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Effect of Nuclear Power Plants on Local Crop Yields

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Abstract

The growing prevalence of clean energy generation raises the question of possible externalities associated with it. This article studies the effects of nuclear power plant development on local crop yields. I find that an average nuclear power plant increases local soybean yields by 2% and hay yields by 0.8%. Such effects translate to \$253 million yearly benefit. I also find less robust evidence that the average nuclear plant increases corn yields increase by 1.1% and wheat yields by 0.7%. A plausible mechanism is the change in microclimate near the power plants caused by increased water in the atmosphere from power plants' evaporative cooling systems and find some evidence supporting this argument.

Energy sources labeled as clean and renewable energy have been found to have some undesirable effects. For example, studies have found that wind turbines reduce local property values (Heintzelman and Tuttle, 2012) and kill hundreds of thousands of birds annually (U.S. Fish & Wildlife Service¹), that wind, solar, and biomass energy development can reduce life satisfaction of nearby residents (von Möllendorff and Welsch, 2017), and that hydropower development can have both negative and positive external effects (for meta-analysis, see Mattman, Logar, and Brouwer, 2016).

This article studies the effects of nuclear power plants on nearby crop yields. Active construction of nuclear power plants in the United States started in the late 1960s and continued until the late 1980s. Only a handful of plants have been built since then, which is usually attributed to opposition from local communities concerned about safety issues. While economic literature has considered the various externalities of power plants², little research has been done on their effects on local agriculture. Effects on agriculture are plausible because many power plants emit water steam into the atmosphere through their cooling systems (a process known as “consumption”). This water may affect local microclimates, and, hence, affect crop yields in the vicinities of power plants.

There are several reasons for focusing on nuclear power plants. First, despite recent low levels of construction, nuclear power plants generate a considerable amount of energy in the United States. According to the Environmental Protection Agency, they generate 19% of electrical power

¹ “Wind Turbines”. *U.S. Fish & Wildlife Service*, accessed January 2, 2020, <https://www.fws.gov/birds/bird-enthusiasts/threats-to-birds/collisions/wind-turbines.php>

² For example, the effect on housing values and rents (Davis, 2011) and the effect on health (Chay and Greenstone, 2003; Clay, Lewis, and Severnini, NBER working)

in the United States. While the Chernobyl and Fukushima disasters may have negatively affected the image of nuclear power plants, nuclear energy is still considered to be attractive because it is “clean,” that is, unlike coal and natural gas power plants, nuclear power plants do not have harmful emissions. In December 2019, the Nuclear Regulatory Commission of the United States extended the operating license of the Turkey Point Nuclear Plant, a decision indicating that nuclear power plants are still welcome to some degree in the US energy sector. It is possible that with further shift towards clean energy, the number of nuclear generating units (one plant can have several units) will increase in the future. Second, nuclear power plants withdraw more water than other types of power plants and consume more than 60% of what they withdraw (Macknick et al., 2011), implying that nuclear plants would have a larger impact on local microclimate. For a sample of nuclear plants used in one of my specifications, back-of-the-envelope calculations indicate a total annual consumption of 650 million cubic meters a year. This is equivalent to covering the entire city of Chicago with 43 inches of water (almost 20% more than its yearly precipitation level). Finally, nuclear power plants emit virtually no gases into the atmosphere other than water steam. Thus, any effects on local crops will come from changes in the amount of water in the atmosphere and not from carbon oxides, nitrogen oxides, or particulate matter, which would be the case for other power plants.

This article contributes to several literatures. First, it explores the externalities of clean energy. While nuclear energy may be preferred because its generation does not have a negative effect on people’s health (in the absence of major accidents) compared to, for example, coal energy, it is important to understand whether there are other effects, positive or negative. Second, it contributes to a growing literature on the effects of power plants on agriculture. Understanding the effect that water steam, produced by nuclear power plants, has on crop yields may be important

for disentangling a complicated effect that power plants emitting both water steam and other gases have on agriculture. Third, it opens a discussion on the net effect of water withdrawals by power plants on agriculture. While water steam emitted into the atmosphere may have a positive effect on crop yields, scarcity of water for irrigation caused by power plants' water withdrawals is an offsetting reason for concern.

Power plants and water

Power plants use water to produce steam to rotate power-generating turbines and also as a coolant. In the process, the cooling water becomes warmer and is discharged into the environment. Because discharges of hot water may negatively affect the environment and because the Clean Water Act requires power plants to use “the best technology available” to minimize the adverse impact on the environment, power plants use various types of cooling systems before water is discharged or reused.

