The Effects of Hydraulic Fracturing on Agricultural Productivity*

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Abstract

There is so much concern by agricultural producers that they will be affected by the large-scale use of hydraulic fracturing, yet there is little evidence of these external effects. I use highly detailed data from Alberta, Canada to quantify the external effects of hydraulic fracturing on agricultural productivity, using temporal and spatial variation in the count of wells and variation in the agricultural production by township. I find that yield of the irrigated crops decreases by 4.2% when hydraulic fracturing wells are drilled during the agriculturally active months within a township. Results also indicate that each 1000 m^3 water use increase for the purpose of hydraulic fracturing during the agricultural months decreases yield of the irrigated crops by 1.4%. These effects become smaller and weaker as the distance between the township and the well location increases. The study has implications for potential spatial and temporal regulations on the use of hydraulic multi-stage fracturing and associated water use.

JEL Classification: Q15, Q18, Q25

Keywords: Agricultural Productivity; Hydraulic Fracturing; Horizontal Drilling Innovation; Water Conservation

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1 Introduction

Recent technological advances in unconventional oil and gas extraction techniques, such as, hydraulic fracturing (HF), have made it possible to extract energy resources that were previously inaccessible.[1] Yet, there is a growing concern that hydraulic fracturing has various negative consequences for other sectors that share factors of production with the oil and gas drilling industry (Mason et al. 2015). One concern that economists have identified is the effect hydraulic fracturing may have upon reducing agricultural productivity (Hitaj et al. 2014). This study investigates the effect that hydraulic fracturing, an oil and gas extraction technique, has upon agricultural production by exploiting variation in proximity to hydraulically fractured wells, variation in the timing of when wells are drilled, and in variation in the types of crops grown.

The overall effect of hydraulic fracturing can be uncertain and it can vary in regional, farm and individual levels. On one hand, advances in horizontal drilling and hydraulic fracturing has increased the global oil and natural gas production and decreased oil and gas prices. This has some benefits for agricultural production.[2] On the other hand, the expanding usage of hydraulic fracturing can affect agriculture adversely through competing for water, land, labor and other inputs of production (Hitaj et al., 2014; CCA, 2014) and by creating possible soil and water contamination through sediment run-off from nearby well-pads (Olmstead et al., 2013; Burton et al., 2014). Furthermore, increased truck traffic for carrying water and other inputs in the nearby well pads can damage roads used by the farmers. This increase in traffic congestion not only can decrease farmers' profitability (Abramzon et al. 2014), but also can create air pollution (Goodman et al. 2016; Gibson 2013).[3] Finally, hydraulic fracturing activity can increase ground-level ozone (Shonkoff et al., 2014; Srebotnjak et al., 2014), and hence, can be associated with soil quality degradation and crop yield reduction (Wilkinson 2012).

One of the major concerns that is related with hydraulic fracturing is that it is very water-intensive. In fact, water use intensity of a hydraulic fracturing well is much higher than an agricultural farm. Total volume of water usage by the oil and gas industry, often however, can be insignificant compared to the agricultural sector. For example, in Alberta, Canada, the average daily water use of an active well for hydraulic fracturing purpose was 1700 m^3 in 2014 (Well Com-

[1] Hydraulic fracturing involves injecting a pressurized mixture of water, sand, and other chemicals (often called proppants) into deep wells. The pressurized mixture creates fractures in the low-permeable rock layer, releasing oil and natural gas, which flows back up the well. Sometimes wells are drilled *horizontally* into shale formations (known as horizontal drilling), instead of vertical drilling done in the conventional oil and gas production (King 2012).

[2] Agricultural sector can directly benefit from low oil and gas price if farm equipment are ran using these fossil fuels. Moreover, agricultural sector indirectly benefits from low oil and natural gas price when oil and natural gas using inputs, for example: nitrogen-based fertilizer, become less costly. (Hitaj et al. 2016, Carter and Novan 2013). The low energy price, often however, may benefit the fertilizer producers more than the fertilizer consumers (Pirog and Ratner 2012; Hitaj et al. 2014). According to Hitaj and Suttles (2016), in spite of the lower natural gas and fuel price, domestic fertilizer price does not decrease and reflects the global price. Thus, impact of hydraulic fracturing on indirect energy use of the agricultural sector becomes almost insignificant.

[3] Goodman et al. (2016) show that CO_2, NO_x, and other polluting air particle emission increase during well drilling periods, while emission of NO_x can increase 30% more than the baseline.

pletion & Frac Database, 2014). This value is approximately 1.5 times higher than the average daily water use of a farm for irrigation purposes, which is 1200 m^3 (Statistics Canada, 2011).[4] Thus, the increased usage of hydraulic fracturing can affect agricultural production and crop productivity by creating water scarcity in places with a history of drought and without any established market for water (Gaudet et al. 2006).

While both the direct and indirect effects of hydraulic fracturing on agriculture has been widely studied (Hitaj et al. 2014; Weber and Hitaj, 2014; Weber and Hitaj, 2015), the external effects of hydraulic fracturing on agriculture was not separated from the direct and indirect estimates.[5] Many of these studies focused the effect on land values (Weber and Hitaj, 2014; Weber and Hitaj, 2015), and thus the effects on the productivity of agricultural sector, which is often confounded with the net effects of hydraulic fracturing, was overlooked. Furthermore, in most of the jurisdictions in the United States mineral rights belongs to the farmers and farmers and land owners gain from increased HF activity (Weber et al. 2014, Weber et al. 2016). Therefore, it becomes a challenge to disentangle the effects through HF externalities from the estimated total HF effects on agriculture. I use a highly detailed data set from Alberta, Canada to estimate the effects of nearby hydraulic fracturing wells on agriculture. Since in Alberta, the mineral rights belong to the province and farmers can not influence on the locations of the HF wells, this study successfully estimates the external effects of hydraulic fracturing on agricultural productivity.

Alberta is the second largest field crop producing province in Canada. In addition to that, Alberta is one of the highest producers of many major food crops, such as, barley, wheat, and oats (Alberta Agriculture and Forestry, 2015).[6] In 2015, the real gross domestic product (GDP) of Alberta from the Agri-food industry was $5.4 billion, accounting for 1.8% of the real GDP earned from all industries in Alberta (Agriculture Statistics Factsheet 2016). In addition, approximately 86% of the total shale oil and tight oil in-place reserves and 41% of the total shale gas in-place reserves of Canada is located in Alberta, which makes this province the highest shale and tight oil producer and the second largest shale gas exporter within Canada (EIA, 2015). These characteristics make Alberta a compelling location to investigate the effects of hydraulic fracturing on agriculture.

To conduct this study, I use township-level crop yield data and well-level hydraulic fracturing data.[7] The data on the hydraulic fracturing wells and the agricultural statistics create a panel for

[4] At 20 m^3 per truck, a hydraulically fractured well requires 85 (=1700/20) water trucks per well, creating congestion, road wear, dust, and other complications that may affect agricultural production.

[5] Direct effects include the close proximity spillover effects, such as, the effects through infrastructure sharing, technological spillovers, increased local demand for goods, etc. The indirect effects include the negative spillover effects, such as, the effects from water sharing, sediment run-off from the well pads, congestion from traffic servicing the well, and labor movement. For more discussion on direct and indirect effects see Hornbeck and Keskin (2015).

[6] Alberta is also among the top honey and cattle producing provinces in Canada (Statistics Canada, 2011)

[7] Alberta Township System (ATS) is a land surveying system used in Alberta. It is also the smallest geographical unit used in the agricultural sector. Each township is a six mile by six mile square. Townships are divided into 36 sections, where each section is one-by-one mile.

the years 2000 to 2014, for 1786 agriculturally active townships. The identification strategy of this analysis relies both upon temporal and spatial variation in agricultural production and hydraulic fracturing wells drilled. The temporal variation comes from the variation in the count of wells drilled over time relative to variation in the agricultural production over time. The spatial variation comes from the geographic proximity of different agriculturally active townships to hydraulic fracturing wells. This proposed identification has the similar characteristics and the advantages and disadvantages of a standard difference-in-differences (DID) strategy.[8] Levels of agricultural land productivity are compared between the townships having hydraulic fracturing wells in close proximity and the townships without any hydraulic fracturing wells in close proximity, before and after the wide scale usage of horizontal drilling and hydraulic multi-stage fracturing. Township-crop fixed effects are included to control for unobserved time-invariant township and crop fixed characteristics, such as- geography, township specific soil quality and productivity, crop specific input requirement, etc. Crop-Year fixed effects are included to control for township invariant and year variant characteristics, such as - technological advancement, and to control for crop and year variant characteristics, such as technological advancements and price variations. In addition to all these, to exploit the water-dependency variation of the crops, I estimate the effect of HF well proximity on land productivity separately for the irrigated crops and the dryland crops. Furthermore, since farmers plant and harvest six months (April to September, inclusive) not all year round, I also examine the difference between the effects of the wells drilled during the agriculturally active months (planting season) and non-agriculturally active months on land productivity.

This analysis reveals three major findings. First, I find that nearby hydraulic fracturing wells decrease crop yield of the irrigated crops. Estimation results show that for a well drilled within a township during the planting season (April to September, inclusive), crop yield of an irrigated crop of the township decreases by approximately 4.2%. In contrast, the effects of drilling a HF well is smaller when the well is drilled during the non-planting season (October to March, inclusive). Notably, the effects of a HF well on crop productivity become smaller and weaker as the distance between the township and the well location increases. Interestingly, no significant negative effect is observed on dryland crop productivity, suggesting that an important channel of the effect hydraulic fracturing has had upon agriculture comes through water usage. Second, to examine if the effects of hydraulically fractured wells are originating from HF water usage, I replace the count of wells drilled with the total water used by the HF wells within various measures of spatial and temporal proximity. I observe similar effects as the count of wells from the hydraulic fracturing water use. Results show each 1000 m^3 water use increase for the purpose of hydraulic fracturing within a township during the planting season, decreases irrigated crop's productivity by 1.4%. The effects of hydraulic fracturing water use are smaller if the wells are drilled during the non-planting season. However, while the effects of counts of wells in different distance intervals disappear after 25 km,

[8] For a similar identification strategy, see Nunn and Qian (2011).

the effects of hydraulic fracturing water use can still be observed from the wells drilled within 45 to 55 km from each township. Third, to ensure that this estimation is not capturing the drilling effect on the land productivity as a result of farmers switching from irrigated crop production to dryland crop production, I also estimate the effects of drilling hydraulic fracturing wells on percentage of acres irrigated. I do not observe any statistically significant evidence that farmers are switching from irrigated crop production to dryland crop production.

To calculate the economic significance of these results, I aggregate the effects of HF wells in different proximity in 2014, for the irrigated crops affected by the wells drilled during April to September. After aggregation, I find that Alberta lost approximately $21 million as revenue from the reduction of the yield of the irrigated crops, or about 16% of the annual average revenue earned from the irrigated crop production in 2014. Since irrigation makes up a small fraction of agriculture, this also means 0.8% of the average revenue earned from total crop production is lost in 2014 due to the agricultural productivity decline. Much of this productivity loss is not compensated since only the farmers who has hydraulically fractured wells within their farmlands receive payment for their loss from the hydraulic fracturing well operators.

This paper contributes to several branches of existing literature. First, findings of this study add to the discourse on the effects shale gas development has on other related sectors, such as housing market, employment, crime, etc. (see Mason, Muehlenbachs, and Olmstead, 2015 for a review). This study finds statistically significant negative relationship between well proximity and agricultural productivity. Second, this study also contributes to the understanding of how unconventional oil and gas development can affect agriculture. Some existing studies examining unconventional oil and gas development industry and agriculture emphasizes on the effects through land values (Weber and Hitaj, 2014; 2015). This study estimates the external effects of HF well proximity on land productivity, since, as mentioned above, in Alberta the mineral rights belong to the Province, not to the farmers. Third, this study suggests several policy implications. The observation that hydraulic fracturing effects are smaller in non-agricultural months than in the agricultural months suggests that some negative effects could be ameliorated by restrictions on when wells are hydraulically fractured. Fourth, while there are many studies examining water quality impacts of unconventional oil and gas drilling (Entrekin 2011, Olmstead et al. 2013), only a few studies mention the effects on water quantity (Hitaj et al. 2014).[9] This study shows that in arid and water-scarce places, such as: Alberta, Canada; Colorado, United States, etc., hydraulic fracturing water use can decrease agricultural productivity. Finally, this study adds to the cost-benefit analysis of unconventional oil and gas development partially by measuring the monetary value of the lost crop productivity due to close proximity to hydraulic fracturing wells. Some

[9]Some studies, in fact have shown that for some places hydraulic fracturing water use quantity is not a concern where fresh water is plentiful (Mitchell, Small, and Casman, 2013). Moreover, according to Kuwayama, Krupnick, and Olmstead (2014), conventional and unconventional oil production and coal production can sometimes be more water-intensive than shale gas production.

studies use survey analysis to measure peoples' willingness to pay to measure the costs of hydraulic fracturing (Siikamaki and Krupnick 2014). However, all negative spillover effects unconventional oil and gas drilling industry can create have not been monetized. This paper adds to this cost-benefit analysis literature by measuring the adverse effects unconventional oil and gas development has on the efficiency of the agricultural sector. In particular, this study shows that some of the effects occur on farms some distance from where the drilling occurs. Nevertheless, this study is not a complete cost-benefit analysis of unconventional oil and gas drilling industry and the debate if unconventional oil and gas development is net-welfare improving for an economy is beyond the scope of this study.

