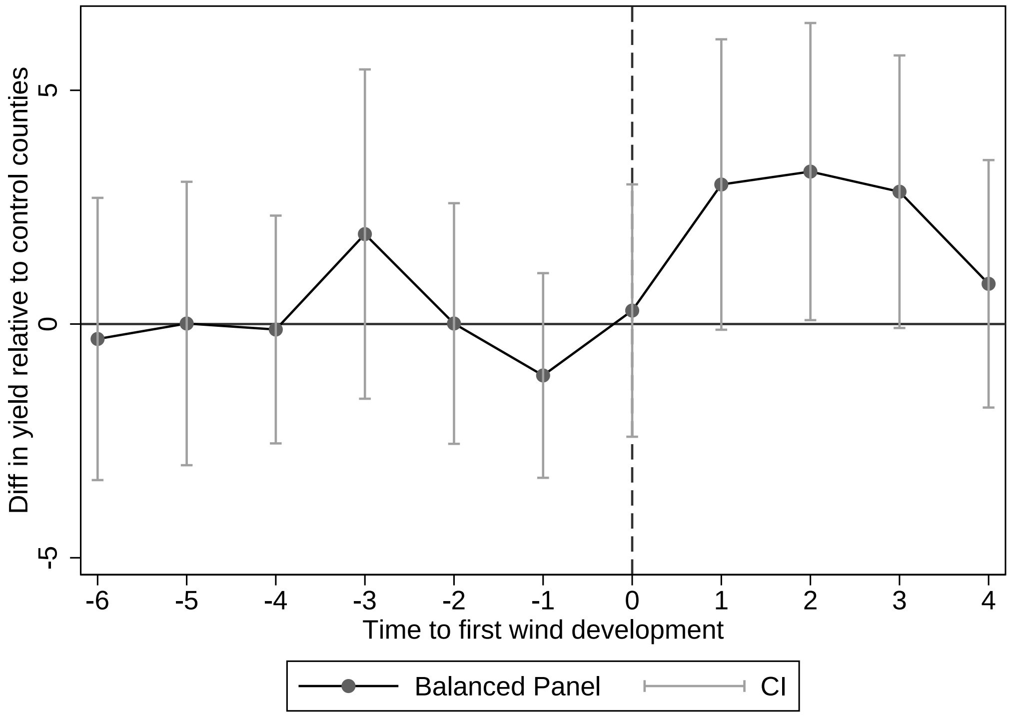

Figure 1: Differences in corn yield for counties that experience wind development, in years pre- and post-development. Balanced Panel specification from Table 7 Panel A.

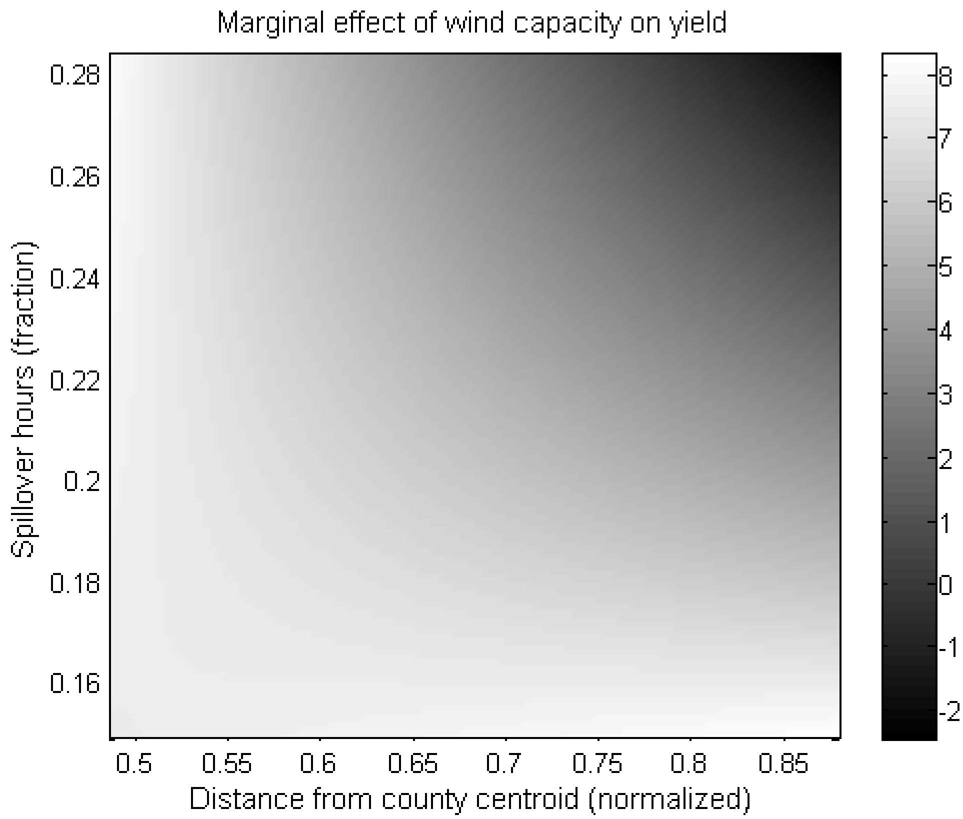

Figure 2: Marginal effect of wind capacity density on yields by distance from county centroid and wind direction spillovers. Horizontal axis is the distance of a county's wind farm from the county centroid, normalized by county size. Vertical axis is the fraction of hours during the growing season that the wind blew in a direction that would likely generate out-of-county spillovers of microclimate effects. Plot range is 25th-75th percentiles for distance and spillovers.

Table 1: Summary statistics - county level - select years

	1997	2001	2005	2009	2013
ALL COUNTIES					
Corn yield (bu/acres)	109.64	116.84	123.41	144.52	147.34
Soybean yield (bu/acres)	34.26	35.78	38.25	41.86	42.53
Hay yield (tons/acres)	3.25	3.27	3.29	3.27	3.21
Wheat yield (bu/acres)	46.58	47.73	50.74	49.12	55.48
Corn acres	34,905	35,725	38,811	48,953	52,357
Soybean acres	41,457	44,900	43,760	53,788	51,879
Hay acres	14,329	15,115	14,140	15,621	15,000
Wheat acres	21,994	18,831	19,922	25,377	24,906
Growing-season precip (in)	18.31	18.08	19.52	22.54	22.91
Growing-season degree days	3,321	3,538	3,599	3,366	3,492
Wind capacity (MW)	0.55	1.50	3.51	15.54	27.44
Wind density (MW/sqmi)	0.000	0.001	0.003	0.017	0.029
WIND COUNTIES					
Corn yield (bu/acres)	128.59	124.02	145.15	164.84	154.23
Soybean yield (bu/acres)	40.18	37.50	45.13	44.67	45.50
Hay yield (tons/acres)	3.48	3.53	3.57	3.44	3.34
Wheat yield (bu/acres)	45.17	45.24	48.54	45.87	50.88
Corn acres	72,087	71,741	83,262	104,708	103,445
Soybean acres	80,272	83,088	77,131	90,610	87,275
Hay acres	17,282	17,867	16,593	21,411	15,435
Wheat acres	48,677	39,151	41,786	48,638	48,143
Growing-season precip (in)	15.18	14.14	16.72	17.51	18.44
Growing-season degree days	3,008	3,214	3,273	3,070	3,245
Wind capacity (MW)	4.78	12.63	28.84	113.46	191.76
Wind density (MW/sqmi)	0.003	0.010	0.026	0.122	0.201

Notes: "Wind counties" are the 315 counties that have any wind development and reported crop yields in 2013.