There are two main types of cooling systems. In once-through cooling systems, the heated water is either discharged directly into the environment (if the water temperature is low enough) or directed into a cooling pond before being discharged into the environment. In recirculating cooling systems, cooling water is reused after being cooled down by the process of evaporation in a cooling pond or a cooling tower.

Evaporation in towers is either “natural,” happening in natural draft towers, or assisted by fans in mechanical draft towers. Natural draft towers are tall, hyperboloid-shaped³ towers, a structure commonly associated with nuclear power plants⁴. Often visible plumes of steam from cooling towers are visible indicators that nuclear power plants emit water into the air. The image of the hyperboloid-shaped towers almost always has a plume of steam rising above it.

On several occasions in the past 10 years the National Weather Service attributed precipitation near power plants to plumes coming from cooling towers. For example, on January 23, 2013, plumes from the Beaver Valley Nuclear Power Station caused snow in an area about 24

³ Such shape provides structural strength and helps evaporation

⁴ Despite such association, hyperboloid-shaped cooling towers are common for other types of power plants.

miles downwind from the power plant⁵. Other cases include precipitation caused by a gas power plant in Dodge City, KS⁶, and by the coal and oil-fueled Miami Fort Power Station⁷.

⁵ *US National Weather Service Pittsburgh PA*, accessed December 4, 2019,

<https://www.facebook.com/NWSPittsburgh/photos/a.121955251235900/367522830012473/?type=3&theater>

⁶ “Unusual Snowfall in Dodge City - Jan 19, 2011”, *The National Weather Service*, accessed December 4, 2019,

<https://www.weather.gov/ddc/dodgecitysnowband>

⁷ *NWS Wilmington OH*, accessed December 4, 2019, <https://twitter.com/NWSILN/status/953612116400984064>

Literature Review

There is little research in the science literature on the effects of power plants on microclimates. One dated exception is a report by Huff et al. (1971), who provide a survey of then-contemporary work on the effects of cooling towers on climate. The authors find that mechanical draft towers can cause fog and icing, events identified most often because it is easy to observe them. On the other hand, natural draft towers (being taller than mechanical draft towers) are claimed to be more likely to affect cloud formation and precipitation. The authors find that cooling tower plumes can cause cloud formation, though no “meteorologically acceptable” study assessing the possibility that these plumes “augment precipitation and cloud systems associated with naturally occurring storms” was found at the time (Huff et al., 1971). It is surprising that no articles can be found written after the 1970s on the subject.

Similarly, little attention has been paid to the effects of power plants on local agriculture. In a recent study, Junkermann and Hacker (2018) find that coal power stations’ emissions of ultrafine particles change global precipitation patterns. One may conjecture that such change affects crop yields but a study confirming this conjecture has yet to be completed. Burney and Ramanathan (2014) report effects of short-lived climate pollutants on wheat and rice yields in India. With respect to clean energy sources, Kaffine (2019) builds on recent findings from natural science literature that wind farms change local microclimate and finds evidence for a positive effect of wind farms on local soybean, corn, and hay yields, and less robust evidence for an effect on wheat yields. Metaxoglou and Smith (2019) find that reduction in NO_x emissions due to closures of coal power plants and installation of abatement technologies on the remaining coal power plants, led to increase in corn and soybean yields.

Data

I combine data on nuclear units' commission years and nameplate capacities with data on crop yields and meteorological data for the period from 1971 to 1991.

The yearly county-level crop yield data come from the United States Department of Agriculture's National Agricultural Statistics Service. In order to analyze a balanced panel, some of the counties are omitted from the final dataset⁸. In order to make my results comparable with Kaffine (2019) and, I focus on soybeans, corn, wheat (winter wheat), and hay (alfalfa). The map of the final dataset for soybeans is presented in Figure 2.

Weather data come from the National Oceanic and Atmospheric Administration (NOAA). The temperature data used to derive growing season (April through September) Growing Degree Days (GDD) values come from NOAA's Global Historical Climatology Network data. Because these are station level data, county-level GDDs were determined as GDDs from the station closest to the county's centroid⁹. NOAA also provides monthly county-level precipitation data. To derive growing season precipitation values, I sum precipitation values from April through September.

The data on nuclear power plants come from the Energy Information Administration's Form EIA-860. The data include location of a unit, the year the unit was commissioned, and the nameplate capacity of the unit. I shift all commission years forward by 1 because some of the power plants were commissioned in the last months of the year and their construction could only

⁸ For example, soybeans were not grown in the Wake County, NC until 1972. Hence, Wake County is omitted from the soybeans regressions even though it is the location of the Shearon Harris nuclear power plant.