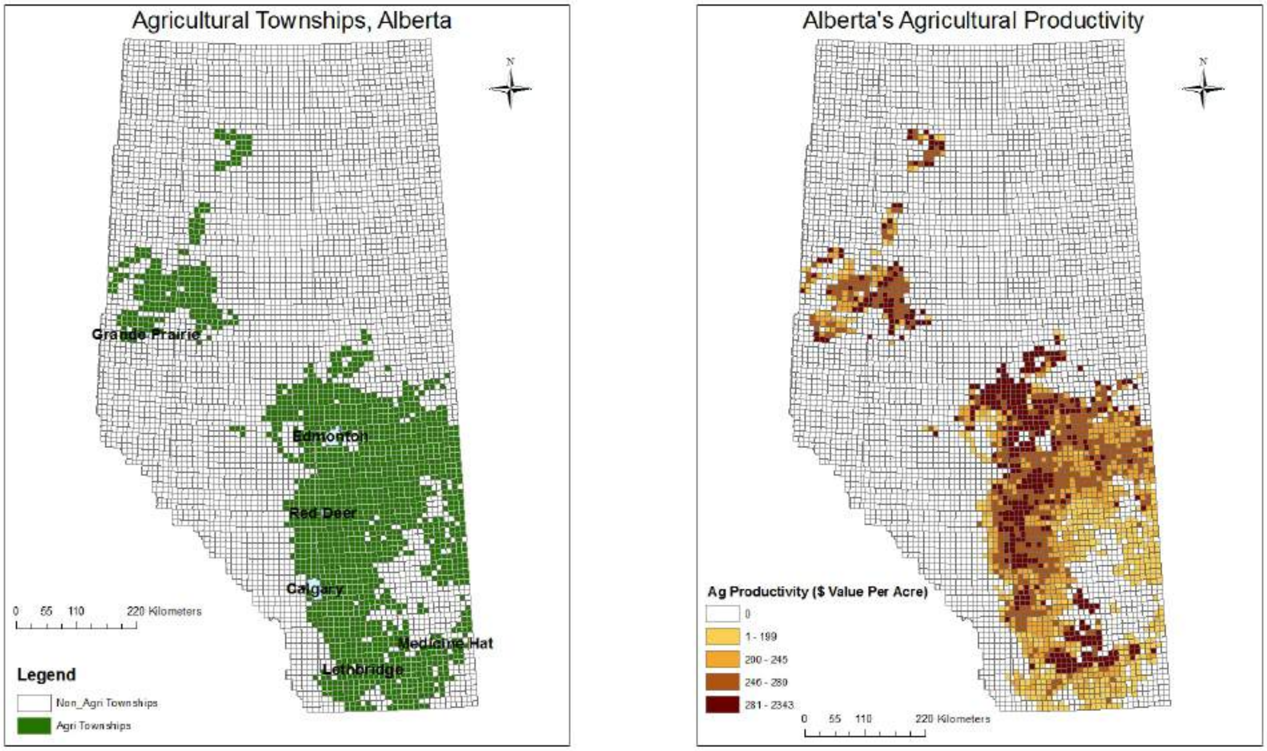
The remainder of the paper is organized as follows. Section 2 provides a brief description of Alberta's agriculture, water allocation system, hydraulic fracturing well locations, and water withdrawal status. Section 3 presents the empirical model, data and results. Section 4 summarizes and concludes.

2 Background

2.1 Alberta's Agriculture

There are in total 7,196 townships in Alberta, of which 1796 are agriculturally active townships. Figure 1 panel A shows the location of the agriculturally active townships, grazing lands and townships producing non-food crops are excluded. Most of the agriculturally active townships are located in the southern part of Alberta, while there are some agricultural activity in the western parts as well. Each township is a 6 mile by 6 mile square and can contain three to four farms (AFSC 2015). The major crops produced in Alberta are wheat, canola, barley, oats, and flexseed. Alberta is the second largest wheat producing province after Saskatchewan, and the top producer of barley (Alberta Agriculture and Forestry 2015). Alberta is also a major producer of cattle, honey, and hay crops, such as tame hay and alfalfa (Statistics Canada, 2011). Land productivity or crop yield varies across the townships. Figure 1 panel B shows the heterogeneous levels of agricultural productivity among the townships. The darker shaded townships have higher yield per acre on average, while the lighter shaded townships have lower yield per acre on average.

In terns of water dependency, there are two kinds of crops in Alberta, irrigated crops and dryland crops or non-irrigated crops. Figure 2 shows trends on production broken down by whether the crops being grown are irrigated or are dryland. Figure 2a shows the total production of the irrigated and dryland crops, Figure 2b shows the total revenue earned from the irrigated crops and dryland crop production, Figure 2c shows the average yield of the irrigated crops and the dryland crops, and 2d shows total area planted by irrigated crops and dryland crops. Figure 2a, 2b and 2d show that dryland crops are produced at a larger amount, earns more revenue, and are planted in larger areas



(a) Agricultural Townships of Alberta

(b) Productivity of the Agricultural Townships

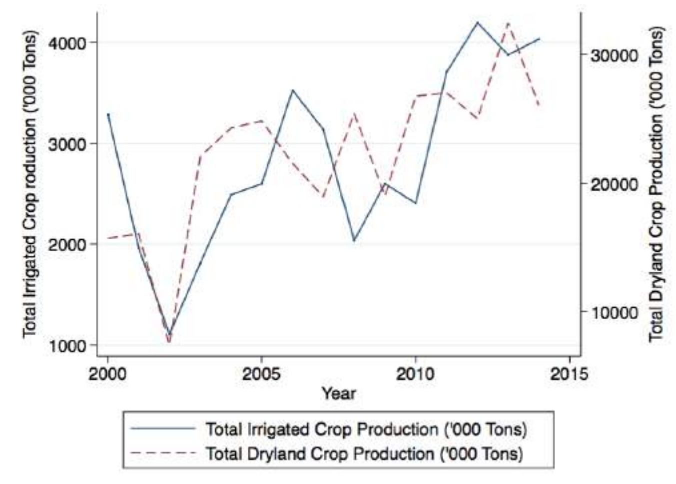
Figure 1: Alberta's Agriculture

Data Source: Agricultural Financial Services Corporation

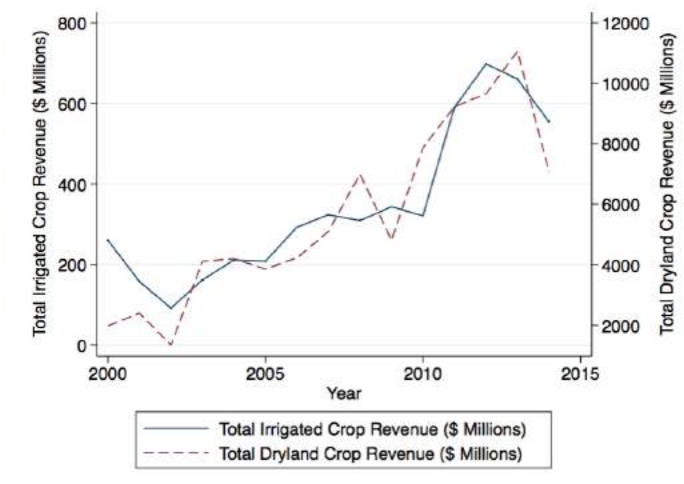
than the irrigated crops. However, Figure 2c shows that the average crop yield is higher for the irrigated crops than the dryland crops. In other words, irrigated crops are more productive than the dryland crops. Figure 2d shows both irrigated crop and dryland crop planted areas have been increasing over time, although there are no indication that farmers are switching from irrigated crop production to dryland crop production.

2.2 Hydraulic Fracturing in Alberta

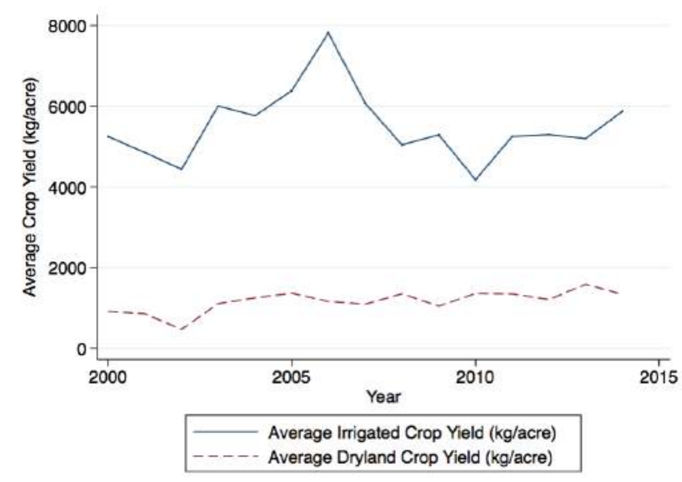
Production of unconventional oil and gas such as shale gas and tight oil started to rise sharply in the late 2000s due to the widespread use of horizontal drilling and hydraulic multi-stage fracturing in Alberta, replicating the fracking boom in the United States phenomena in the United States. Although hydraulic fracturing has been used in Alberta by the oil and gas industries for more than sixty years (Canadian Society for Unconventional Resources, 2015), the number of wells hydraulically fractured increased approximately six-fold from 2005 to 2014 due to the innovation



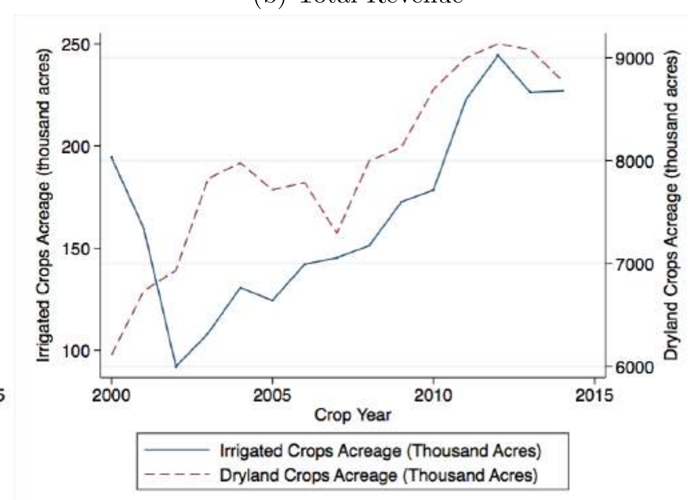
(a) Total Production



(b) Total Revenue



(c) Yield per Acre



(d) Total Acreage

Figure 2: Alberta Agricultural Yield, Revenues, Acreage by Irrigated and Drylands

Data Source: Agricultural Financial Services Corporation

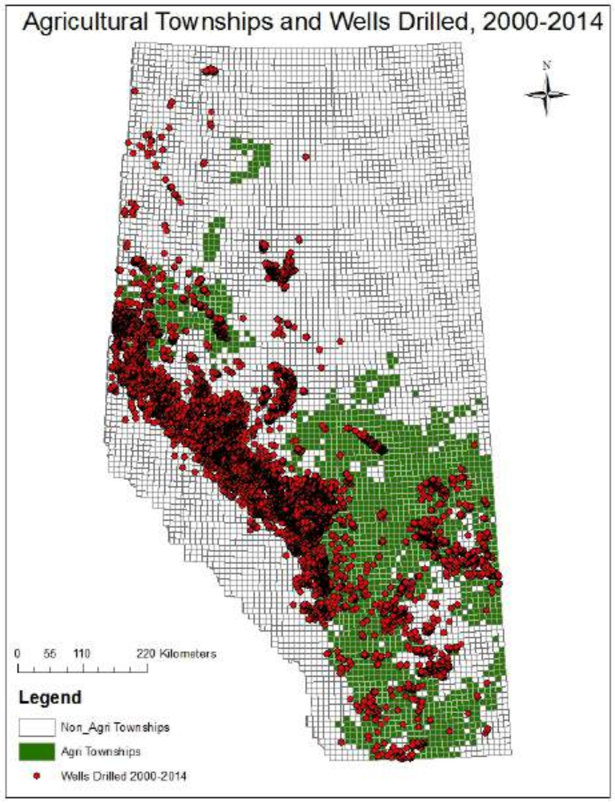


Figure 3: Agricultural Townships and HF Wells
Data Source: Well Completion and Frac Database, Canadian Discovery Ltd.

of horizontal drilling (Natural Resources Canada, 2016).[10]

During 2000 to 2014, hydraulic fracturing wells were drilled in 1734 townships. Figure 3 shows the locations of the hydraulically fractured wells and the agriculturally active townships in Alberta. Approximately 40% of the wells drilled were on or around 55 km radius of the agriculturally active townships. Although hydraulic fracturing (HF) wells are being drilled in Alberta since 1960, wide use of this technique started after the innovation of horizontal drilling in the late 2000s. This technological innovation led to the unconventional oil and gas production boom in Alberta, coinciding with the shale gas boom in the United States. Since 2014 in total approximately 15,000 hydraulic multistage fracturing wells were drilled in Alberta. Figure 4a shows the total number of wells hydraulically fractured during 2000-2014. The number of HF wells drilled in 2014 was approximately 30 times higher than the number of wells drilled in 2000. Figure 4a shows well count has been increasing continuously in the post-2010 years (Canadian Discovery Ltd.). Figure

[10] In 2014 about 86% of crude oil wells and 64% of natural gas wells placed in production were from Horizontal wells in Alberta (Alberta Energy Outlook 2015).