Table 2: Estimates of effect of wind capacity density on corn yields - US counties 1997-2013

	I	II	III	IV	V	VI
Variables	yield	yield	yield	yield	lnyield	lnyield
Wind density	26.94***	7.506***	7.537***	12.06***	0.0604***	0.0912***
(MW/sqmi)	(6.272)	(2.511)	(2.505)	(2.616)	(0.0219)	(0.0226)
Precip	-0.239	0.894***				
	(0.646)	(0.256)				
Precip^2	0.00424	-0.0147***				
	(0.0110)	(0.00502)				
GDD	0.128***	0.0420***				
	(0.0312)	(0.0149)				
GDD^2	-1.92e-05***	-8.06e-06***				
	(4.99e-06)	(2.32e-06)				
Precip x Wet			1.297***	1.288***	0.0104***	0.0103***
			(0.357)	(0.355)	(0.00329)	(0.00328)
Precip x Dry			0.108	0.0991	-0.00750	-0.00759
			(0.605)	(0.605)	(0.00674)	(0.00673)
Precip^2 x Wet			-0.0213***	-0.0211***	-0.000160**	-0.000159**
			(0.00671)	(0.00664)	(6.24e-05)	(6.21e-05)
Precip^2 x Dry			0.0110	0.0113	0.000534	0.000537
			(0.0419)	(0.0418)	(0.000427)	(0.000427)
GDD x Wet			0.0417**	0.0411**	0.000468***	0.000464***
			(0.0160)	(0.0159)	(0.000156)	(0.000156)
GDD x Dry			0.0383***	0.0379**	0.000624***	0.000620***
			(0.0141)	(0.0140)	(0.000211)	(0.000211)
GDD^2 x Wet			-8.03e-06***	-7.95e-06***	-8.86e-08***	-8.81e-08***
			(2.43e-06)	(2.42e-06)	(2.36e-08)	(2.35e-08)
GDD^2 x Dry			-7.53e-06***	-7.47e-06***	-1.10e-07***	-1.09e-07***
			(2.20e-06)	(2.18e-06)	(3.12e-08)	(3.13e-08)
County FE	N	Y	Y	Y	Y	Y
State-Year FE	Y	Y	Y	Y	Y	Y
Trim	N	N	N	Y	N	Y
N	31,839	31,839	31,839	31,775	31,338	31,274
R^2	0.532	0.543	0.543	0.543	0.549	0.549
Counties	2,341	2,341	2,341	2,341	2,293	2,293

*Notes: Coefficient of interest is the effect of a change in wind generation capacity density (MW/sqmi) on corn yield (bu/acre) or log of corn yield. Precip is measured as total precipitation (inches) during growing season (April 1 - September 30). GDD is measured as total growing degree days during growing season. Dry (irrigated) counties are defined by less than 15 inches of growing-season precipitation. All columns exclude the county of Benton, IN 2010-2013. Trimmed samples drop high leverage 5% tail of wind density observations. Results are for all counties in US based on NASS survey data for 1997-2013. Standard errors clustered at the state level in parenthesis. * indicates 10 percent significance.** indicates 5 percent significance. *** indicates 1 percent significance.*

Table 3: Specification robustness - corn yield in US counties 1997-2013

	I	II	III	IV	V	VI
Variables	yield	yield	yield	yield	yield	yield
Wind density	17.69***	7.580***	7.189***	6.695**	6.396**	11.14***
(MW/sqmi)	(5.976)	(2.556)	(2.518)	(2.477)	(2.637)	(2.969)
Wind density^2	-15.98					
	(9.848)					
Precip	0.893***	0.137				
	(0.256)	(0.486)				
Precip^2	-0.0147***	0.0183				
	(0.00502)	(0.0197)				
Precip^3		-0.000421				
		(0.000264)				
GDD	0.0419***	0.156***				
	(0.0149)	(0.0429)				
GDD^2	-8.04e-06***	-4.19e-05***				
	(2.31e-06)	(1.19e-05)				
GDD^3		3.22e-09***				
		(1.11e-09)				
County FE	Y	Y	Y	Y	Y	Y
State-Year FE	Y	Y	Y	Y	Y	Y
Precip-GDD	N	N	Y	N	N	N
Weather-State	N	N	N	Y	N	N
Dry-Weather-State	N	N	N	N	Y	Y
Trim	N	N	N	N	N	Y
N	31,839	31,839	31,839	31,839	31,839	31,775
R^2	0.543	0.544	0.543	0.555	0.561	0.561
Counties	2,341	2,341	2,341	2,341	2,341	2,341

Notes: Coefficient of interest is the effect of a change in wind generation capacity density (MW/sqmi) on corn yield (bu/acre). Precip is measured as total precipitation (inches) during growing season (April 1 - September 30). GDD is measured as total growing degree days during growing season. Precip-GDD fully interacts weather variables (quadratic). Weather-State interacts weather variables (quadratic) with state. Dry-Weather-State interacts an indicator for dry (irrigated) counties with weather variables (quadratic) and with state. All columns exclude the county of Benton, IN 2010-2013. Trimmed samples drop high leverage 5% tail of wind density observations. Results are for all counties in US based on NASS survey data for 1997-2013. Standard errors clustered at the state level in parenthesis. indicates 10 percent significance.** indicates 5 percent significance. *** indicates 1 percent significance.*

Table 4: Robustness to inputs - corn yield in US counties 1997-2013

	I	II	III	IV	V	VI
Variables	yield	yield	yield	yield	lnyield	lnyield
Wind density	6.392**	6.587	5.701	9.106	0.106**	0.155*
(MW/sqmi)	(2.555)	(4.814)	(4.245)	(6.179)	(0.0526)	(0.0895)
Acres/sqmi	0.0588*	0.0368	0.0280	0.0309	0.000112	0.000140
	(0.0328)	(0.0733)	(0.0817)	(0.0818)	(0.000833)	(0.000832)
Tractors/sqmi			-1.292	-1.261	-0.0149	-0.0147
			(1.106)	(1.115)	(0.0137)	(0.0136)
Labor/sqmi			0.000124*	0.000131*	7.80e-07	8.61e-07
			(7.22e-05)	(7.37e-05)	(7.84e-07)	(7.98e-07)
Fert/sqmi			5.16e-05	5.31e-05	6.83e-07	6.62e-07
			(0.000140)	(0.000144)	(1.64e-06)	(1.68e-06)
County FE	Y	Y	Y	Y	Y	Y
State-Year FE	Y	Y	Y	Y	Y	Y
Dry-Weather	Y	Y	Y	Y	Y	Y
Trim	N	N	N	Y	N	Y
Sample	Survey	Census	Census	Census	Census	Census
N	31,338	7,625	7,546	7,530	7,546	7,530
R^2	0.589	0.584	0.586	0.587	0.533	0.533
Counties	2,293	2,199	2,191	2,191	2,191	2,191

*Notes: Coefficient of interest is the effect of a change in wind generation capacity density (MW/sqmi) on corn yield (bu/acre) or log of corn yield. Acres/sqmi is acres of harvested corn per square mile. Tractors/sqmi is number of tractors per square mile. Labor/sqmi is hired labor expenditures per square mile. Fert/sqmi is fertilizer expenditures per square mile. Dry-Weather interacts an indicator for dry (irrigated) counties with weather variables (quadratic). All columns exclude the county of Benton, IN 2010-2013. Trimmed samples drop high leverage 5% tail of wind density observations. Results are for all counties in US based on NASS survey data for 1997-2013 or NASS census data for 1997, 2002, 2007, and 2012 as indicated. Standard errors clustered at the state level in parenthesis. * indicates 10 percent significance.** indicates 5 percent significance. *** indicates 1 percent significance.*