⁹ I follow Kaffine (2019) in his definition of growing season GDD: $\sum_{d=Apr\ 1}^{Sept\ 30} [\frac{T_{max,d}+T_{min,d}}{2} - 50]$, where $T_{max,d}$ is the maximum temperature and $T_{min,d}$ is the minimum temperature on day d in degrees Fahrenheit. If for a given day $\frac{T_{max,d}+T_{min,d}}{2} - 50 < 0$, then for this day $\frac{T_{max,d}+T_{min,d}}{2} - 50 = 0$.

affect crop yields in the following year. Because most nuclear power plants were built prior to the year EIA-860 was first gathered, only 2006 data were used, with missing information complemented by the data found on the International Atomic Energy Agency's Power Reactor Information System. Only power plants with cooling towers (both natural and mechanical draft towers) were used in the final estimates.

As Figure 3 shows, most of the nuclear units in the United States were built in the 1970s and 1980s. Earlier units were smaller in size, those built prior to 1970 being less than 300 MW. In comparison, units built after 1980 had a capacity of 1,200 MW. The period I focus on is the 21 years from 1971 to 1991. 1971 was chosen as the start year because it is the earliest commission year in my data. 1991 was chosen as the end year because it represents a reasonable balance between a longer time period (with more nuclear units built but possibly more variation in yields not caused by construction of nuclear power plants) and a shorter time period (with more counties in my balanced panel). Also, this period was chosen because it covers the years of most active nuclear power plant construction.

Summary statistics of the data for the main specification for soybeans are presented in Table 1. Summary statistics for other crops are presented in Appendix A. Yield is measured in bushels per acre for soybeans, corn, and wheat, and in tons per acre for hay.

In addition, an alternative definition of control and treatment counties, taking into account wind direction, was considered. Data on wind directions from NOAA's Integrated Surface Database were used to identify the average wind directions at the stations closest to the power plants. Counties within 30 miles of a power plant that lay downwind in a 180 degree sector were

chosen as treatment counties. Counties within the same distance that are not downwind of any power plant were chosen as control counties¹⁰.

¹⁰ That is, if an average wind direction (direction from which the wind originates) was found to be 90 degrees, all the counties whose centroids lay within 30 miles in the sector between the South (180 degrees) and the North (360 degrees) were considered as treated counties.

Empirical Strategy

I estimate the following model:

$$y_{ct} = \alpha + \beta density_{ct} + \psi X_{ct} + \eta_c + \lambda_{st} + \epsilon_{ct}, \quad (1)$$

where y_{ct} is yield in county c in year t , $density_{ct}$ is cumulative nameplate capacity divided by the county's area, X_{ct} is vector of weather variables. Equation (1) also includes county and state-year fixed effects, η_c and λ_{st} .

The effect of power plants on yields is studied through a *density* variable, defined as cumulative nameplate capacity in the county divided by the county's area. Similarly to Clay et al. (2019), a county's nameplate capacity is the sum of nameplate capacities of the nuclear power plants within 30 miles of the county's centroid. I choose this distance for several reasons. First, in the absence of the exact estimates on water dispersion from cooling towers, estimates by Levy et al. (2002) on particulate matter, on which Clay et al. rely, are assumed to be a close approximation. Second, cases of precipitation caused by cooling towers mentioned in the earlier "Power plants and water" section also suggest that 30 miles is a reasonable distance to choose.

While later in this article, I find some evidence that nuclear power plants cause higher precipitation in the counties nearby, I include precipitation in my yield regressions. In regressions including both the density and precipitation, the density coefficient stands for the effect of nuclear power plants through more complex mechanisms (for example, fog, icing, or limited access to sunlight due to cloud formation). As shown in the results section, this does not affect the density coefficients considerably; in all of the specifications, including precipitation decreases the size of the density coefficient, thus, implying that my final estimates are conservative.

Also similar to Clay et al., control counties are chosen in one of two ways. First, control counties are defined to be those whose centroids lie within 30 to 90 miles from a nuclear power plant. This specification will be considered as main. Second, control counties are defined to be the non-treated counties in any state where nuclear power plants were built.

Crop yields vary by region. For example, soybean and corn yields are usually higher in the Midwestern United States (the so-called Soybean and Corn belts). Therefore, I include county fixed effects, η_c . While crop yields vary from year to year, there is a clear upward trend across all states. I include state-year fixed effects, λ_{st} , to control for these changes in yields. Standard errors are clustered at the state level. Alternative clustering levels (county and agricultural district) are considered as well.

Results

The results for soybeans are presented in Table 2. The results for corn, wheat, and hay are presented in Table 3. The observed coefficients imply that an average nuclear power plant would increase the soybean yields in nearby counties by 2.1%¹¹, corn yields by 1.1%, wheat yields by 0.7%, and alfalfa yields by 0.8%. However, results for corn and wheat are less robust across different specifications and different standard error choices. Because density and precipitation are likely positively correlated and because density has a positive coefficient, coefficient in column (3) is greater than in column (1) due to positive bias of the coefficient in column (1).