4b shows average per well total water use (solid line) and average daily water use (dashed line) during 2000-2014. Both total water use and daily water use by a well have been increasing since late 2000s, following the horizontal drilling innovation. A HF well used approximately 4000 m^3 during the whole hydraulic fracturing process in 2014. However, this amount could be as much as 84,400 m^3 (Well Completion and Frac Database, Canadian Discovery Ltd). Average per well daily water use was approximately 2000 m^3 in 2014. Similar to per well water use, daily water use of a well varies as well, and it can be as high as 58,000 m^3 (Well Completion and Frac Database, Canadian Discovery Ltd).

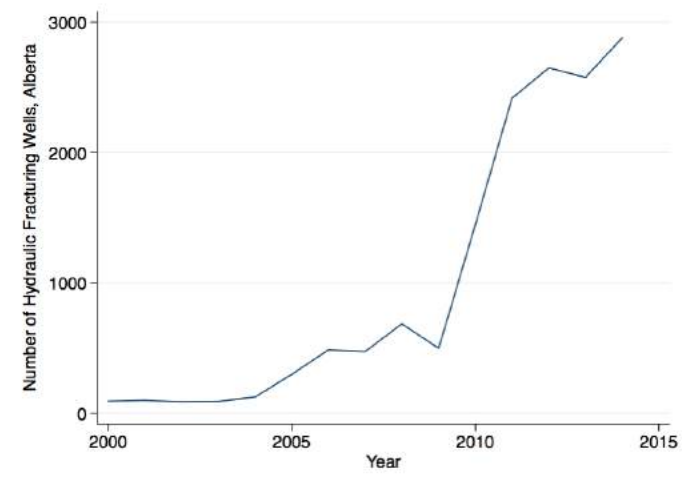
Figure 4c shows total oil and gas production from the hydraulic fracturing wells in Alberta during 2000-2014. Both oil and gas production increased after the horizontal drilling innovation in late 2000. Although production of oil has been decreasing and gas production has been increasing slightly, total water use by the wells is rising continuously.

Figure 5 shows the distribution of the hydraulic fracturing drilling months. Of the 15,000 wells drilled between 2000-2014, approximately 30% wells were drilled during April to September, the agriculturally active months. Figure 5 shows higher number of the wells are drilled after the end of extreme winter, in March. HF well drilling slows down during the rainy season, April to June, and drilling increases again from July.

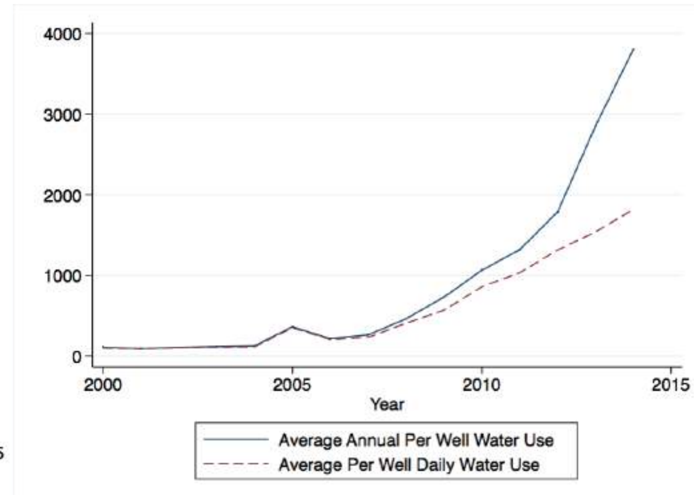
2.3 Water Allocation System in Alberta

The existing water allocation system in Alberta is called *Priority Allocation System* or *First in time, first in right*, where older licensees hold priority over newer/more recent license holders (Government of Alberta, 2011). According to the *Alberta Water Act*, any person who needs to use water in excess of 1,250 m^3 per year is required to obtain a license for water use (Government of Alberta, 2014). Alberta Environment and Parks (AEP) regulates the license distribution and water allocation among the license holders. Since August 2006, however, AEP stopped issuing new licenses for surface water allocation in the Bow River, Oldman River, and in the South Saskatchewan River basin due to a water crisis (Alberta Water Portal, 2011). Since 2006, AEP has approved the law of temporary or permanent water transfer among the license holders. Based on this transferring system, a user can temporarily or permanently transfer all or a part of his or her water allocation to another user under certain conditions. All transfers are, often however, monitored and approved by AEP (Adamowicz et al, 2010). These licenses can also vary by duration; for instance, there are temporary diversion licenses (maximum one year duration) and term licenses (five years duration) (AEP, 2011). Figure 6 panel (a) shows HF wells drilled during 2000-2014 and the major river basins of Alberta.

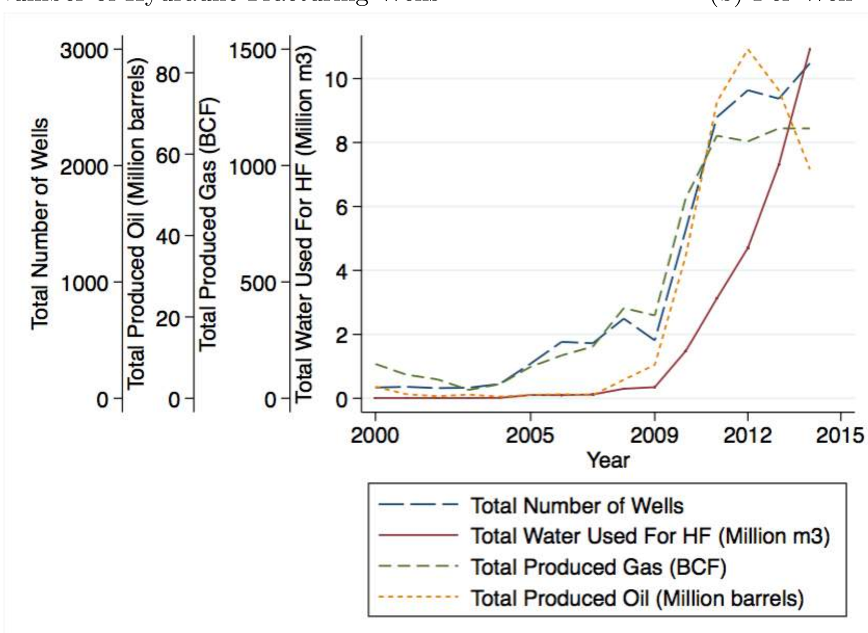
Approved water withdrawal sources for the purpose of hydraulic fracturing are located using water allocation data from AEP. Alberta Environment has started to allocate water for hydraulic



(a) Total Number of Hydraulic Fracturing Wells



(b) Per Well Water Use



(c) Number of Wells, Water Use and Production, 2000-2014

Figure 4: Hydraulic Fracturing in Alberta

Data Source: Well Completion and Frac Database, Canadian Discovery Ltd.

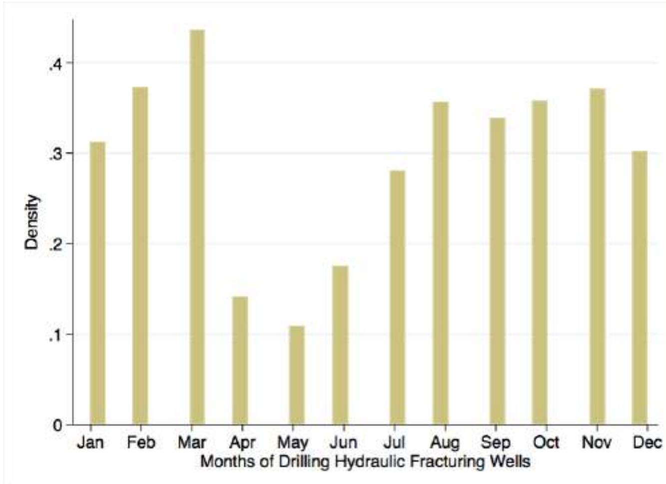
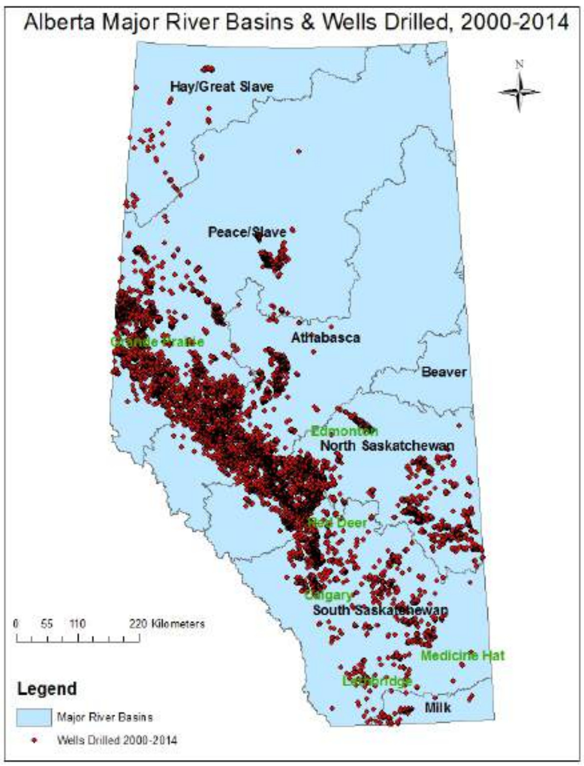


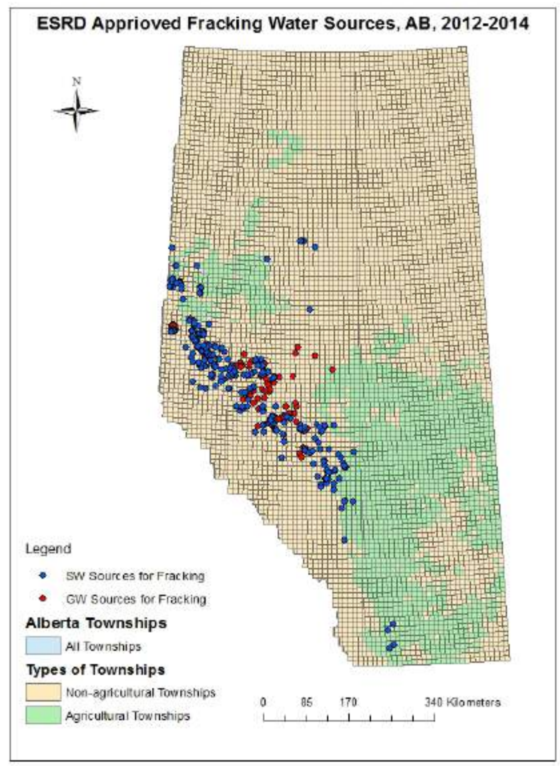
Figure 5: Distribution of HF Wells by Month

Data Source: Well Completion and Frac Database, Canadian Discovery Ltd.

fracturing since 2012. Figure 6 panel B shows approved water withdrawal locations for hydraulic fracturing purpose for the years 2012 to 2014. Figure 6 shows except a few locations, almost all of the water allocation points for hydraulic fracturing purpose are located at the western part of Alberta. For limitations of data availability, I have not been able to determine from where wells which do not have an approved water withdrawal source nearby are getting their water. Therefore, question remains whether these wells, which do not have an AEP approved water withdrawal source nearby, are affecting water use of the other major users, particularly of the neighboring farmers.



(a) HF Wells & Major River Basins, 2000-2014



(b) HF Wells and AEP Approved Water Withdrawal Points, 2012-2014

Figure 6: Hydraulic Fracturing in Alberta

Data Source: Well Completion and Frac Database, Canadian Discovery Ltd. and Alberta Environment and Parks

3 Empirical Analysis and Results

This section describes how proximity to hydraulic fracturing wells in different distance intervals can have differentiated effects on crop productivity. Estimated effect of proximity to wells are also differentiated based on the water requirement of the crops.

3.1 Estimation Strategy

The goal of this study is to identify the spillover effects of nearby hydraulic fracturing on agricultural productivity. I expect to see a negative effect since the intense water use for the purpose of hydraulic fracturing can affect irrigation water use; sediment run-off from the nearby well pads can affect soil quality and crop productivity, traffic congestion from heady use of the local roads can affect agricultural activity and increase air particulate matters (PM), labor movement from the agricultural sector to the hydraulic fracturing wells can affect farm's production.

The first set of estimations shows how count of wells in different distance intervals affect agricultural land productivity. This estimation strategy follows the same logic as a standard difference-in-differences (DID) strategy. I compare the relative change in the crop productivity of the townships which have hydraulic fracturing (HF) wells within fifty-five kilometer radius relative to the townships which do not have HF activity within fifty-five kilometers. The major difference between this estimation and a standard DID estimation is that this model assumes a continuous shock of the intensity of the treatment (that is, the degree of hydraulic fracturing); thus this estimation captures more variation in the data.