Table 5: Production estimates for corn (bushels) - US counties 1997-2013

Variables	I production	II production	III production	IV prodsqmi	V prodsqmi	VI prodsqmi
Wind density	1.151e+06**	1.151e+06**	2.039e+06**	2,035**	3,283***	2,712**
(MW/sqmi)	(533,679)	(539,773)	(863,918)	(771.9)	(1,205)	(1,214)
Precip	44,731**					
	(21,457)					
$Precip^2$	-782.3*					
	(428.7)					
GDD	1,613					
	(1,042)					
GDD^2	-0.299*					
	(0.156)					
Precip x Wet		86,739***	84,966***	151.4***	148.7***	141.9***
		(29,387)	(28,821)	(51.71)	(50.74)	(51.14)
Precip x Dry		30,181	29,611	23.30	23.71	25.43
		(52,901)	(52,912)	(75.28)	(75.50)	(73.39)
$Precip^2$ x Wet		-1,489**	-1,453**	-2.581**	-2.522**	-2.398**
		(556.6)	(542.4)	(0.970)	(0.942)	(0.942)
$Precip^2$ x Dry		-2,907	-2,899	-3.848	-3.901	-3.570
		(3,965)	(3,961)	(6.184)	(6.191)	(6.167)
GDD x Wet		1,729*	1,636	3.641**	3.503**	3.716**
		(1,015)	(990.7)	(1.764)	(1.723)	(1.706)
GDD x Dry		575.9	496.7	1.776	1.672	1.704
		(1,022)	(1,007)	(1.569)	(1.544)	(1.509)
GDD^2 x Wet		-0.319**	-0.309**	-0.000649**	-0.000633**	-0.000670**
		(0.150)	(0.147)	(0.000274)	(0.000270)	(0.000267)
GDD^2 x Dry		-0.157	-0.149	-0.000393	-0.000382	-0.000396
		(0.152)	(0.150)	(0.000247)	(0.000245)	(0.000241)
Acres	146.9***	146.8***	146.5***			
	(8.929)	(8.890)	(8.788)			
Acres/sqmi				155.2***	154.8***	
				(8.509)	(8.411)	
County FE	Y	Y	Y	Y	Y	Y
State-Year FE	Y	Y	Y	Y	Y	Y
Acres-State	N	N	N	N	N	Y
Trim	N	N	Y	N	Y	Y
N	31,338	31,338	31,274	31,338	31,274	31,274
R^2	0.736	0.738	0.738	0.722	0.721	0.729
Counties	2,293	2,293	2,293	2,293	2,293	2,293

*Notes: Coefficient of interest is the effect of a change in wind generation capacity density (MW/sqmi) on corn production (bushels) or corn production per square mile. Precip is measured as total precipitation (inches) during growing season (April 1 - September 30). GDD is measured as total growing degree days during growing season. Dry (irrigated) counties are defined by less than 15 inches of growing-season precipitation. Acres-State interacts acres with state. All columns exclude the county of Benton, IN 2010-2013. Trimmed samples drop high leverage 5% tail of wind density observations. Results are for all counties in US based on NASS survey data for 1997-2013. Standard errors clustered at the state level in parenthesis. * indicates 10 percent significance.** indicates 5 percent significance. *** indicates 1 percent significance.*

Table 6: Estimates of wind farm effect on other crop yields - US counties 1997-2013

Variables	I Soy yield	II Soy lnyield	III Hay yield	IV Hay lnyield	V Wheat yield	VI Wheat lnyield
Wind density	2.403*	0.0413	0.234	0.105**	-2.776	-0.0967
(MW/sqmi)	(1.229)	(0.0269)	(0.148)	(0.0449)	(2.606)	(0.0751)
Precip x Wet	0.453***	0.0136***	0.0310***	0.00945***	-0.122	-0.00501**
	(0.0618)	(0.00220)	(0.00904)	(0.00300)	(0.0990)	(0.00212)
Precip x Dry	-0.469**	-0.0192**	0.00808	-0.000165	0.284	0.0108
	(0.229)	(0.00825)	(0.0141)	(0.00556)	(0.609)	(0.0181)
Precip^2 x Wet	-0.00675***	-0.000195***	-0.000449***	-0.000135**	0.000695	5.26e-05
	(0.000987)	(3.42e-05)	(0.000155)	(5.38e-05)	(0.00160)	(3.52e-05)
Precip^2 x Dry	0.0223	0.000955*	2.09e-05	0.000344	0.0202	0.000435
	(0.0142)	(0.000511)	(0.000958)	(0.000371)	(0.0418)	(0.00131)
GDD x Wet	0.0277***	0.000877***	0.000287	1.28e-05	0.000122	-3.54e-05
	(0.00601)	(0.000206)	(0.000381)	(0.000129)	(0.00222)	(8.13e-05)
GDD x Dry	0.0232***	0.000755***	-4.98e-05	-8.06e-05	-0.00112	-9.74e-05
	(0.00562)	(0.000176)	(0.000368)	(0.000144)	(0.00225)	(6.87e-05)
GDD^2 x Wet	-4.45e-06***	-1.41e-07***	-9.88e-08	-2.87e-08	-2.09e-07	-1.49e-09
	(9.19e-07)	(3.02e-08)	(6.12e-08)	(1.94e-08)	(2.44e-07)	(7.53e-09)
GDD^2 x Dry	-3.81e-06***	-1.23e-07***	-4.87e-08	-1.21e-08	-1.76e-07	3.84e-09
	(8.79e-07)	(2.77e-08)	(6.46e-08)	(2.38e-08)	(3.63e-07)	(8.41e-09)
County FE	Y	Y	Y	Y	Y	Y
State-Year FE	Y	Y	Y	Y	Y	Y
Trim	Y	Y	Y	Y	Y	Y
N	26,113	26,113	20,661	20,661	25,863	25,768
R-squared	0.588	0.565	0.366	0.407	0.427	0.411
Counties	1,905	1,905	1,700	1,700	2,164	2,151

*Notes: Coefficient of interest is the effect of a change in wind generation capacity density (MW/sqmi) on soybean, hay (alfalfa), or wheat (winter) yields (bu/acre) or log yields. Precip is measured as total precipitation (inches) during growing season (April 1 - September 30 for hay and soy, and October 1st - March 31st for wheat). GDD is measured as total growing degree days during growing season. Dry (irrigated) counties are defined by less than 15 inches of growing-season precipitation (10 inches for wheat). All columns exclude the county of Benton, IN 2010-2013. Trimmed samples drop high leverage 5% tail of wind density observations. Results are for all counties in US based on NASS survey data for 1997-2013. Standard errors clustered at the state level in parenthesis. * indicates 10 percent significance.** indicates 5 percent significance. *** indicates 1 percent significance.*