For soybeans, regression excluding density variable and including only weather variables indicates that yields are maximized at growing season GDD of 2,715 and growing season precipitation of 30.03 inches. While the average growing season GDD is greater than 2,715, the average growing season precipitation is less than 30.03. This supports the argument that water steam from cooling towers may increase yields through higher precipitation.

Robustness of results

This section presents results of alternative specifications. A specification with control counties being all the non-treated counties in the states with nuclear power plants (see Table 4) shows a significant and positive coefficient. It is close to the coefficient in the main specification and implies increase of soybean yields by 2.8%. The coefficients are slightly larger than the ones reported in Table 2. A possible explanation is that the yields in some of the control counties in the

¹¹ The average nameplate capacity of the nuclear plants in the data is 1589 MW. The average county area is 540 square miles. Thus, construction of a typical power plant would increase density by $\frac{1589}{540} = 2.94$. Such density would increase yields by $2.94 * 0.202 \approx 0.59$. The average soybean yield in this period is 27.96. $\frac{0.57}{27.96} \approx 0.021$ or 2.1%.

main specification were affected by the construction of nuclear power plants¹². In contrast, the control group in this specification includes counties far away from the power plants. Results for the other crops (Table 12) also show coefficients larger than those in the main specification.

While, the specification taking into account wind direction yields results significant only at a 10% level (with the p-value for soybeans being about 6.1%), the coefficient of this specification implies increase of 2.8% (Table 5).

Table 11 (Appendix B) presents results for the main specification with alternative levels of standard error clustering. While results for soybeans and hay are robust across all specifications, results for corn and wheat are only robust with state-level clustering.

Parallel pre-trends

One of the key assumption behind the analysis above is the parallel trends in treatment and control groups in the absence of treatment. That is, it is assumed that if nuclear power plants were not constructed, yields in the treatment and control counties would be evolving in the same way. Hence, the yields data are tested for the presence of parallel pre-trends. To do this, I follow Kaffine (2019) and estimate the following regression:

$$y_{ct} = \alpha + \sum_{l=-3}^3 \beta_l I_{ct}(t - T_c = l) A_c + \psi X_{ct} + \eta_c + \lambda_{st} + \epsilon_{ct}, \quad (2)$$

where A_c is an indicator variable for a county that witnessed a nuclear power plant development nearby, $I_{ct}(t - T_c = l)$ is an indicator variable for an observation l years prior/after the first nuclear power plant was built nearby. Thus, β_l should be close to zero for negative l because it can be interpreted as the effect of nuclear power plant development l years prior to actual

¹² Thus, making these coefficients a conservative estimate of the effect

development. Similarly, β_l should be significant for positive l as it can be interpreted as the effect after a nuclear power plant was built nearby.

Table 6 presents the results of pre-trends regression. Overall, coefficients for years prior to power plant development are not significant. This provides a support for the assumption of parallel trends. In addition, some of the coefficients for years after power plant development are positive and significant.

Mechanism

In order to explore the effect of nuclear power plants on local precipitation I estimate a simple model specified as follows:

$$\ln(\text{precipitation}_{ct}) = \alpha + \beta \text{density}_{ct} + \gamma \text{density}_{ct}^2 + \eta_c + \lambda_{st} + \epsilon_{ct}, \quad (3)$$

where the variables are defined the same way as in the main regression. The main specification shows evidence for increased precipitation in spring, while the upwind-downwind specification shows evidence for increased precipitation over the entire growing season. The coefficients in column (1) imply that a typical power plant would increase spring precipitation in main specification by 3%. Assuming spring precipitation contains a third of growing season precipitation, according to Table 2, holding density constant, 1% increase in growing season precipitation would increase soybean yields by 2.7%. Such increase is consistent with the results in Table 2.

Economic implications

Based on the results in the previous section, I can perform back-of-the-envelope calculations on the economic implications of external effects of nuclear power plants on crop yields. I estimate that in 1991, the total external benefits to soybean and hay farmers were \$17.4 million and \$4 million (in 2019 US dollars), respectively. Table 8 also presents benefits to corn and wheat farmers. However, I do not include these values in final calculations because they are not as robust. With 90% capacity factor for nuclear power plants, my estimates translate to benefits of 17.1¢/MWh per year. While this estimate is lower than Kaffine's result of \$5.33/MWh, the total benefits are still considerable and should not be ignored.