The stylized facts presented in section 2 suggests that extensive adoption of horizontal drilling in Alberta began during the late 2000s. Since the timing of the intensity of drilling and the adoption of the horizontal drilling vary among the townships, the treatment variable, count of wells, is not interacted with any specific year. The spatial variation in this estimation comes from the difference between the set of townships and temporal variation comes from the intensity of hydraulic fracturing. In Alberta, the subsurface mineral rights are owned by the province, except on lands granted to railroads, or lands where title was granted prior to the province being formed in 1907 (Alberta Energy). Therefore, the decision to drill unconventional oil and gas wells and the locations of the farmlands are not correlated, and the location of the hydraulic fracturing wells are randomly assigned to the agricultural productivity of the townships.

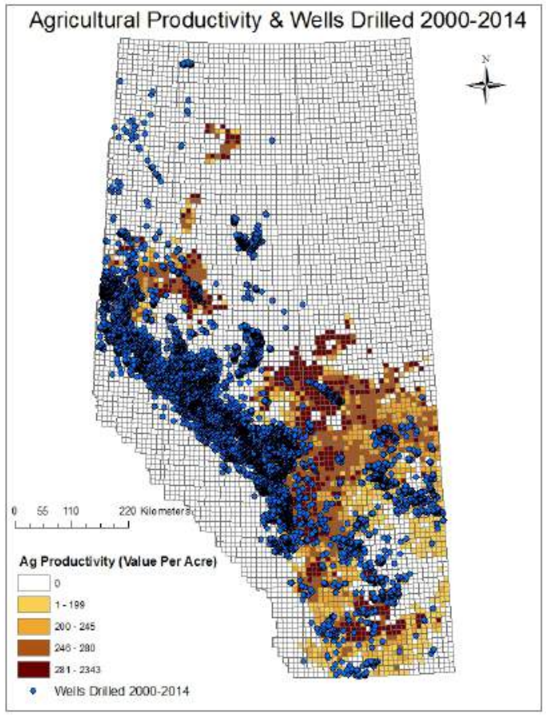


Figure 7: Agricultural Productivity and Well Locations

Figure 7 shows the distribution of the townships based on their agricultural productivity and the location of the wells drilled between 2000 to 2014. This figure also shows hydraulic fracturing wells are evenly distributed across Alberta and agricultural productivity does not affect their locations.

Equation (1) assumes that a township's percentage change in the agricultural land productivity linearly depends on the count of wells in different distance intervals. This is written as

$$log\,(\text{Crop Yield})_{ict} = \alpha_0 + \sum_{d\,\epsilon\,B} \alpha_d \,\text{Count of Wells}_{dit} + \alpha_1 X_{it} + \mu_{ic} + \nu_{ct} + \epsilon_{ict},$$

$$\text{Here, } B = (0-5, 5-15, 15-25, 25-35, 35-45)(\text{distances in kilometers}),$$

$$+\,55km = \text{reference group}$$

$$i = 1, \ldots, 1786(\text{townships});\ c = 1, 2, \ldots, 25(\text{crops});\ t = 2000, 2001, \ldots, 2014(\text{years}); \quad (1)$$

The dependent variable Crop Yield_{ict} is the agricultural land productivity measured as kilogram of crops produced per acreage of land.[11] The variable of interest Count of Wells is the count of

[11] Crop yield data is collected from a premier insurance company of Alberta, AFSC. This data set only includes statistics of those farms that buy insurance from AFSC. Thus, this measure of land productivity only includes food crops grown in Alberta and does not include hay crops and animal production.

hydraulic fracturing wells in distance interval d. The variable X_{it} includes average precipitation index constructed by WorldClim.[12] Since this precipitation index only varies by township and not over time, this variable is interacted with year dummies to capture the year and township specific weather shocks. Equation 1 also includes μ_{ic} township-crop pair fixed effects and ν_{ct} crop-year fixed effects. ϵ_{ict} is random error.

The coefficients of interest α_d measures the estimated effect of different degrees of hydraulic fracturing at different distance intervals d in B on agricultural productivity percentage change. The closest distance interval, which is 5 km away from each township's centroid, represents approximately the area of that particular township.The closest distance interval can include two kinds of effects on the crops' productivity: direct effects and indirect effects. Direct effects include the close proximity spillover effects, such as, the effects through infrastructure sharing, technological spillovers, increased local demand for goods, etc. The indirect effects include the negative spillover effects, such as, the effects from water sharing, sediment run-off from the well pads, congestion from traffic servicing the well, and labor movement. The closest distance intervals, such as, 0-5 km, can contain both direct and indirect effects. On the other hand, the distant distance intervals, such as the distance intervals 16-25 km and the 26-35 km from the township centroid contain the indirect effects of the hydraulic fracturing wells. [13]

This estimation strategy has all the advantages and disadvantages of the standard difference-in-differences estimators. Township-Crop fixed effects control for all the time-invariant factors that vary over the township-crop pairs. Crop-Year fixed effects control for all the factors that vary over both crop and time and affects all the townships similarly. This identification strategy has the limitation in this sense that this relies on the assumption that there are no other factors, beyond those that have been controlled for in (1), that are correlated both with proximity to hydraulic fracturing activity and agricultural land productivity.

To examine if the spillover effects of hydraulic fracturing occurs through water use, total volume of water used by the wells in different distance intervals are used as control variable instead of count of wells in (1).

3.2 Data

3.2.1 Agricultural Productivity

Data on crop yield, acres cultivated, crop price ($ per kg) are obtained from Agricultural Financial Services (AFSC), which is the only agricultural production insurance provider of Alberta.[14] These

[12] Methods used to construct this index is described in the section 3.2.

[13] For more discussion on direct and indirect effects see Hornbeck and Keskin (2015).

[14] AFSC is the only agency that offers production insurance program in Alberta which covers farmers from their production shortfall. Some other agencies provide insurance for losses due to hail similar to the straight hail insurance program of AFSC.

statistics are available for 25 different types of crops, including 13 which are produced as dryland crops and 12 which are produced as irrigated crops. The major produced crops of Alberta are wheat, canola, barley, potato, and sugerbeets. The agricultural statistical data from AFSC is available for fifteen years, 2000-2014 in township level. Since AFSC has been insuring approximately 75% of the arable acres in Alberta under it's annual crop insurance programs, therefore the data set used in this study represents approximately 75% of Alberta's food crop production and does not include hay crops and animal production.[15]

3.2.2 Hydraulic Fracturing Wells

Data on hydraulic fracturing drilling activity in Alberta are obtained from Well Completion and Frac Database (WCFD) of Canadian Discovery Ltd.[16] This data set include geographic locations of the wells, days of hydraulic fracturing, types of drilling (horizontal/ vertical), type of base fluid used, volume of water used for the purpose of hydraulic fracturing, and total amount of extracted oil and gas per well. These statistics are available for the wells drilled since 1960 and were reported to Alberta Energy Regulator.

3.2.3 Hydraulic Fracturing and Agricultural Yield

Figure 8 shows average crop yield of the irrigated crops and dryland crops. Figure shows irrigated crops are more productive than the dryland crops. The land productivity or average crop yield of the irrigated crops has been declining since 2005. Since 2009, irrigated crop yield has been fluctuating, although it did not reach to the previous high level. While the total count of hydraulic fracturing wells and the water use for hydraulic fracturing have been increasing since 2009, dryland average crop yield has remained approximately at the same level during 2000-2014.

3.2.4 Global Climate Index

Global climate index is obtained from WorldClim- Global Climate Data. This database contains variables on monthly total precipitation, monthly temperature, and other bio-climatic variables. The data layers are generated through interpolation of average monthly climate data obtained from respective weather stations.[17] To get the highest resolution of the 30 arc-seconds, Alberta's precipitation index was constructed from number 12 tile. This index was constructed using the weather station data for the years 1960 to 1990. Since the variable we are using, *Precipitation Index (milimeter)*, only varies across the townships and does not vary oevr the years, we interact

[15] This information was obtained through personal email communication with AFSC's Business Manager, Saroj Aryal, dated 18th September, 2015.

[16] Well Completion and Frac Database (WCFD) is a proprietary data set of Canadian Discovery Limited. The author of this paper has gained a free access to this unique data set for research purpose only.

[17] Each weather stations are located on a 30 arc-second resolution grid (this is also referred to as 1 square km resolution). For details on the methodology how this index is constructed see `http://www.worldclim.org/current`.

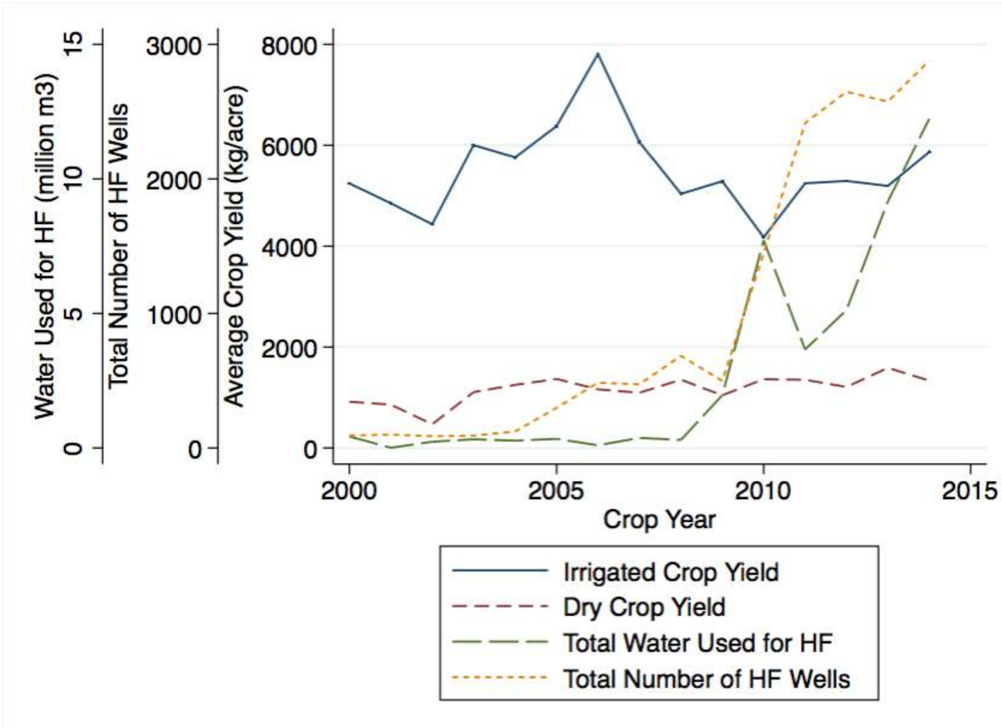


Figure 8: Average Crop Yield, Irrigated vs. Dry and HF Wells, 2000-2014

the precipitation index with year dummies to vary it over time and to capture the year specific shocks. Thus, the control, Global Climate Index interacted with year dummy, captures both township varying and year varying weather shocks.

Table 1 shows summary statistics used for major variables in this analysis.

Table 1: Summary Statistics

Variable	Observations	Mean	Std. Dev.	Min	Max
Crop Yield (kg/acre)	46,608	1352	1933	0	32,380
Irrigated Crop Yield (kg/acre)	2015	5485	7704	42	32,380
Dry Crop Yield (kg/acre)	44,593	1165	648	0	11,578
Price per Kg	46,608	0.25	0.13	0.03	1.1
Acres Cultivated	46,608	2611	1772	53	13,373
Irrigated Acres Cultivated	2015	1250	840	133	6303
Dry Acres Cultivated	44,593	2673	1778	53	13,373
Hydraulic Fracturing Days	14,740	4	25	1	1827
Per Well Total Water Used for Hydraulic Fracturing (m^3)	14,631	1952	4095	0.8	84,406
Per Well Daily Water Use (m^3)	14,474	1171	1558	0.16	58,740
Count of Hydraulic Fracturing Wells in township (0-5 km)	46,608	0.12	1	0	42
Count of Hydraulic Fracturing Wells in township (6-15 km)	46,608	0.1	4	0	86
Count of Hydraulic Fracturing Wells in township (16-25 km)	46,608	2	7	0	96
Count of Hydraulic Fracturing Wells in township (26-35 km)	46,608	3	9	0	124
Count of Hydraulic Fracturing Wells in township (36-45 km)	46,608	4	10	0	128
Count of Hydraulic Fracturing Wells in township (46-55 km)	46,608	5	12	0	164
Global Climate Index (Precipitation (millimeter))	46,591	421	42	308	567