Table 7: Balanced Panel - all crop yields in US counties 1997-2013

	I	II	III	IV
	Corn	Soy	Hay	Wheat
Panel A: Linear specification				
Variables	yield	yield	yield	yield
Wind density	12.25***	3.488***	0.825**	-3.897
(MW/sqmi)	(4.149)	(0.939)	(0.376)	(3.545)
N	17,425	16,235	5,236	9,044
R^2	0.649	0.636	0.462	0.556
Counties	1,025	955	308	532
Panel B: Log-linear specification				
Variables	ln(yield)	ln(yield)	ln(yield)	ln(yield)
Wind density	0.116***	0.0803***	0.370***	-0.121
(MW/sqmi)	(0.0328)	(0.0242)	(0.138)	(0.0899)
N	17,374	16,235	5,236	9,044
R^2	0.62	0.616	0.477	0.501
Counties	1,022	955	308	532
County FE	Y	Y	Y	Y
State-Year FE	Y	Y	Y	Y
Dry-Weather	Y	Y	Y	Y
Trim	Y	Y	Y	Y

*Notes: Coefficient of interest is the effect of a change in wind generation capacity density (MW/sqmi) on corn, soybean, hay (alfalfa), or wheat (winter) yields (bu/acre) or log yields. Precip is measured as total precipitation (inches) during growing season (April 1 - September 30 for corn, hay and soy, and October 1st - March 31st for wheat). GDD is measured as total growing degree days during growing season. Dry-Weather interacts an indicator for dry (irrigated) counties with weather variables (quadratic). All columns exclude the county of Benton, IN 2010-2013. Trimmed samples drop high leverage 5% tail of wind density observations. Results are for all counties in US with reported yields in every year based on NASS survey data for 1997-2013. Standard errors clustered at the state level in parenthesis. * indicates 10 percent significance.** indicates 5 percent significance. *** indicates 1 percent significance.*

Table 8: Benefits of microclimate effects - 2013 counties with wind development

	Corn	Soy	Hay	Total
Microclimate effect[a]	12.06	2.403	0.234	
	(2.616)	(1.209)	(0.148)	
Average MW/sqmi	0.238	0.255	0.188	
Average acres	103,444	87,274	15,435	
Price (2013)	$5.65	$14.13	$180	
Counties	160	130	121	
2013 Benefits	$295,963,122	$98,165,048	$14,788,980	$408,917,149
	(64,198,966)	(49,388,907)	(9,353,714)	(81,536,883)
2013 Benefits	$3.677	$1.536	$0.236	$5.450
per MWh[b]	(0.798)	(0.773)	(0.149)	(1.120)

Notes: [a] Estimated change in yield per wind capacity MW/sqmi from Tables 2 and 6. [b] Assumed wind capacity factor of 0.33.

A Appendix Figures and Tables

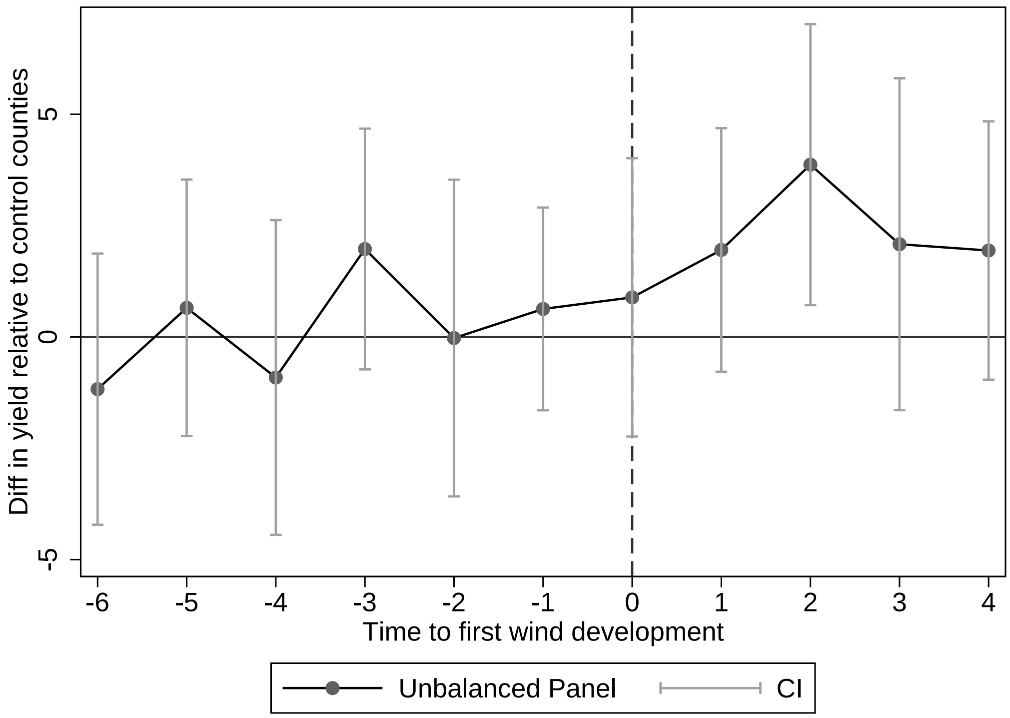

Figure A.1: Differences in corn yield for counties that experience wind development, in years pre- and post-development. Unbalanced Panel specification from Table 2 Column IV.

Table A.1: Inputs as dependent variable

	I	II	III	IV
Panel A: Linear specification				
	Acres/sqmi	Tractors/sqmi	Labor/sqmi	Fert/sqmi
Wind density	9.883*	0.0111	1,787	9,184**
(MW/sqmi)	(5.614)	(0.0385)	(1,986)	(3,527)
N	31,338	9,571	9,486	9,548
R-squared	0.398	0.299	0.297	0.731
Counties	2,293	2,620	2,615	2,617
Panel B: Log-linear specification				
	ln(Acres/sqmi)	ln(Tractors/sqmi)	ln(Labor/sqmi)	ln(Fert/sqmi)
Wind density	-0.0218	0.0208	0.0461	0.115**
(MW/sqmi)	(0.0713)	(0.0235)	(0.0826)	(0.0428)
N	31,338	9,571	9,486	9,548
R-squared	0.335	0.274	0.451	0.837
Counties	2,293	2,620	2,615	2,617
County FE	Y	Y	Y	Y
State-Year FE	Y	Y	Y	Y
Dry-Weather	Y	Y	Y	Y

*Notes: Coefficient of interest is the effect of a change in wind generation capacity density (MW/sqmi) on listed inputs (density). Precip is measured as total precipitation (inches) during growing season (April 1 - September 30 for corn, hay and soy, and October 1st - March 31st for wheat). GDD is measured as total growing degree days during growing season. Dry-Weather interacts an indicator for dry (irrigated) counties with weather variables (quadratic). All columns exclude the county of Benton, IN 2010-2013. Results are for all counties in US based on NASS survey data for 1997-2013 for acreage and NASS census data for 1997, 2002, 2007, and 2012 for tractors, labor and fertilizer. All columns exclude the county of Benton, IN 2010-2013. Standard errors clustered at the state level in parenthesis. * indicates 10 percent significance.** indicates 5 percent significance. *** indicates 1 percent significance.*