Assuming that nuclear power plants operate for 35 years¹³, with the interest rate of 3%, the annual benefits combine into an annuity with the present value of \$197 million for soybean farmers and \$46 million for hay farmers¹⁴.

Metaxoglu and Smith (2019) point out that crops like corn and soybeans have low elasticities of supply and demand. Thus, an increase in yields would make consumers better off and farmers worse off. Following similar procedures I estimate welfare changes for soybeans, corn, wheat, and hay consumers and producers. I find that consumer surplus increased annually for soybean consumers by \$276 million, for corn producers by \$286 million, for wheat consumers by \$14.12 million, and for hay consumers by \$23 million. Producer surplus decreased annually for soybean farmers by \$159 million, corn farmers \$167 million, wheat farmers by \$8.26 million, and hay farmers by \$13 million.

¹³ Design lifespan. Many nuclear power plants operate longer than this.

¹⁴ $PV = AnnualBenefit * \left(\frac{1-(1+r)^{-n}}{r} \right) = 9,161,088 * \left(\frac{1-(1+0.03)^{-35}}{0.03} \right) \approx 197 \text{ million}$

Conclusion

Nuclear power is an attractive source of energy since it does not have “dirty” emissions that would have negative effects on human health or contribute to global climate change through carbon emissions. However, just like many other power plants, nuclear power plants emit significant amount of water steam into the atmosphere through their cooling systems. I investigate the effect of nuclear power plants on nearby agriculture and find a significant positive effect on soybean and hay yields. An average nuclear power plant increases local soybean yields by 2% and hay yields by 0.8%. I also find confirmatory, but less robust, evidence that corn yields increase by 1.1% and wheat yields increase by 0.7%. This translates to benefits of \$253 million (2019 US dollars), a combination of \$347 million loss to farmers and \$600 million benefit to consumers. While the effect on total surplus is positive, it would be easy to imagine dissatisfied farmers calling for compensations or arguing against construction of a nuclear power plant next to their farms, or arguing for a shutdown of an existing plant.