3.3 Graphical Evidence

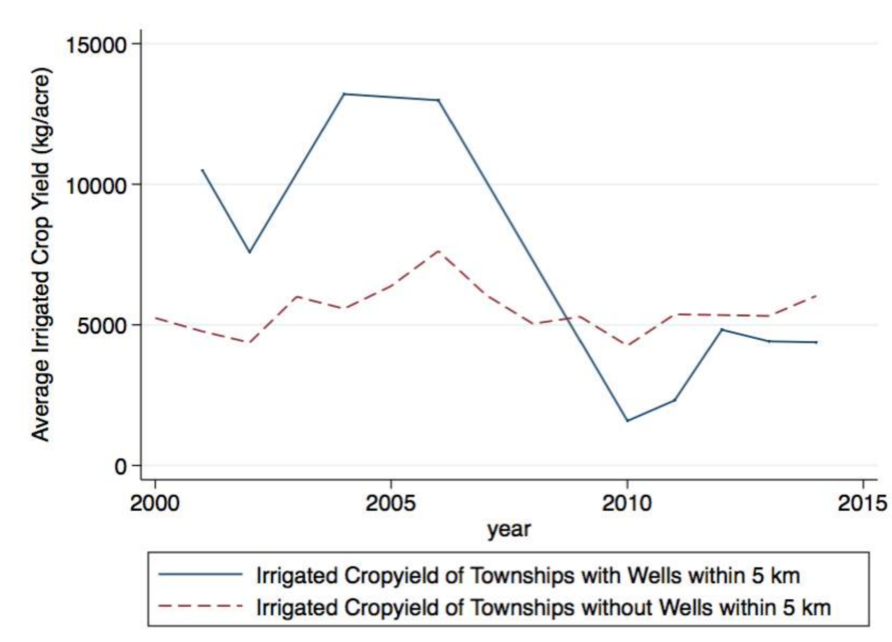


Figure 9: Irrigated Crop-yield of Townships With and Without HF Wells

Figure 9 shows the average irrigated crop yield of the townships which have HF wells within 5 km or within township and the average irrigated crop yield of the townships which do not have wells within 5 km or within township. Before the timing of the horizontal drilling innovation, irrigated crop yield of the townships with HF wells within 5 km radius was higher and was moving

Table 2: Effects of Hydraulic Fracturing Well Proximity on log(Crop Yield)

	Panel A: Wells Drilled Any Month		Panel B: Wells Drilled April- September	
	(1)	(2)	(3)	(4)
	Irrigated	Dryland	Irrigated	Dryland
Count of Hydraulic Fracturing Wells				
0- 5 km or Within Township	-0.954	0.331	*-4.229	0.0785
	(1.207)	(0.246)	(2.325)	(0.718)
6-15 km	-0.211	0.0977	-2.655	0.287
	(0.614)	(0.0654)	(1.959)	(0.201)
16-25 km	***-1.640	0.0382	-1.143	-0.207
	(0.617)	(0.0523)	(1.338)	(0.143)
26-35 km	-0.373	-0.0283	-0.582	* -0.228
	(0.310)	(0.0404)	(0.616)	(0.123)
36-45 km	0.00188	-0.00927	0.524	-0.0862
	(0.219)	(0.0347)	(0.525)	(0.104)
46-55 km	0.240	***-0.138	-0.476	***-0.411
	(0.236)	(0.0266)	(0.816)	(0.0774)
Constant	***901.9	***594.0	***902.3	***593.7
	(34.61)	(10.30)	(34.55)	(10.28)
Township-Crop FE	Y	Y	Y	Y
Crop-Year FE	Y	Y	Y	Y
Global Climate Index* Year Dummy	Y	Y	Y	Y
Observations	2015	44523	2015	44523
No. of Townships (Cluster)	117	1747	117	1747
No. of Groups (Fixed Effects)	433	6715	433	6715
R^2	0.307	0.508	0.310	0.508

Notes: Dependent variable: log (Crop Yield)*100. Crop yield is measured is kg per acre. Standard Errors (in parentheses) are clustered by township. Significance levels: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

in the similar direction as the townships which never had HF wells within 5 km radius. After the horizontal drilling innovation period in the late 2000, average irrigated crop productivity of the townships with HF wells within their own boundaries has decreased and are now lower then the average crop productivity of the townships' without HF wells within 5 km radius. However since this figure does not include township, crop, or year fixed effects, the decrease in the crop yield of the townships with HF wells within 5 km radius can be associated with other variables besides hydraulic fracturing.

3.4 Estimation Results

3.4.1 Proximity To Wells

Table 2 summarizes the effects of proximity to hydraulic fracturing wells on agricultural productivity, based on the regression showed in equation 1. Columns (1) to (2) in Panel A show the effects of count of hydraulic fracturing wells drilled during all year round; Column (1) shows the effects on the irrigated crops and Column (2) shows the effects on the dryland crops. Panel B repeats the specifications of Column (1) and (2) in Column (3) and (4) using the count of wells drilled during summer, April to September (inclusive). All specifications includes township-crop pair fixed effects, crop-year fixed effects, and Global Climate Index interacted with year variable.

From column (2), when a well is drilled within township (0-5 km) or 6-15 km, negative signed coefficients are observed, although they are statistically not different from zero. While if a well is drilled within 16-25 km of the township during any month of the year, irrigated crop's productivity decreases by 1.6%. No significant effect is observed after 35 km on the irrigated crops for the wells drilled during any month of the year. The reason why no effect is observed within the close distance intervals, such as 0-5 km or 6 to 15 km, might be because there can be direct positive spillover effects from the wells drilled very close to the farmlands. Negative spillovers from the HF wells, such as, sediment run-off, water competition, road congestion from truck traffic, and increased cost from labor mobility, can be counterbalanced by the positive spillovers, such as shared infrastructure, or direct productivity spillovers (Hornbeck and Keskin 2015).

Column (3) repeats column (1), using the wells drilled during summer. Column (3) shows for a well drilled within 0-5 km or within township, irrigated crop's productivity decreases on average by 4.3%. After 5 km, the effect of count of wells drilled becomes smaller and weaker as the distance from the wells and the township increases.

Column (2) shows the effect of HF well drilling proximity on dryland crop productivity, using the wells drilled during any month of the year. Column (2) shows there is no significant effect of hydraulic fracturing activity on the dryland crops. However, we observe that if a well is drilled within 46 to 55 km, dryland crop's productivity decreases by 0.1%. Similar result is observed in panel B, when only the wells drilled during April to September is controlled for. From Column (8), no effect is observed on the dryland crop's productivity when wells are drilled in different distance intervals during April to September, except in 46 to 55 km. A well drilled within 46 to 55 km during April to September, dryland crop's productivity decreases by 0.4%.[18]

3.4.2 Hydraulic Fracturing Water Use

Table 3 repeats Table 2 using total water used for the purpose of hydraulic fracturing in different distance intervals, instead of well counts. All specifications in Panel A and B are same as in Table 2. From Column (2) for 1000 m^3 water use increase by the wells drilled during any month of the year, irrigated crop's productivity decreases by 0.8% if the wells are drilled within 6 to 15 km, productivity decreases by 0.6% if the wells are drilled within 16 to 25 km, productivity decreases by 0.2%, and if the wells are drilled within 26 to 35 km, productivity decreases by 0.1%. No significant

[18]When all these regressions in Columns (1) to (4) were ran without including Global Climate Index, similar results are obtained.

Table 3: Effects of Hydraulic Fracturing Water Use on log(Crop Yield)

	Panel A: Wells Drilled Any Month		Panel B: Wells Drilled April- September	
	(1)	(2)	(3)	(4)
	Irrigated	Dryland	Irrigated	Dryland
Total Water Use for Hydraulic Fracturing (1000 m^3)				
0- 5 km or Within Township	-0.526	0.0741	***-1.442	0.0979
	(0.400)	(0.0656)	(0.403)	(0.0602)
6-15 km	*-0.752	0.0291	**-1.853	0.0356
	(0.400)	(0.0203)	(0.782)	(0.0357)
16-25 km	**-0.581	-0.0135	*-0.855	*-0.0982
	(0.290)	(0.0266)	(0.455)	(0.0521)
26-35 km	*-0.176	-0.0196	*-0.527	-0.0362
	(0.102)	(0.0202)	(0.267)	(0.0342)
36-45 km	*-0.127	0.000179	-0.332	0.0110
	(0.0754)	(0.0144)	(0.204)	(0.0235)
46-55 km	-0.199	***-0.0347	*-0.581	***-0.0707
	(0.141)	(0.0122)	(0.315)	(0.0226)
Constant	***894.6	***591.1	***827.4	***653.5
	(33.89)	(10.34)	(31.98)	(10.06)
Township-Crop FE	Y	Y	Y	Y
Global Climate Index* Year Dummy	Y	Y	Y	Y
Crop-Year FE	Y	Y	Y	Y
Observations	2015	44523	2015	44523
No. of Townships (Cluster)	117	1747	117	1747
No. of Groups (Fixed Effects)	433	6715	433	6715
R^2	0.305	0.507	0.310	0.508

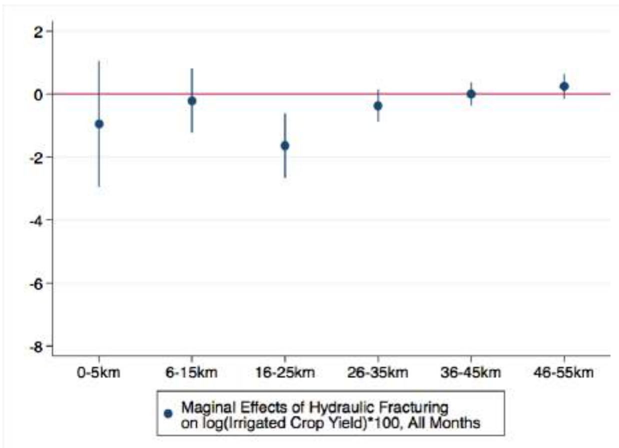
Notes: Dependent variable: log (Crop Yield)*100. Crop yield is measured is kg per acre. Standard Errors (in parentheses) are clustered by township. Significance levels: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

effect is observed of the water use increase by the HF wells on irrigated crop's productivity after 45 km, if the wells are drilled during any month of the year. The coefficient for the water use increase effect within 5 km of the township is of negative sign, although it is not significant. Again, this could be happening because direct positive spillover effects might be offsetting negative indirect spillover effects.

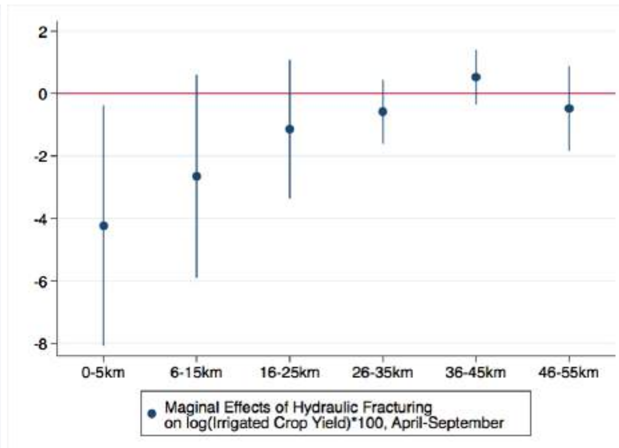
From Column (3), for 1000 m^3 water use increase by the wells drilled during April to September, irrigated crop's productivity decreases by 1.4% if the wells are drilled within 5 km radius, productivity decreases by 1.9% if the wells are drilled within 6 to 15 km radius, productivity decreases by 0.9% if the wells are drilled within 26-35 km radius, and productivity decreases by 0.6% if the wells are drilled within 46 to 55 km. In case of water use increase, effects become smaller as the distance between the wells and the township increase, but the effects do not become statistically different from zero.

Similar to Table 2, we observe that the dryland crop productivity is also not significantly affected from HF wells' water use. From Column (2) and (4) no significant effect is observed on the dryland crop's productivity except in the most distant distance interval 46 to 55 km. For 1000 m^3 water use increase in the 46 to 55 km radius of the township, dryland crop's productivity decreases by 0.03% if the wells are drilled during any month of the year and productivity decreases by 0.07% if the wells are drilled during April to September. Since dryland crops do not require irrigation water, this effect might be coming from the positive correlation between hydraulic fracturing water use and other negative effects, such as, sediment run-off.[19]

Results shown in Table 3 are similar to the results shown in Table 2.