Table A.2: Difference-in-Differences - corn yield in US counties 1997-2013

Variables	I yield	II yield	III yield	IV yield	V yield
Any Wind	3.191***	3.476***	3.421***	3.586***	3.465***
$1(A_{it})$	(0.954)	(0.938)	(0.969)	(0.974)	(1.010)
Precip x Wet	1.296***	1.295***	1.297***	1.295***	1.290***
	(0.357)	(0.357)	(0.354)	(0.357)	(0.358)
Precip x Dry	0.125	0.118	0.126	0.112	0.132
	(0.603)	(0.602)	(0.611)	(0.601)	(0.622)
Precip^2 x Wet	-0.0213***	-0.0213***	-0.0213***	-0.0213***	-0.0212***
	(0.00672)	(0.00671)	(0.00665)	(0.00672)	(0.00672)
Precip^2 x Dry	0.0103	0.0106	0.0106	0.0109	0.0104
	(0.0417)	(0.0416)	(0.0417)	(0.0416)	(0.0418)
GDD x Wet	0.0417**	0.0417**	0.0419**	0.0416**	0.0416**
	(0.0159)	(0.0160)	(0.0160)	(0.0159)	(0.0162)
GDD x Dry	0.0385***	0.0384***	0.0387***	0.0383***	0.0382**
	(0.0141)	(0.0141)	(0.0140)	(0.0141)	(0.0142)
GDD^2 x Wet	-8.03e-06***	-8.02e-06***	-8.03e-06***	-8.00e-06***	-7.98e-06***
	(2.43e-06)	(2.43e-06)	(2.43e-06)	(2.43e-06)	(2.45e-06)
GDD^2 x Dry	-7.54e-06***	-7.53e-06***	-7.55e-06***	-7.52e-06***	-7.47e-06***
	(2.19e-06)	(2.19e-06)	(2.18e-06)	(2.19e-06)	(2.20e-06)
County FE	Y	Y	Y	Y	Y
State-Year FE	Y	Y	Y	Y	Y
Trim	N	N	N	N	N
N	31,844	31,844	31,707	31,844	31,542
R^2	0.543	0.543	0.543	0.543	0.544
Counties	2,341	2,341	2,341	2,341	2,340

Notes: Coefficient of interest on "Any Wind" is the average treatment effect of wind development on corn yield (bu/acre). In Column I, the variable Any Wind takes the value of 1 for any county in any year with positive wind capacity. In columns II-III, the variable Any Wind takes the value of 1 for any county in any year with wind capacity per square mile in the top 90 percentile, with column II including those small wind counties in the control group and column III excluding them. In columns IV-V, the variable Any Wind takes the value of 1 for any county in any year with wind capacity per square mile in the top 75 percentile, with column IV including those small wind counties in the control group and column V excluding them. Precip is measured as total precipitation (inches) during growing season (April 1 - September 30). GDD is measured as total growing degree days during growing season. All columns exclude the county of Benton, IN 2010-2013. Trimmed samples drop high leverage 5% tail of wind density observations. Results are for all counties in US based on NASS survey data for 1997-2013. Standard errors clustered at the state level in parenthesis. indicates 10 percent significance.** indicates 5 percent significance. *** indicates 1 percent significance.*

Table A.3: Pre-trend cohort comparisons

	I	II	III	IV	V	VI
Trend prior to	2001	2003	2005	2007	2009	2011
Panel A: All wind adopters, yields all years prior to 200X						
cap x trend	-1.205***	-0.236	0.299	0.323**	0.197	0.144
	(0.339)	(0.346)	(0.209)	(0.139)	(0.179)	(0.161)
N	9,901	13,655	17,290	20,686	23,118	25,622
R-squared	0.576	0.550	0.581	0.563	0.579	0.562
Counties	2,178	2,177	2,176	2,164	2,126	2,093
Panel B: All wind adopters, yields 5 years prior to 200X						
capt x trend	-1.205***	0.0819	1.638**	0.890*	-0.428	-0.511
	(0.339)	(0.767)	(0.633)	(0.474)	(0.586)	(0.965)
N	9,901	9,602	9,422	9,166	8,210	7,598
R-squared	0.576	0.554	0.566	0.440	0.487	0.496
Counties	2,178	2,092	2,032	1,992	1,936	1,866
Panel C: 5 year forward wind adopters, yields 5 years prior to 200X						
cap x trend	-0.661	0.614	2.134***	0.904*	-0.428	-0.511
	(0.799)	(1.074)	(0.714)	(0.481)	(0.586)	(0.965)
N	9,901	9,602	9,422	9,166	8,210	7,598
R-squared	0.575	0.554	0.566	0.440	0.487	0.496
Counties	2,178	2,092	2,032	1,992	1,936	1,866
County FE	Y	Y	Y	Y	Y	Y
State-Year FE	Y	Y	Y	Y	Y	Y
Dry-Weather	Y	Y	Y	Y	Y	Y

*Notes: Coefficient of interest is the differential corn yield (linear) trend for eventual wind adopters relative to non-adopters, cap x trend, in years prior to 200X. All estimates include state-year fixed effects, county fixed effects, and controls for total precipitation (inches) during growing season (April 1 - September 30), total growing degree days during growing season, and dry (irrigated) counties interacted with weather variables (quadratic). All columns exclude the county of Benton, IN 2010-2013. Standard errors clustered at the state level in parenthesis. * indicates 10 percent significance.** indicates 5 percent significance. *** indicates 1 percent significance.*

Table A.4: Yield estimates controlling for wind speed and soil quality

	I	II	III	IV
	Corn	Soy	Hay	Wheat
Panel A: Wind speed control				
Variables	yield	yield	yield	yield
Wind density	20.47***	5.336*	0.608**	-6.783
(MW/sqmi)	(5.474)	(2.622)	(0.251)	(4.474)
N	31,839	26,171	20,694	25,909
R-squared	0.584	0.671	0.530	0.646
Panel B: Wind speed and soil quality controls				
Variables	yield	yield	yield	yield
Wind density	20.29**	5.712**	0.752**	-9.087**
(MW/sqmi)	(8.697)	(2.251)	(0.329)	(4.183)
N	25,316	20,262	16,750	22,080
R-squared	0.585	0.674	0.563	0.664
County FE	N	N	N	N
State-Year FE	Y	Y	Y	Y
Dry-Weather	Y	Y	Y	Y

*Notes: Coefficient of interest is the effect of a change in wind generation capacity density (MW/sqmi) on corn, soybean, hay (alfalfa), or wheat (winter) yields (bu/acre). Panel A controls for wind speed interacted by state. Panel B includes the wind-by-state control as well as 9 cross-sectional soil quality measures from Deschênes and Greenstone (2012). Precip is measured as total precipitation (inches) during growing season (April 1 - September 30 for corn, hay and soy, and October 1st - March 31st for wheat). GDD is measured as total growing degree days during growing season. Dry-Weather interacts an indicator for dry (irrigated) counties with weather variables (quadratic). All columns exclude the county of Benton, IN 2010-2013. Results are for all counties in US based on NASS census data for 1997, 2002, 2007, and 2012. Standard errors clustered at the state level in parenthesis. * indicates 10 percent significance.** indicates 5 percent significance. *** indicates 1 percent significance.*

Table A.5: Alternative irrigation measure - corn yield in US counties 1997-2013 (Census only)