Tables and Figures

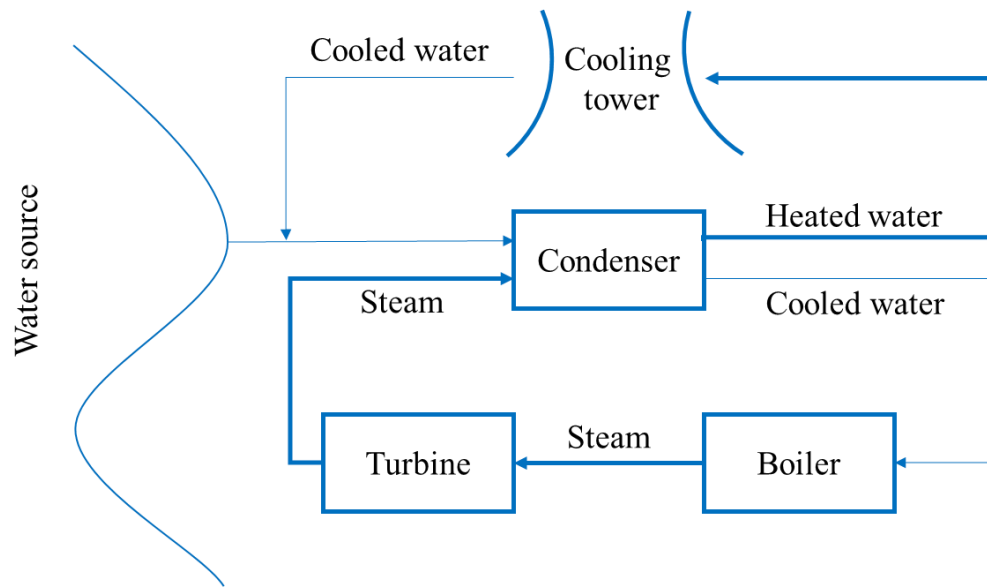


Figure 1. Recirculating cooling system with a cooling tower

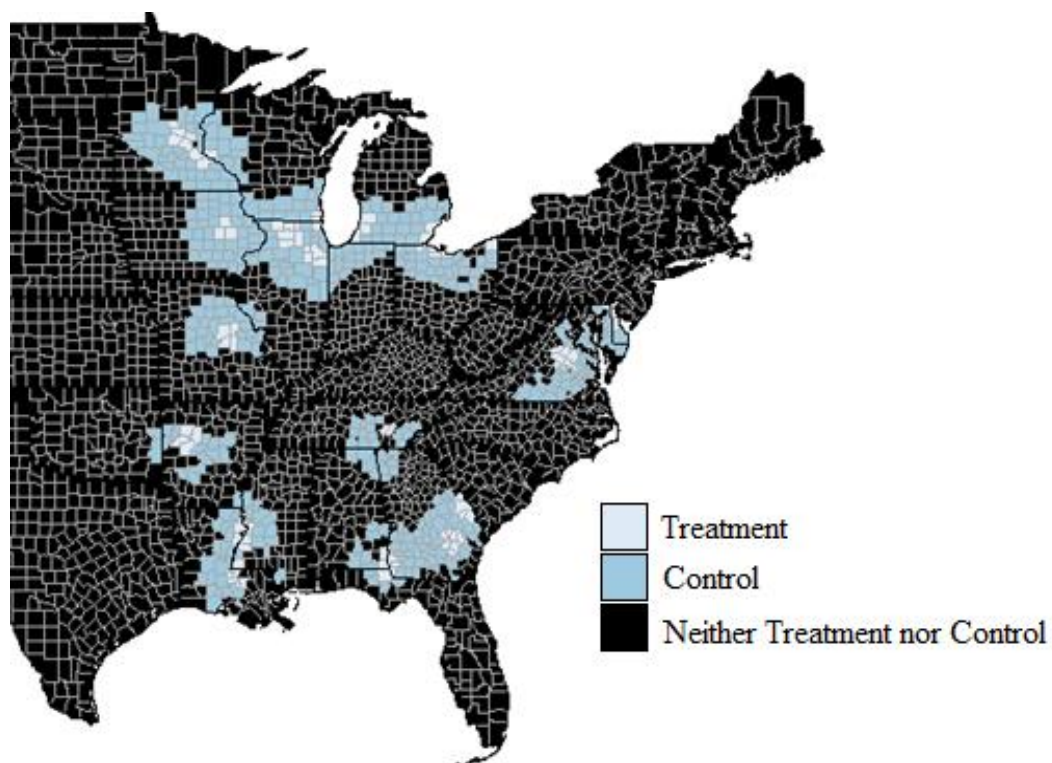


Figure 2. Soybean counties near nuclear power plants

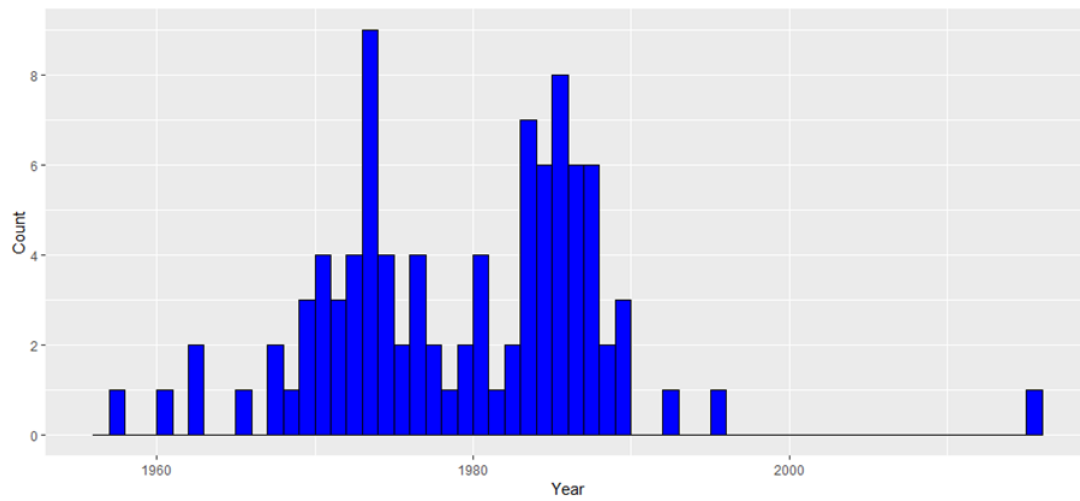


Figure 3. Nuclear Units built in the United States

Table 1. Summary Statistics for Soybean Counties

	1971	1991
<hr/>		
All counties		
<hr/>		
Yield	25.93	32.87
Growing season precipitation, in	21.95	25.36
Growing season GDD / 1000	3.42	3.67
Density, MW/mi ²	0.04	0.63
 Treated counties		
<hr/>		
Yield	24.99	31.45
Growing season precipitation, in	22.45	26.29
Growing season GDD / 1000	3.44	3.76
Density, MW/mi ²	0.26	3.78
 Control counties		
<hr/>		
Yield	26.12	33.16
Growing season precipitation, in	21.85	25.17
Growing season GDD / 1000	3.43	3.66
Density, MW/mi ²	0	0