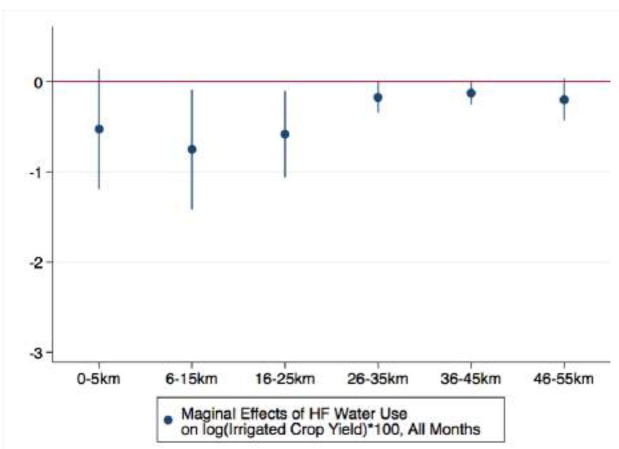


(a) All Months

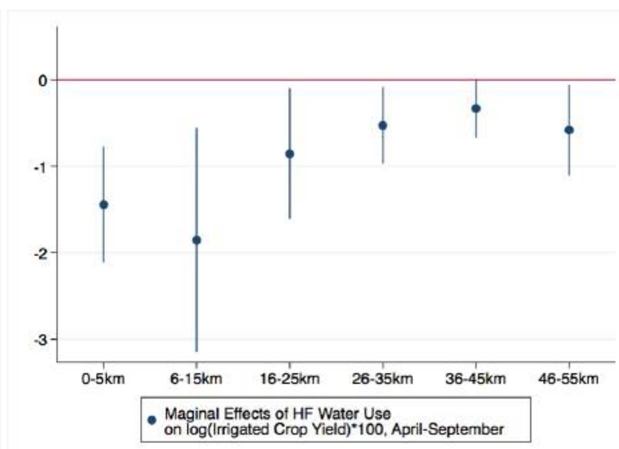


(b) April-September

Marginal Effects of Hydraulic Fracturing Well Count on Irrigated Crop's Land Productivity



(c) All Months

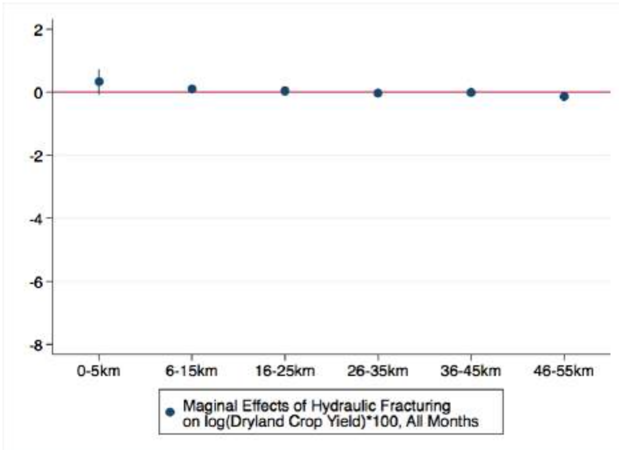


(d) April-September

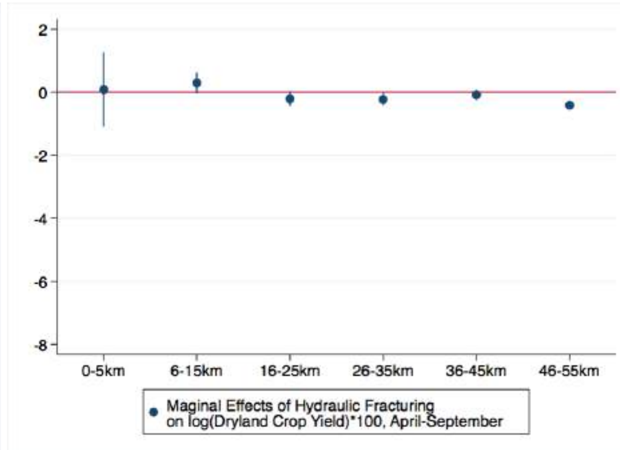
Marginal Effects of Hydraulic Fracturing Water Use on Irrigated Crop's Land Productivity

Figure 10: Hydraulic Fracturing Effects on the Irrigated Crops

[19]When these regressions were ran without including Global Climate Index, similar results are obtained.

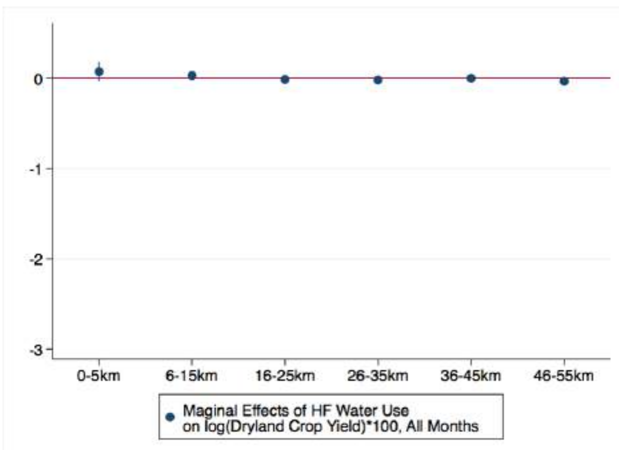


(a) All Months

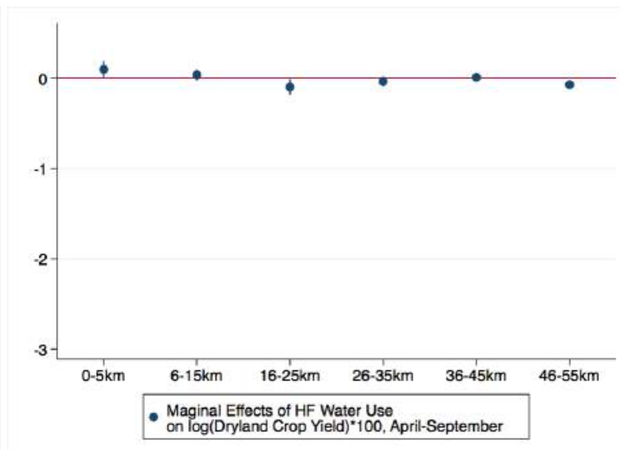


(b) April-September

Marginal Effects of Hydraulic Fracturing Well Count on Productivity of Dryland Crops



(c) All Months



(d) April-September

Marginal Effects of Hydraulic Fracturing Water Use on Productivity of Dryland Crops

Figure 11: Hydraulic Fracturing Effects on the Dryland Crops

Figure 10 and 11 summarize the effects of unconventional oil and gas drilling or hydraulic fracturing well proximity effects on the irrigated crops and the dryland crops, respectively. Panels (a), (b), (c), and (d) in Figure 10 show land productivity is affected mostly when the wells are drilled nearby. As the distance between the wells and the township increases, the effect of the hydraulic fracturing wells becomes small and weak. From panel (b) and (d), the adverse effect of hydraulic fracturing on agricultural productivity is observed prominently when the wells are drilled during the agriculturally active months, April to September. Figure 11 shows dryland crops are not much affected by the HF wells. Panels (a), (b), (c), and (d) show dryland crop productivity is only negatively affected when wells are drilled within 46 to 55 km (also in 16 to 25 km in panel (d)).

Table 4: Effects of Proximity to Wells on Fraction of Acres Irrigated

	(1) Fraction Irrigated
Count of Hydraulic Fracturing Wells	
0-5km (Within Township)	-0.0318
	(0.0367)
6-15 km	0.00459
	(0.00864)
16-25 km	0.00201
	(0.0102)
26-35 km	0.00864
	(0.00551)
36-45 km	-0.000818
	(0.00460)
46-55 km	-0.00366
	(0.00381)
Constant	-1.670**
	(0.781)
Global Climate Index*Year Dummy	Y
Township-Crop FE	Y
Crop-Year FE	Y
R^2	0.291
Observations	2015
No. of Townships (Cluster)	117
No. of Groups (Fixed Effects)	433

Notes: Dependent variable: log(Fraction of Acres Irrigated). Standard Errors (in parentheses) are clustered by township. Significance levels: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

3.4.3 Effects on Crop Composition

In this section I examine if crop composition is changing due to close proximity to hydraulic fracturing wells. If farmers decide to produce more dryland crops and less irrigated crops, then because of lower production of the irrigated crops results obtained from the above regressions would incorrectly conclude that irrigated crop's land productivity is decreasing because of close proximity to unconventional oil and gas drilling. To check if this endogeneity is not occurring within the data, fraction of acres producing irrigated crops is regressed on count of wells in different distance intervals. Table 4 summarizes the effect of hydraulic fracturing well proximity on fraction of acres producing irrigated crops. Column (1) includes count of wells in different distance intervals, township-crop fixed effects, and crop-year fixed effects, and Global Climate Index interacted with year fixed effect. None of the coefficients of the count of wells variables in any of the distance intervals is significant. This implies that farmers are not changing their irrigated and dryland crop planting choices due to nearby unconventional oil and gas drilling activity.

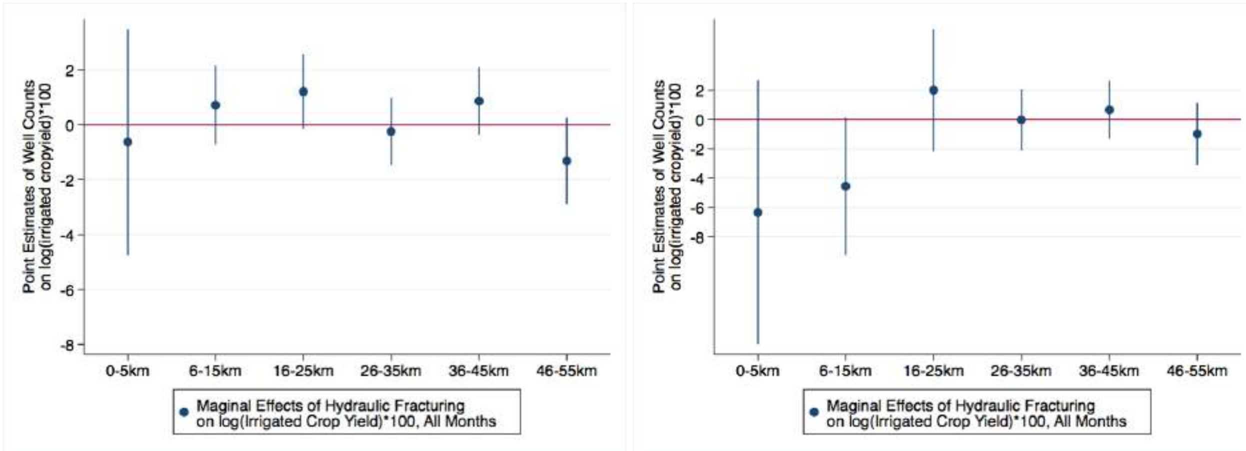
3.5 Robustness Check

3.5.1 Placebo Test

To check the robustness of our results and to verify the credulity of the relationship between crop yield and hydraulic fracturing is not spurious, I randomly assign the location of the wells among different years. Through assigning random hydraulic fracturing start date and then calculating the count of wells in different distance intervals for each township, the regression shown in (1) is estimated. Table 5 summarizes the effects of random HF well location proximity on crop yield and Table 6 summarizes the effects of water use of randomly assigned wells on crop yield. Figure 12 and 13 plot these coefficients. Figure 12 panel (a) and (b) summarizes the effects of randomly plotted well proximity on the irrigated crops for all years and for April to September. Panel (c) and (d) summarizes the effects of randomly plotted well's water use for the purpose of hydraulic fracturing on the irrigated crops for the wells drilled all year round and for the wells drilled April to September. I find no significant effect from the randomly assigned wells on the productivity of the irrigated crops, except for the HF water use during April to September for 6-15 km distance interval.

Figure 13 summarizes the effects of randomly assigned HF well proximity effects on the dryland crops in panel (a) and (b), and the effects of water use of the randomly assigned HF wells on the dryland crops in panel (c) and (d). I observe small negative effects on the dryland crops in distant distance intervals, such as, 46 to 55 km or 26 to 35 km. But mostly the effects of the randomly assigned HF wells' effects on the dryland crops are statistically not different from zero.

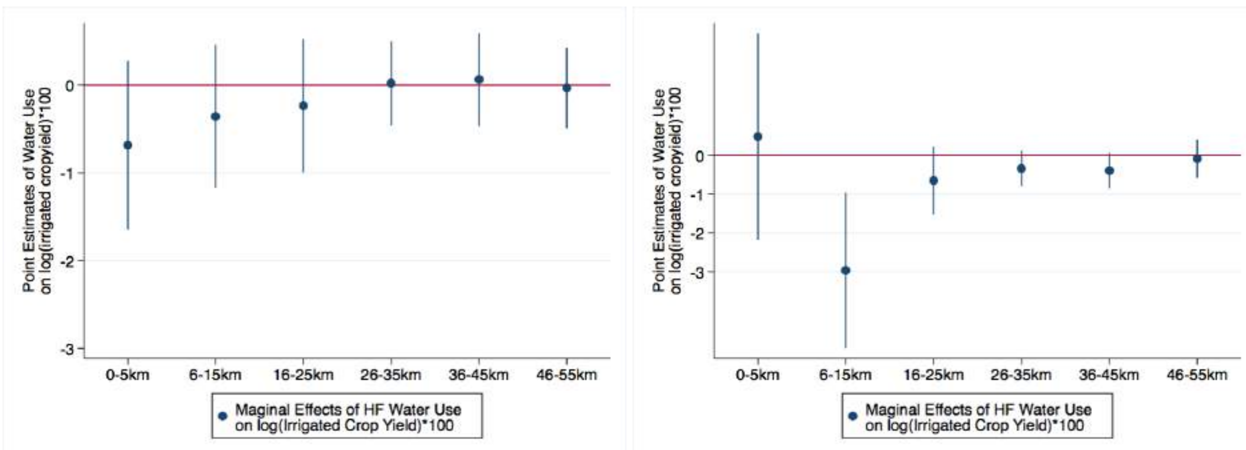
These results show that the negative effects of hydraulic fracturing well proximity and hydraulic fracturing water use on agricultural productivity is not randomly generated.