	I	II	III	IV	V	VI
Variables	yield	yield	yield	yield	lnyield	lnyield
Wind density	29.08***	8.495*	8.850*	12.56*	0.132**	0.182*
(MW/sqmi)	(8.119)	(4.706)	(4.728)	(6.717)	(0.0598)	(0.0970)
IrrShare	53.62***	12.77***	6.144	5.498	0.177	0.171
	(7.326)	(3.172)	(79.52)	(79.34)	(0.615)	(0.612)
Precip	-0.00131	0.453	0.825**	0.820**	0.00632	0.00626
	(0.355)	(0.437)	(0.399)	(0.400)	(0.00591)	(0.00592)
Precip^2	0.00842	-0.00258	-0.00755	-0.00755	-3.52e-05	-3.50e-05
	(0.00670)	(0.00746)	(0.00674)	(0.00674)	(9.93e-05)	(9.95e-05)
GDD	0.0853***	0.0269	0.0247	0.0245	0.000315	0.000313
	(0.0258)	(0.0258)	(0.0258)	(0.0257)	(0.000242)	(0.000240)
GDD^2	-1.33e-05***	-5.52e-06	-5.73e-06	-5.69e-06	-6.76e-08*	-6.71e-08*
	(3.86e-06)	(4.04e-06)	(3.99e-06)	(3.98e-06)	(3.89e-08)	(3.86e-08)
Precip x IrrShare			-2.103***	-2.109***	-0.0175**	-0.0175**
			(0.650)	(0.649)	(0.00786)	(0.00787)
Precip^2 x IrrShare			0.0256	0.0258	0.000157	0.000158
			(0.0174)	(0.0174)	(0.000182)	(0.000182)
GDD x IrrShare			2.88e-06	0.000452	-9.22e-05	-8.85e-05
			(0.0437)	(0.0436)	(0.000347)	(0.000346)
GDD^2 x IrrShare			2.00e-06	1.94e-06	3.24e-08	3.18e-08
			(5.82e-06)	(5.80e-06)	(4.69e-08)	(4.67e-08)
County FE	N	Y	Y	Y	Y	Y
State-Year FE	Y	Y	Y	Y	Y	Y
Trim	N	N	N	Y	N	Y
N	7,708	7,708	7,708	7,692	7,625	7,609
R^2	0.604	0.570	0.578	0.578	0.537	0.538
Counties	2,237	2,237	2,237	2,237	2,199	2,199

*Notes: Coefficient of interest is the effect of a change in wind generation capacity density (MW/sqmi) on corn yield (bu/acre) or log of corn yield. Precip is measured as total precipitation (inches) during growing season (April 1 - September 30). GDD is measured as total growing degree days during growing season. IrrShare is the share of irrigated acres in a county. All columns exclude the county of Benton, IN 2010-2013. Trimmed samples drop high leverage 5% tail of wind density observations. Results are for all counties in US based on NASS survey data for 1997-2013. Standard errors clustered at the state level in parenthesis. * indicates 10 percent significance.** indicates 5 percent significance. *** indicates 1 percent significance.*

Table A.6: Extreme degree days - all crops

	I	II	III	IV
	Corn	Soy	Hay	Wheat
Panel A: Unbalanced panel				
Variables	yield	yield	yield	yield
Wind density	11.59***	2.248*	0.252*	-2.941
(MW/sqmi)	(2.745)	(1.268)	(0.144)	(2.772)
XDD	-0.0312***	-0.0118***	-0.000661***	0.0157
	(0.00474)	(0.00128)	(0.000111)	(0.0151)
N	31,775	26,113	20,661	25,863
R-squared	0.550	0.599	0.370	0.427
Number of counties	2,341	1,905	1,700	2,164
Panel B: Balanced panel				
Variables	yield	yield	yield	yield
Wind density	11.91***	3.347**	0.828*	-4.169
(MW/sqmi)	(3.067)	(1.460)	(0.411)	(3.293)
XDD	-0.0381***	-0.0127***	-0.000453***	0.00648
	(0.00578)	(0.00168)	(0.000128)	(0.0330)
N	17,425	16,235	5,236	9,044
R-squared	0.657	0.647	0.465	0.556
Number of counties	1,025	955	308	532
County FE	Y	Y	Y	Y
State-Year FE	Y	Y	Y	Y
Dry-Weather	Y	Y	Y	Y
Trim	Y	Y	Y	Y

*Notes: Coefficient of interest is the effect of a change in wind generation capacity density (MW/sqmi) on corn, soybean, hay (alfalfa), or wheat (winter) yields (bu/acre). XDD is measured as total extreme degree days during growing season (April 1 - September 30 for corn, hay and soy, and October 1st - March 31st for wheat). Precip is measured as total precipitation (inches) during growing season. GDD is measured as total growing degree days during growing season. Dry-Weather interacts an indicator for dry (irrigated) counties with weather variables (quadratic). Trimmed samples drop high leverage 5% tail of wind density observations. All columns exclude the county of Benton, IN 2010-2013. Unbalanced panel results are for all counties in US based on NASS survey data for 1997-2013. Balanced panel results are for all counties in US with reported yields in every year based on NASS survey data for 1997-2013. Standard errors clustered at the state level in parenthesis. * indicates 10 percent significance.** indicates 5 percent significance. *** indicates 1 percent significance.*

Table A.7: Alternative weather specifications

	I	II	III	IV
	Corn	Soy	Hay	Wheat
Panel A: Disaggregated growing degree days				
Variables	yield	yield	yield	yield
Wind density	11.62***	3.431**	0.827*	-3.750
(MW/sqmi)	(2.687)	(1.254)	(0.410)	(3.133)
XDD	-0.0416***	-0.0147***	-0.000349***	0.0106
	(0.00596)	(0.00160)	(0.000119)	(0.0301)
N	17,425	16,235	5,236	9,044
R-squared	0.659	0.649	0.464	0.558
Number of counties	1,025	955	308	532
County FE	Y	Y	Y	Y
State-Year FE	Y	Y	Y	Y
Dry-Weather-Month	Y	Y	Y	Y
Trim	Y	Y	Y	Y
Panel B: No weather controls				
Variables	yield	yield	yield	yield
Wind density	12.79***	3.577**	0.840**	-3.523
(MW/sqmi)	(3.168)	(1.697)	(0.403)	(3.279)
N	17,425	16,235	5,236	9,044
R-squared	0.642	0.623	0.459	0.548
Number of counties	1,025	955	308	532
County FE	Y	Y	Y	Y
State-Year FE	Y	Y	Y	Y
Dry-Weather	N	N	N	N
Trim	Y	Y	Y	Y

*Notes: Coefficient of interest is the effect of a change in wind generation capacity density (MW/sqmi) on corn, soybean, hay (alfalfa), or wheat (winter) yields (bu/acre). XDD is measured as total extreme degree days during growing season (April 1 - September 30 for corn, hay and soy, and October 1st - March 31st for wheat). Precip is measured as total precipitation (inches) during growing season. GDD is measured as total growing degree days during growing season. Dry-Weather interacts an indicator for dry (irrigated) counties with precipitation (quadratic) and disaggregates GDD by month of growing season. Trimmed samples drop high leverage 5% tail of wind density observations. All columns exclude the county of Benton, IN 2010-2013. Unbalanced panel results are for all counties in US based on NASS survey data for 1997-2013. Balanced panel results are for all counties in US with reported yields in every year based on NASS survey data for 1997-2013. Standard errors clustered at the state level in parenthesis. * indicates 10 percent significance.** indicates 5 percent significance. *** indicates 1 percent significance.*

Table A.8: Wind farm effect interacted wind speed and hub height - corn yields

Variables	I yield	II yield	III yield	IV yield
Wind density x Wind Speed < 8 mi/hr	5.262	12.01***		
	(3.352)	(3.259)		
Wind density x Wind Speed > 8 mi/hr	10.40***	12.08***		
	(2.518)	(2.816)		
Wind density x Hub Height < 235 feet			6.708	9.969
			(12.62)	(18.10)
Wind density x Hub Height > 235 feet			7.575***	12.23***
			(2.490)	(2.080)
County FE	Y	Y	Y	Y
State-Year FE	Y	Y	Y	Y
Dry-Weather	Y	Y	Y	Y
Trim	N	Y	N	Y