Table 2. Yield Regressions for Soybeans

	(1)	(2)	(3)
	Yield	Yield	Yield
density	0.204**	0.217***	0.202***
	(0.0727)	(0.0678)	(0.0584)
gdd/1000		1.017	2.121
		(1.414)	(1.425)
(gdd/1000) ²		-0.267	-0.392*
		(0.214)	(0.222)
precip			0.891***
			(0.137)
precip ²			-0.0148***
			(0.00241)
_cons	27.89***	27.68***	13.18***
	(0.0252)	(2.381)	(3.777)
County FE	Y	Y	Y
State-Year FE	Y	Y	Y
<i>N</i>	10206	10206	10206
adj. <i>R</i> ²	0.864	0.864	0.870

Standard errors clustered at the state level in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 3. Yield Regressions for Corn, Wheat, and Hay

	Corn		Wheat		Hay	
	(1)	(2)	(1)	(2)	(1)	(2)
	Yield	Yield	Yield	Yield	Yield	Yield
density	0.346**	0.321**	0.113**	0.0982*	0.0173***	0.0113***
	(0.151)	(0.122)	(0.0489)	(0.0477)	(0.00154)	(0.000927)
gdd/1000		7.905		-3.678*		0.225
		(6.086)		(1.932)		(0.224)
(gdd/1000) ²		-1.060		0.595**		-0.0506
		(0.943)		(0.278)		(0.0390)
precip		3.461***		0.313**		0.157***
		(0.355)		(0.126)		(0.0176)
precip ²		-0.0546***		-0.00724**		-0.00292***
		(0.00650)		(0.00286)		(0.000462)
_cons	82.62***	19.58	39.05***	41.32***	3.068***	0.869
	(0.0517)	(12.19)	(0.0214)	(3.416)	(0.000639)	(0.420)
County FE	Y	Y	Y	Y	Y	Y
State-Year FE	Y	Y	Y	Y	Y	Y
<i>N</i>	15078	15078	9261	9261	2751	2751
adj. <i>R</i> ²	0.870	0.877	0.873	0.873	0.804	0.814

Standard errors clustered at the state level in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

**Table 4. Control are All Non-treated Counties in the States with Nuclear Power Plants
(Soybeans)**

	Yield	Yield
density	0.276***	0.266***
	(0.0555)	(0.0448)
Weather variables	N	Y
County FE	Y	Y
State-Year FE	Y	Y
<i>N</i>	19446	19446
adj. R^2	0.845	0.853

Standard errors clustered at the state level in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 5. Taking into Account the Wind Directions (Soybeans)

	Yield	Yield
density	0.386*	0.375*
	(0.172)	(0.191)
Weather variables	N	Y
County FE	Y	Y
State-Year FE	Y	Y
<i>N</i>	840	840
adj. R^2	0.755	0.764

Standard errors clustered at the state level in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 6. Pre-trends Regressions for Soybean Counties

	(1)	(2)
	Yield	Yield
l = -3	0.232	0.376
	(0.337)	(0.398)
l = -2	-0.0518	-0.230
	(0.473)	(0.470)
l = -1	-0.0666	-0.0876
	(0.469)	(0.494)
l = 0	-0.422	-0.545
	(0.374)	(0.340)
l = 1	0.520 [*]	0.324
	(0.298)	(0.303)
l = 2	-0.575	-0.563
	(0.406)	(0.413)
l = 3	1.369 ^{**}	1.317 ^{**}
	(0.601)	(0.593)
_cons	27.95 ^{***}	13.54 ^{***}
	(0.0124)	(3.780)
Weather variables	N	Y
County FE	Y	Y
State-Year FE	Y	Y
N	10206	10206

adj. R^2	0.863	0.870
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Standard errors clustered at the state level in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 7. Effect on Microclimate for Soybean Counties

	(1)	(2)
	log(precip)	log(precip)
	Spring	Growing season
	main specification	upwind-downwind
density	0.0144*** (0.00407)	0.0215*** (0.00394)
density ²	-0.00167*** (0.000518)	-0.00340*** (0.000647)
_cons	2.373*** (0.000650)	3.201*** (0.00179)
County FE	Y	Y
State-Year FE	Y	Y
<i>N</i>	10206	840
adj. <i>R</i> ²	0.871	0.868

Standard errors clustered at the state level in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 8. Benefits per average power plant

	Soybeans	Corn	Wheat	Hay
Price received, 1991	\$5.58/bu	\$2.37/bu	\$2.92/bu	\$74.6/ton
Benefit, 1991	\$9,161,088	\$9,569,909	\$3,162,368	\$2,143,410
PV of annuity, 1991	\$196,846,313	\$205,630,740	\$67,950,497	\$46,055,922
PV of annuity, 2019 USD	\$369,494,404	\$385,983,392	\$127,547,872	\$86,450,211
Benefit, 2019 USD	\$17,412,859	\$18,189,922	\$5,908,557	\$4,074,068
Benefit per MWh, 2019 USD	6.9¢	5.1¢	1.9¢	3.2¢