(a) All Months

(b) April-September

Marginal Effects of Hydraulic Fracturing Well Count on Irrigated Crop's Land Productivity

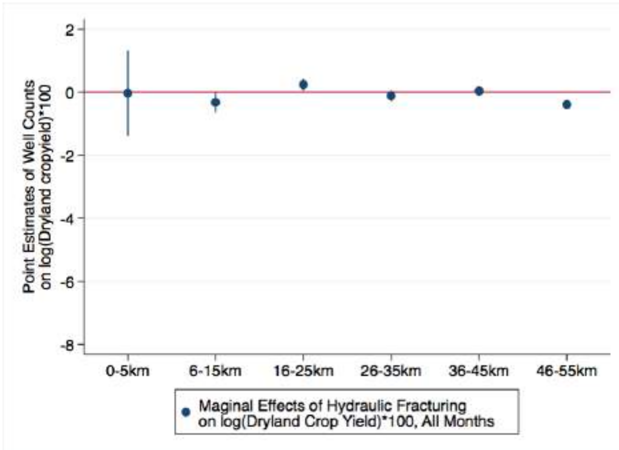


(c) All Months

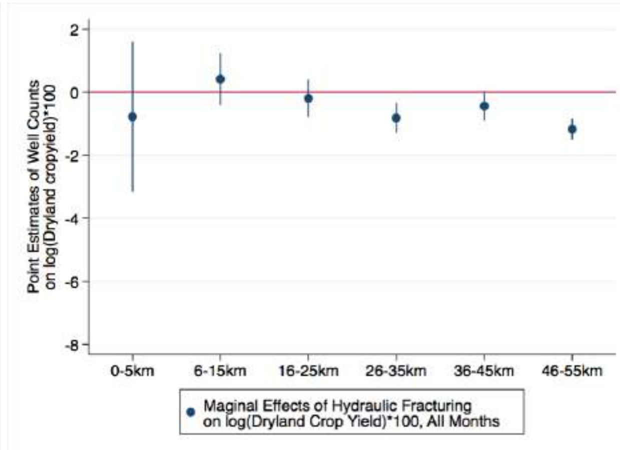
(d) April-September

Marginal Effects of Hydraulic Fracturing Water Use on Irrigated Crop's Land Productivity

Figure 12: Placebo test: Hydraulic Fracturing Effects on the Irrigated Crops

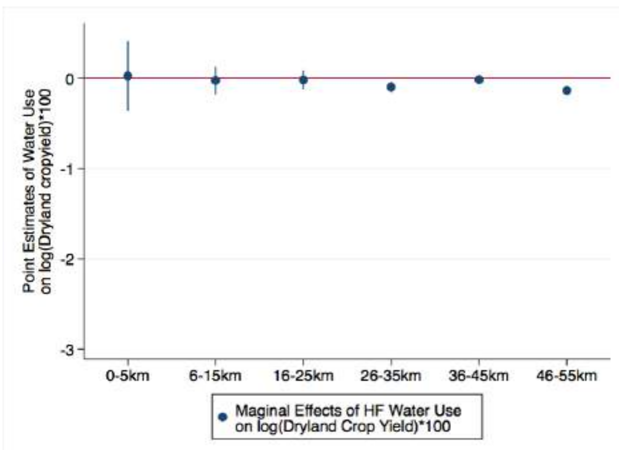


(a) All Months

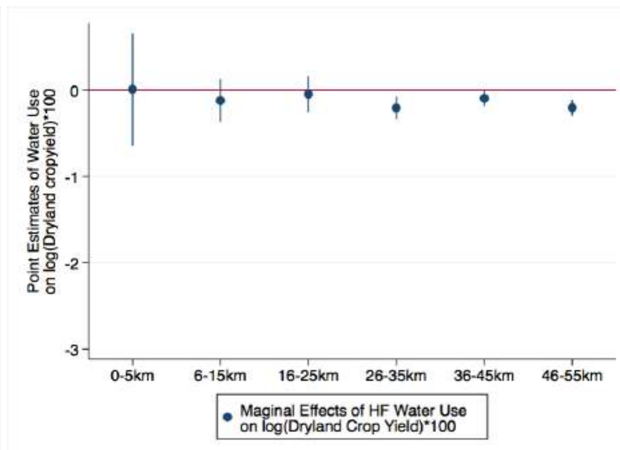


(b) April-September

Marginal Effects of Hydraulic Fracturing Well Count on Productivity of Dryland Crops



(c) All Months



(d) April-September

Marginal Effects of Hydraulic Fracturing Water Use on Productivity of Dryland Crops

Figure 13: Placebo Test: Hydraulic Fracturing Effects on the Dryland Crops

3.6 Discussion and Implication of the Results

To calculate the implied total effect of the well proximity effects, I aggregate the results for all the distance intervals in Table 2. For simplicity, in this section I show how much Alberta lost due to the productivity decline of the irrigated crops in 2014. To calculate the aggregate provincial effect, I use the coefficients from Column (6) Table 2, which shows the effects of the wells drilled during April to September on the irrigated crops' productivity. After multiplying all the coefficients with the count of wells in the respective distance intervals from each township and then aggregating the count of well effects on crop yield productivity by all the townships for all the distance intervals,

Table 5: Placebo Test: Effects of Hydraulic Fracturing Well Proximity on log(Crop Yield)

	Panel A: Wells Drilled Any Month		Panel B: Wells Drilled April- September	
	(1)	(2)	(3)	(4)
	Irrigated	Dryland	Irrigated	Dryland
Count of Hydraulic Fracturing Wells				
0- 5 km or Within Township	-0.627	-0.0314	-6.345	-0.781
	(2.484)	(0.823)	(5.440)	(1.447)
6-15 km	0.725	-0.327*	-4.556	0.411
	(0.869)	(0.195)	(2.845)	(0.500)
16-25 km	1.212	0.235**	2.005	-0.194
	(0.815)	(0.118)	(2.521)	(0.359)
26-35 km	-0.237	-0.117	-0.0121	-0.817***
	(0.740)	(0.107)	(1.268)	(0.291)
36-45 km	0.868	0.0354	0.661	-0.437
	(0.738)	(0.0931)	(1.194)	(0.281)
46-55 km	-1.315	-0.390***	-0.983	-1.180***
	(0.953)	(0.0719)	(1.289)	(0.203)
Constant	903.2***	582.7***	893.1***	599.6***
	(42.14)	(10.74)	(33.84)	(10.30)
Township-Crop FE	Y	Y	Y	Y
Crop-Year FE	Y	Y	Y	Y
Global Climate Index* Year Dummy	Y	Y	Y	Y
Observations	2015	44523	2015	44523
No. of Townships (Cluster)	117	1747	117	1747
No. of Groups (Fixed Effects)	433	6715	433	6715
R^2	0.299	0.508	0.298	0.508

Notes: Dependent variable: log (Crop Yield)*100. Crop yield is measured is kg per acre. Standard Errors (in parentheses) are clustered by township. Significance levels: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

I find that Alberta lost approximately $20.9 million in 2014 due to the loss in the productivity of the irrigated crops.[20]According to Agricultural Financial Services Corporation (AFSC) crop yield statistics, Alberta earned approximately $128 million as revenue from the irrigated crops and $2.67 billion as revenue from producing both irrigated and dryland crops in 2014. The revenue loss from the aggregated productivity loss implies that in 2014 Alberta lost approximately 16.3% of the annual revenue earned from the irrigated crop production and 0.8% of the annual revenue earned from the total crop production because of the decline in the productivity due to the increased hydraulic fracturing activity. However, since the crop yield data used in this analysis is from the only agricultural production insurance company of Alberta, so the irrigated crop yield used in this analysis are only for the insured farms. Furthermore, these data set do not contain statistics on animal production and hay crops, such as, tame hay. Therefore, the $20.9 million is a lower bound

[20]On average each 73 irrigated crop producing township lost $285.7 thousand (±$950.3 thousand) at 5% level of significance in 2014 due to loss of land productivity.

Table 6: Placebo Test: Effects of Hydraulic Fracturing Water Use on log(Crop Yield)

	Panel A: Wells Drilled Any Month		Panel B: Wells Drilled April- September	
	(1)	(2)	(3)	(4)
	Irrigated	Dryland	Irrigated	Dryland
Total Water Use for Hydraulic Fracturing (1000 m^3)				
0- 5 km or Within Township	-0.683	0.0257	0.485	0.0102
	(0.581)	(0.236)	(1.607)	(0.396)
6-15 km	-0.354	-0.0252	-2.967**	-0.120
	(0.491)	(0.0946)	(1.212)	(0.150)
16-25 km	-0.233	-0.0193	-0.654	-0.0454
	(0.458)	(0.0633)	(0.527)	(0.125)
26-35 km	0.0236	-0.0988***	-0.341	-0.205***
	(0.288)	(0.0371)	(0.273)	(0.0781)
36-45 km	0.0658	-0.0164	-0.394	-0.0931*
	(0.319)	(0.0314)	(0.277)	(0.0543)
46-55 km	-0.0318	-0.135***	-0.0875	-0.202***
	(0.278)	(0.0271)	(0.299)	(0.0568)
Constant	811.9***	650.6***	891.1***	650.8***
	(36.33)	(10.06)	(32.27)	(10.06)
Township-Crop FE	Y	Y	Y	Y
Global Climate Index* Year Dummy	Y	Y	Y	Y
Crop-Year FE	Y	Y	Y	Y
Observations	2015	44523	2015	44523
No. of Townships (Cluster)	117	1747	117	1747
No. of Groups (Fixed Effects)	433	6715	433	6715
R^2	0.294	0.508	0.301	0.507

Notes: Dependent variable: log (Crop Yield)*100. Crop yield is measured is kg per acre. Standard Errors (in parentheses) are clustered by township. Significance levels: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

of the value of the effect of nearby hydraulic fracturing on agricultural productivity. This amount might vary over years depending on the scale of farming, unconventional oil and gas production and other uncontrolled factors.

Table 7 shows total loss from the irrigated crop productivity, total crop revenue in 2014 from AFSC data and total crop market receipts reported in Alberta Statistical Yearbook 2014. Given that, 0.8% of the total annual revenue earned from all crops are lost due to nearby hydraulic fracturing activity, this result implies that Alberta might have actually lost $472 million because of the lost productivity of the irrigated crops. Furthermore, from Table 7, total crop revenue from AFSC statistics is approximately 45% of the total crop receipts reported by Alberta Agricultural Statistics Yearbook 2014 (Alberta Agriculture and Forestry 2015). Therefore, the $20.9 million productivity loss of the irrigated crops might be actually as high as $46.4 million in 2014 if hydraulic fracturing effects on all crops produced in Alberta are taken into account.

Table 7: Implied Effects of Well Proximity on Irrigated Crop's Productivity

Year		
2014	Calculated Total Irrigated Revenue Loss	$ 20.9 million
2014	Revenue from the Irrigated Crop Production (AFSC data)	$128 million
2014	Total Revenue from both Irrigated and Dryland Crop Production (AFSC data)	$2.67 billion
2014	Total Crop Market Receipts (Reported in AB Statistics Yearbook 2014)	$5.9 billion

Table 8: Total Production of the Major Crops, 2014

		Wheat	Canola	Barley
Year	Source	Total Production ('000 tonnes)		
2014	Total Production (AB Statistics Yearbook 2014)	9,348.9	5488.5	4,131.3
2014	Total Production (AFSC Statistics)	1080	1810	886
	Ratio	0.12	0.33	0.21

3.6.1 Compensation Payment to Farmers

In Alberta, the province owns 81% of the province's oil, natural gas, and other mineral resources.[21] Oil and natural gas producers acquire this mineral right by participating in a competitive bidding process (Alberta Energy 2014). If the minerals are underneath a farmland or if the producers with the mineral rights have to use the land for drilling or any other related purpose they pay the landowner or the farmer certain land compensation fees. The compensation fee is different in the first year and in the subsequent years. The first year's compensation fee includes an entry fee $500 per acre, the value of land, initial nuisance, inconvenience and noise, loss of the use of the land, and other adverse effects (if applicable). After the first year of the drilling, the subsequent year's annual compensation fees basically includes loss of the use of the land and other adverse effects (Environment Law Center, Consumer Fact Sheet; Alberta Agriculture and Forestry 2008). Thus, the farmers in Alberta receive compensation if the well is drilled on the farmland, but do not receive any compensation if the well is drilled in the neighboring land, for example: within 6-15 km radius or 16-20 km radius. This implies the productivity loss due to drilling outside of the farmland are not compensated.

In 2014, the total value of the produced marketable natural gas was $15.5 billion (AER 2015). Since shale gas consisted of 3% of the total natural gas production in 2014, the value of produced shale gas in 2014 was approximately $466.1 million (AER 2015). On the other hand, in 2014 the total value of the produced marketable crude oil was $18.5 billion (AER 2015). Since the amount of tight oil production is not reported separately from the total crude oil production, we can not estimate the value of tight oil production in 2014. Although the value of the productivity loss of the irrigated crops seems negligible when compared to the value of the produced shale gas, this has to be noted that the calculated $20.9 million (or $46.4 million) productivity loss is only one of the

[21]The remaining 19% are owned by the federal government on behalf of the first nation, or in the national parks, or by individuals or companies (Alberta Energy, Goa).

spillover effects from unconventional oil and gas production, and therefore the total loss should not be compared with the gross revenue earned from unconventional oil and gas industry.