*Notes: Coefficients of interest are the effect of a change in wind generation capacity density (MW/sqmi) on corn yields (bu/acre) depending on wind speed and hub height (above or below median). Precip is measured as total precipitation (inches) during growing season (April 1 - September 30 for corn, hay and soy, and October 1st - March 31st for wheat). GDD is measured as total growing degree days during growing season. Dry-Weather interacts an indicator for dry (irrigated) counties with weather variables (quadratic). Trimmed samples drop high leverage 5% tail of wind density observations. All columns exclude the county of Benton, IN 2010-2013. Results are for all counties in US based on NASS survey data for 1997-2013. Standard errors clustered at the state level in parenthesis. * indicates 10 percent significance.** indicates 5 percent significance. *** indicates 1 percent significance.*

Table A.9: Wind farm effect interacted with irrigation - all crops

	I	II	III	IV
	Corn	Soy	Hay	Wheat
Panel A: Unbalanced panel				
Variables	yield	yield	yield	yield
Wind density	12.85***	2.324	0.218	-2.885
(MW/sqmi)	(4.515)	(1.416)	(0.139)	(2.173)
Irrigation interaction	-3.957	0.577	0.0489	-0.0543
	(13.57)	(2.765)	(0.262)	(4.656)
N	31,775	26,113	20,661	25,863
R-squared	0.543	0.588	0.366	0.427
Number of counties	2,341	1,905	1,700	2,164
Panel B: Balanced panel				
Variables	yield	yield	yield	yield
Wind density	11.28**	3.222*	0.838	-2.226
(MW/sqmi)	(5.221)	(1.663)	(0.595)	(2.348)
Irrigation interaction	0.951	1.064	-0.0202	-2.829
	(17.15)	(2.884)	(1.042)	(3.794)
N	17,601	16,387	5,236	9,120
R-squared	0.649	0.637	0.462	0.556
Number of counties	1,039	967	308	538
County FE	Y	Y	Y	Y
State-Year FE	Y	Y	Y	Y
Dry-Weather	Y	Y	Y	Y
Trim	Y	Y	Y	Y

*Notes: Coefficients of interest are the effect of a change in wind generation capacity density (MW/sqmi) on corn, soybean, hay (alfalfa), or wheat (winter) yields (bu/acre), and the interaction between wind generation capacity density (MW/sqmi) and a dummy indicating irrigated counties. Precip is measured as total precipitation (inches) during growing season (April 1 - September 30 for corn, hay and soy, and October 1st - March 31st for wheat). GDD is measured as total growing degree days during growing season. Dry-Weather interacts an indicator for dry (irrigated) counties with weather variables (quadratic). Trimmed samples drop high leverage 5% tail of wind density observations. All columns exclude the county of Benton, IN 2010-2013. Unbalanced panel results are for all counties in US based on NASS survey data for 1997-2013. Balanced panel results are for all counties in US with reported yields in every year based on NASS survey data for 1997-2013. Standard errors clustered at the state level in parenthesis. * indicates 10 percent significance.** indicates 5 percent significance. *** indicates 1 percent significance.*

Table A.10: Wind capacity interacted with terrain - corn yields

	I	II	III	IV	V	VI
Variables	yield	yield	yield	yield	lnyield	lnyield
Wind density	37.24***	12.96**	13.02**	21.59***	0.106**	0.204***
(MW/sqmi)	(11.58)	(5.101)	(5.127)	(5.713)	(0.0454)	(0.0545)
Wind density x	-0.0192**	-0.0107*	-0.0106*	-0.0315*	-0.000117**	-0.000468***
Slope length	(0.00873)	(0.00598)	(0.00597)	(0.0171)	(5.76e-05)	(0.000148)
Precip	-0.479	0.704***				
	(0.590)	(0.229)				
Precip^2	0.00862	-0.0107**				
	(0.0100)	(0.00419)				
GDD	0.140***	0.0322**				
	(0.0274)	(0.0151)				
GDD^2	-2.09e-05***	-6.88e-06***				
	(4.49e-06)	(2.30e-06)				
Precip x Wet			1.067***	1.070***	0.00812***	0.00815***
			(0.300)	(0.300)	(0.00287)	(0.00287)
Precip x Dry			-0.0581	-0.0571	-0.00991	-0.00991
			(0.657)	(0.656)	(0.00718)	(0.00719)
Precip^2 x Wet			-0.0167***	-0.0167***	-0.000112**	-0.000113**
			(0.00531)	(0.00532)	(5.41e-05)	(5.41e-05)
Precip^2 x Dry			0.0207	0.0205	0.000628	0.000627
			(0.0472)	(0.0471)	(0.000444)	(0.000443)
GDD x Wet			0.0315*	0.0311*	0.000411**	0.000408**
			(0.0167)	(0.0167)	(0.000167)	(0.000167)
GDD x Dry			0.0317**	0.0315**	0.000612**	0.000611**
			(0.0145)	(0.0145)	(0.000231)	(0.000231)
GDD^2 x Wet			-6.78e-06***	-6.73e-06***	-8.17e-08***	-8.14e-08***
			(2.47e-06)	(2.47e-06)	(2.48e-08)	(2.48e-08)
GDD^2 x Dry			-6.75e-06***	-6.72e-06***	-1.09e-07***	-1.08e-07***
			(2.22e-06)	(2.21e-06)	(3.38e-08)	(3.39e-08)
County FE	N	Y	Y	Y	Y	Y
State-Year FE	Y	Y	Y	Y	Y	Y
Trim	N	N	N	Y	N	Y
N	25,316	25,316	25,316	25,287	24,881	24,852
R^2	0.518	0.535	0.535	0.535	0.545	0.545
Counties	1,856	1,856	1,856	1,856	1,816	1,816

*Notes: Coefficient of interest is the effect of a change in wind generation capacity density (MW/sqmi) on corn yield (bu/acre) or log of corn yield. Slope length is a proxy for terrain, with higher values indicating more rugged terrain. Precip is measured as total precipitation (inches) during growing season (April 1 - September 30). GDD is measured as total growing degree days during growing season. Dry (irrigated) counties are defined by less than 15 inches of growing-season precipitation. All columns exclude the county of Benton, IN 2010-2013. Trimmed samples drop high leverage 5% tail of wind density observations. Results are for all counties in US based on NASS survey data for 1997-2013. Standard errors clustered at the state level in parenthesis. * indicates 10 percent significance.** indicates 5 percent significance. *** indicates 1 percent significance.*

Table A.11: Wind capacity interacted with distance to county centroid - corn yields