Table 9. Welfare change

	Soybeans	Corn	Wheat	Hay
Price received, 1991	\$5.58/bu	\$2.37/bu	\$2.92/bu	\$74.6/ton
Nuclear units in the sample	32	43	38	15
Quantity, 1989-1991 average	651.80	2,877.68	180.92	9.96
Δ CS, 1991	\$147.27	\$152.29	\$7.52	\$12.08
Δ PS, 1991	-\$84.94	-\$88.71	-\$4.40	-\$7.06
Δ TS, 1991	\$62.33	\$63.58	\$3.12	\$5.02
Δ CS, 2019 USD	\$276.44	\$285.86	\$14.12	\$22.68
Δ PS, 2019 USD	-\$159.44	-\$166.51	-\$8.26	-\$13.25
Δ TS, 2019 USD	\$117.00	\$119.35	\$5.86	\$9.42
PV of annuity (Δ TS), 2019 USD	\$2,514	\$2,564	\$125	\$202

Note: Quantity is measured in millions of bushels for soybeans, corn, and wheat, and in millions of tons for hay. Changes in consumer surplus, producer surplus, total surplus, and present value of the annuity are measured in millions.

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Appendix A

Table 10. Data Summary for Corn, Wheat, and Hay

	Corn		Wheat		Hay	
	1971	1991	1971	1991	1971	1991
All counties						
Yield	70.71	92.49	38.22	39.20	2.94	3.10
Growing season precip, in	22.71	23.68	21.95	22.03	19.57	21.89
Growing season GDD / 1000	3.37	3.62	3.34	3.61	2.68	2.92
Density, MW/mi ²	0.03	0.73	0.04	0.90	0	0.95
Treated counties						
Yield	68.77	91.12	37.88	39.25	3.02	3.20
Growing season precip, in	22.80	23.65	22.01	22.33	21.77	20.20
Growing season GDD / 1000	3.36	3.65	3.32	3.61	2.88	3.10
Density, MW/mi ²	0.15	4.29	0.18	4.60	0	4.16
Control counties						
Yield	71.11	92.78	38.31	39.18	2.92	3.08
Growing season precip, in	22.69	23.68	21.94	21.96	18.92	22.40
Growing season GDD / 1000	3.37	3.61	3.35	3.61	2.63	2.87

Appendix B

Table 11. Coefficients and Standard Errors for Density Variable

	Soybeans	Corn	Wheat	Hay
State-level clustering	0.202*** (0.0584)	0.321** (0.122)	0.0982* (0.0477)	0.0113*** (0.000927)
Agricultural district-level clustering	0.202*** (0.0482)	0.321 (0.236)	0.0982 (0.0671)	0.0113*** (0.00340)
County-level clustering	0.202*** (0.0673)	0.321 (0.223)	0.0982 (0.0654)	0.0113** (0.00456)

Standard errors in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Appendix C

**Table 12. Control are All Non-treated Counties in the States with Nuclear Power Plants
(Other Crops)**

	Corn		Wheat		Hay	
	(1)	(2)	(1)	(2)	(1)	(2)
	Yield	Yield	Yield	Yield	Yield	Yield
density	0.248*	0.224*	0.150***	0.135***	0.0177***	0.0116***
	(0.141)	(0.125)	(0.0502)	(0.0436)	(0.00137)	(0.00165)
Weather variables	N	Y	N	Y	N	Y
County FE	Y	Y	Y	Y	Y	Y
State-Year FE	Y	Y	Y	Y	Y	Y
<i>N</i>	26313	26313	17199	17199	4683	4683
adj. R^2	0.846	0.857	0.837	0.839	0.828	0.836

Standard errors clustered at the state level in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 13. Taking into Account the Wind Directions (Other Crops)

	Corn		Wheat		Hay	
	(1)	(2)	(1)	(2)	(1)	(2)
	Yield	Yield	Yield	Yield	Yield	Yield
density	0.709	0.434	0.158	0.130	0.00302**	0.000499
	(0.484)	(0.264)	(0.202)	(0.169)	(0.000187)	(0.00360)
Weather variables	N	Y	N	Y	N	Y
County FE	Y	Y	Y	Y	Y	Y
State-Year FE	Y	Y	Y	Y	Y	Y
<i>N</i>	1659	1659	1155	1155	483	483
adj. R^2	0.875	0.884	0.881	0.884	0.670	0.677

Standard errors clustered at the state level in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$