	I	II	III	IV	V	VI
Variables	yield	yield	yield	yield	lnyield	lnyield
Wind density	42.06***	15.30**	15.21**	20.07***	0.133**	0.209***
(MW/sqmi)	(13.92)	(5.865)	(5.900)	(6.455)	(0.0556)	(0.0605)
Wind density x	-58.44***	-18.53*	-18.24*	-22.12*	-0.134	-0.211**
Distance index	(21.33)	(9.975)	(9.964)	(11.22)	(0.0887)	(0.0964)
Precip	-0.454	0.904***				
	(0.614)	(0.249)				
Precip^2	0.00820	-0.0145***				
	(0.0107)	(0.00490)				
GDD	0.119***	0.0301***				
	(0.0303)	(0.0106)				
GDD^2	-1.82e-05***	-6.14e-06***				
	(4.96e-06)	(1.80e-06)				
Precip x Wet			1.290***	1.280***	0.0103***	0.0102***
			(0.357)	(0.354)	(0.00331)	(0.00330)
Precip x Dry			-0.0468	-0.0496	-0.0136	-0.0137
			(0.504)	(0.506)	(0.00908)	(0.00908)
Precip^2 x Wet			-0.0209***	-0.0207***	-0.000156**	-0.000154**
			(0.00671)	(0.00664)	(6.30e-05)	(6.26e-05)
Precip^2 x Dry			0.0194	0.0195	0.000820	0.000822
			(0.0382)	(0.0383)	(0.000532)	(0.000532)
GDD x Wet			0.0356***	0.0352***	0.000403***	0.000401***
			(0.0128)	(0.0127)	(0.000127)	(0.000127)
GDD x Dry			0.0313***	0.0310***	0.000542***	0.000541***
			(0.0107)	(0.0107)	(0.000176)	(0.000177)
GDD^2 x Wet			-6.79e-06***	-6.74e-06***	-7.74e-08***	-7.70e-08***
			(2.07e-06)	(2.06e-06)	(2.03e-08)	(2.03e-08)
GDD^2 x Dry			-6.22e-06***	-6.18e-06***	-9.71e-08***	-9.68e-08***
			(1.80e-06)	(1.79e-06)	(2.72e-08)	(2.73e-08)
County FE	N	Y	Y	Y	Y	Y
State-Year FE	Y	Y	Y	Y	Y	Y
Trim	N	N	N	Y	N	Y
N	31,829	31,829	31,829	31,765	31,328	31,264
R^2	0.533	0.543	0.543	0.543	0.549	0.549
Counties	2,341	2,341	2,341	2,341	2,293	2,293

*Notes: Coefficient of interest is the effect of a change in wind generation capacity density (MW/sqmi) on corn yield (bu/acre) or log of corn yield. The Distance index represents the distance between wind farms and county centroid, normalized by county size. Precip is measured as total precipitation (inches) during growing season (April 1 - September 30). GDD is measured as total growing degree days during growing season. Dry (irrigated) counties are defined by less than 15 inches of growing-season precipitation. All columns exclude the county of Benton, IN 2010-2013. Trimmed samples drop high leverage 5% tail of wind density observations. Results are for all counties in US based on NASS survey data for 1997-2013. Standard errors clustered at the state level in parenthesis. * indicates 10 percent significance.** indicates 5 percent significance. *** indicates 1 percent significance.*

Table A.12: Wind capacity interacted by spillover observations - corn yields

	I	II	III	IV	V	VI
Variables	yield	yield	yield	yield	lnyield	lnyield
Wind density	29.58***	7.785***	7.813***	13.16***	0.0639***	0.104***
(MW/sqmi)	(5.708)	(2.554)	(2.547)	(2.624)	(0.0218)	(0.0218)
Wind density x	-167.4***	-40.48**	-39.60**	-48.87**	-0.341	-0.431
spillover	(44.39)	(19.39)	(19.58)	(20.62)	(0.339)	(0.367)
Precip	-0.478	0.904***				
	(0.619)	(0.250)				
Precip^2	0.00863	-0.0145***				
	(0.0108)	(0.00492)				
GDD	0.119***	0.0302***				
	(0.0309)	(0.0106)				
GDD^2	-1.82e-05***	-6.17e-06***				
	(5.03e-06)	(1.81e-06)				
Precip x Wet			1.292***	1.284***	0.0103***	0.0103***
			(0.358)	(0.356)	(0.00332)	(0.00331)
Precip x Dry			-0.0549	-0.0591	-0.0137	-0.0138
			(0.503)	(0.505)	(0.00914)	(0.00914)
Precip^2 x Wet			-0.0210***	-0.0208***	-0.000156**	-0.000155**
			(0.00673)	(0.00667)	(6.31e-05)	(6.29e-05)
Precip^2 x Dry			0.0197	0.0198	0.000824	0.000826
			(0.0383)	(0.0383)	(0.000534)	(0.000535)
GDD x Wet			0.0358***	0.0354***	0.000405***	0.000402***
			(0.0128)	(0.0127)	(0.000127)	(0.000127)
GDD x Dry			0.0315***	0.0311***	0.000543***	0.000541***
			(0.0108)	(0.0107)	(0.000177)	(0.000177)
GDD^2 x Wet			-6.83e-06***	-6.77e-06***	-7.76e-08***	-7.72e-08***
			(2.08e-06)	(2.07e-06)	(2.04e-08)	(2.03e-08)
GDD^2 x Dry			-6.25e-06***	-6.20e-06***	-9.73e-08***	-9.69e-08***
			(1.80e-06)	(1.80e-06)	(2.73e-08)	(2.74e-08)
County FE	N	Y	Y	Y	Y	Y
State-Year FE	Y	Y	Y	Y	Y	Y
Trim	N	N	N	Y	N	Y
N	31,829	31,829	31,829	31,765	31,328	31,264
R^2	0.532	0.543	0.543	0.543	0.549	0.549
Counties	2,341	2,341	2,341	2,341	2,293	2,293

*Notes: Coefficient of interest is the effect of a change in wind generation capacity density (MW/sqmi) on corn yield (bu/acre) or log of corn yield. A 'spillover' observation is defined as falling into the top quartile of distance from county centroid and the top quartile of the fraction of hours that the wind direction would generate spillovers. Precip is measured as total precipitation (inches) during growing season (April 1 - September 30). GDD is measured as total growing degree days during growing season. Dry (irrigated) counties are defined by less than 15 inches of growing-season precipitation. All columns exclude the county of Benton, IN 2010-2013. Trimmed samples drop high leverage 5% tail of wind density observations. Results are for all counties in US based on NASS survey data for 1997-2013. Standard errors clustered at the state level in parenthesis. * indicates 10 percent significance.** indicates 5 percent significance. *** indicates 1 percent significance.*

Table A.13: Benefits of microclimate effects - Alternative specifications

	Corn	Soy	Hay	Wheat	Total
Panel A: Wind speed and soil quality controls					
Microclimate effect[a]	20.29	5.712	0.752	-9.087	
	(8.697)	(2.251)	(0.329)	(4.183)	
2013 Benefits	$497,934,639	$233,341,137	$47,526,978	-$80,417,939	$698,384,815
	(213,432,112)	(91,955,690)	(20,793,053)	(37,018,624)	(236,245,307)
2013 Benefits	$6.187	$3.652	$0.759	-$1.021	$9.577
per MWh[b]	(2.652)	(1.439)	(0.332)	(0.470)	(3.072)
Panel B: Unbalanced panel, full sample					
Microclimate effect[a]	7.537	0.869	0.153	-3.974	
	(2.505)	(0.919)	(0.177)	(1.431)	
2013 Benefits	$184,964,681	$35,499,553	$9,669,717	-$35,169,020	$194,964,931
	(61,474,927)	(37,542,105)	(11,186,536)	(12,664,033)	(73,987,111)
2013 Benefits	$2.298	$0.556	$0.154	-$0.447	$2.562
per MWh[b]	(0.764)	(0.588)	(0.179)	(0.161)	(0.993)
Panel C: Balanced panel, trimmed sample					
Microclimate effect[a]	12.25	3.488	0.825	-3.897	
	(4.149)	(0.939)	(0.376)	(3.545)	
2013 Benefits	$300,625,891	$142,488,425	$52,140,634	-$34,487,587	$460,767,363
	(101,820,149)	(38,359,126)	(23,763,489)	(31,372,465)	(115,705,230)
2013 Benefits	$3.735	$2.230	$0.833	-$0.438	$6.360
per MWh[b]	(1.265)	(0.600)	(0.379)	(0.398)	(1.505)

Notes: [a] *Estimated change in yield per wind capacity MW/sqmi.* [b] *Assumed wind capacity factor of 0.33.*