4 Conclusion

This study empirically examines whether hydraulic fracturing activity in Alberta is affecting agricultural productivity through sectoral water competition, sediment run-off, and labor mobility. Using a difference in differences estimation, this study finds that nearby hydraulic fracturing activity decreases land productivity of the irrigated crops. According to the regression results, one additional well drilled during the agricultural months, April to September, within a township decreases productivity of an irrigated crop by approximately 4.2%. On the other hand, wells drilled during any other month of the year and within 16-25 kilometer radius of a township decreases agricultural productivity of an irrigated crop by 1.6%. These effects decline and become weaker as wells in the distant areas are included. This paper also finds that, for each 1000 m^3 water increase pumped by the wells for hydraulic fracturing within each township during April to September, irrigated crop's productivity goes down by 1.4%. These results has implications to the debate on the hydraulic fracturing drilling well location and water use.

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6 Appendix

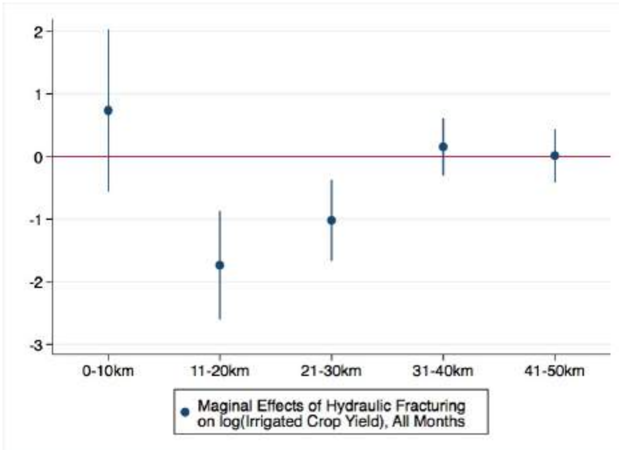
6.1 Alternative Distance Intervals

To check the robustness of the estimated results, I use the same specifications showed in Table 2 and 3 but use different distance intervals. The equation that is used with different distance intervals is:

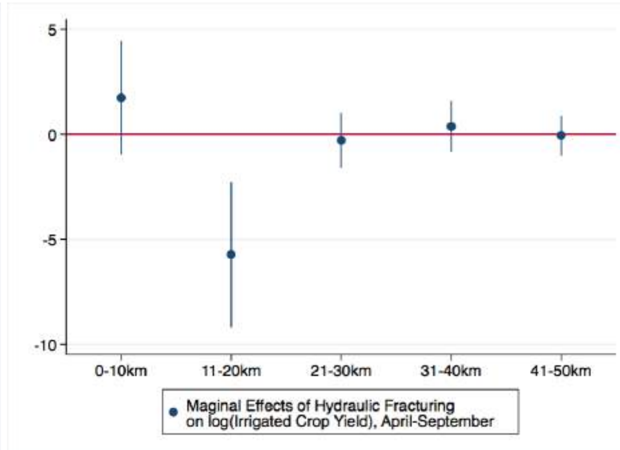
$$
\begin{aligned}
log\,(\text{Crop Yield})_{ict} = \alpha_0 + \sum_{d\,\epsilon\,B} \alpha_d\,\text{Count of Wells}_{dit} + \alpha_1 X_{it} + \mu_{ic} + \nu_{ct} + \epsilon_{ict}, \\
\text{Here, } B = (0-10, 11-20, 21-30, 31-40, 41-50)(\text{distances in kilometers}), \\
+\,50km = \text{reference group} \\
i = 1, \ldots, 1786(\text{townships});\; c = 1, 2, \ldots, 25(\text{crops});\; t = 2000, 2001, \ldots, 2014(\text{years}); \quad (2)
\end{aligned}
$$

All variables and indicators in equation 2 is same as equation 1 except the distance intervals, d. The variable of interest Count of Wells in year t contains count of wells in every 10 km radius from the township centroid up to 50 km.

The results using count of wells and total water used for hydraulic fracturing based on equation 2 are showed in Figure 14 and 15 for irrigated crops and dryland crops, respectively. From Figure 14 panel (a) and (b), the effects of hydraulic fracturing wells are high when the wells are close to the townships. These effects become weak after 30 km. The magnitude of the effects are also large when the wells are drilled during April to September. Panel (c) and (d) show the effects of hydraulic fracturing water use on the irrigated crop's productivity. Similar to count of wells effects, the effects are maximum when wells are drilled within 20 km radius of the township, and is of higher magnitude when the wells are drilled during April to September. Figure 15 summarizes the effects of hydraulic fracturing well proximity on the dryland crops. Similar to Figure 11, it can be observed that hydraulic fracturing proximity does not affect the productivity of the dryland crops significantly. The adverse effect is observed only in the most distant interval 41 to 50 km.

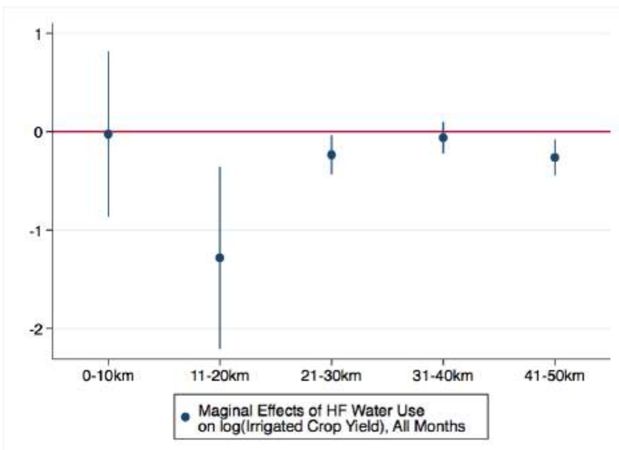


(a) All Months

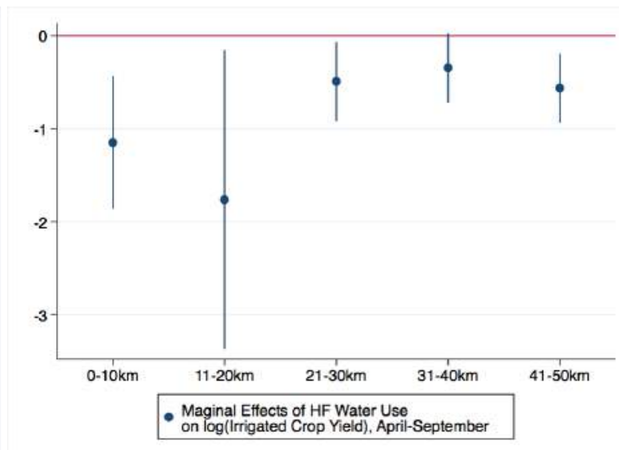


(b) April-September

Marginal Effects of Hydraulic Fracturing Well Count on Irrigated Crop's Land Productivity



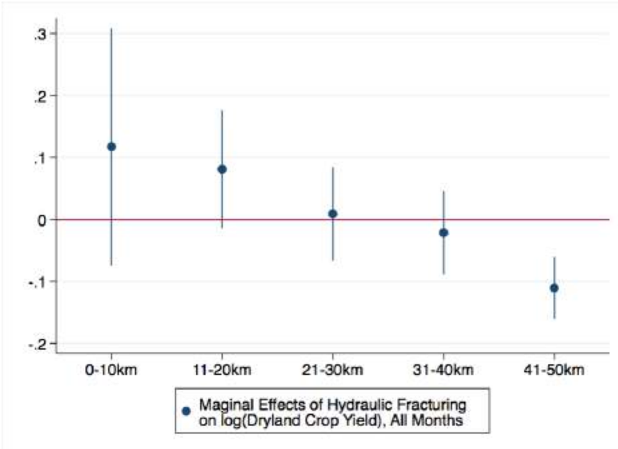
(c) All Months



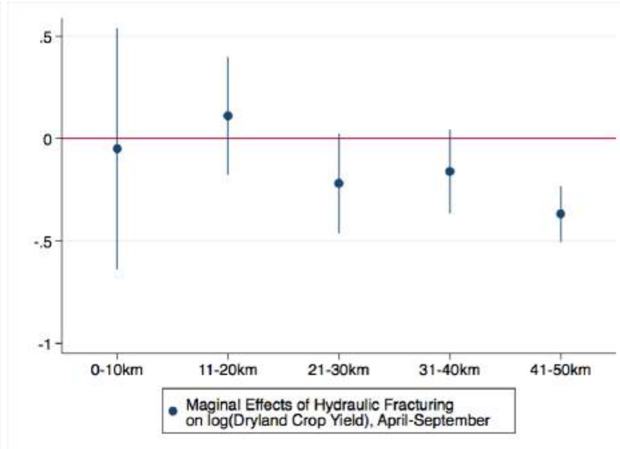
(d) April-September

Marginal Effects of Hydraulic Fracturing Water Use on Irrigated Crop's Land Productivity

Figure 14: Alternative Distance Interval: Hydraulic Fracturing Effects on Irrigated Crops

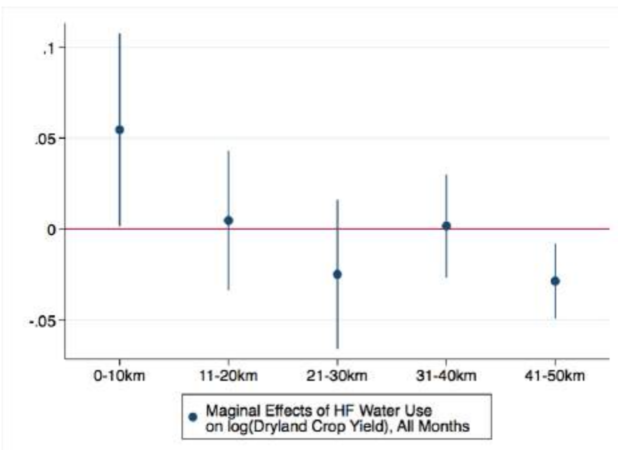


(a) All Months

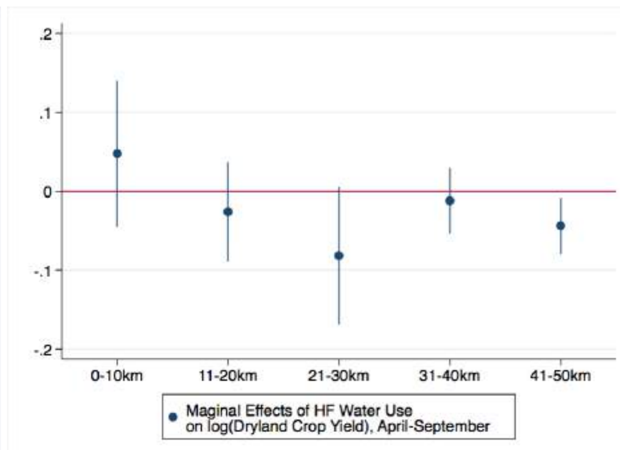


(b) April-September

Marginal Effects of Hydraulic Fracturing Well Count on Productivity of Dryland Crops



(c) All Months



(d) April-September

Marginal Effects of Hydraulic Fracturing Water Use on Productivity of Dryland Crops

Figure 15: Alternative Distance Interval: Hydraulic Fracturing Effects on Dryland Crops

6.2 Alternative Measure of Productivity: Value Per Acre

Table 9: Effect of Well Proximity on log(Value Per Acre) (Township level)

	Panel A: Wells Drilled Any Month		Panel B: Wells Drilled April- September	
	(1)	(2)	(3)	(4)
	Irrigated	Dryland	Irrigated	Dryland
Count of Hydraulic Fracturing Wells				
0-10km	-0.00263	-0.0585	-0.0107	-0.0967
	(0.0142)	(0.0625)	(0.0315)	(0.102)
11-20km	***-0.0211	***-0.0992	***-0.0760	**-0.212
	(0.00773)	(0.0248)	(0.0241)	(0.0851)
21-30km	0.000211	-0.0132	0.0287	0.0668
	(0.00930)	(0.0263)	(0.0203)	(0.0679)
31-40km	**0.0132	0.0113	***0.0275	0.0311
	(0.00604)	(0.0179)	(0.00957)	(0.0447)
41-50km	0.00399	0.00652	0.0133	0.0241
	(0.00647)	(0.0104)	(0.0130)	(0.0241)
Constant	***-1.246	***-3.550	***-1.245	***-3.561
	(0.0533)	(0.0884)	(0.0533)	(0.0967)
Year FE	√	√	√	√
Township FE	√	√	√	√
Observations	1028	491	1028	491
R^2	0.198	0.606	0.204	0.600
F	18.14	40.05	16.00	35.39

Notes: Dependent variable: log(Crop yield Value per Acre). Crop yield is measured as kg per acre. All specifications include Township FE and Year FE. Standard Errors (in parentheses) are clustered by township. Significance levels: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

As a robustness check, I use the dollar value from the produced crops per acre of land is used as the measurement of land productivity. Since the dependent variable is in monetary terms, this analysis is done in township level, instead of township-crop level. Panel A uses the wells drilled in any month of the year, whereas panel B uses the wells drilled during summer. Column (1) and (3) are for the irrigated crops, and Column (3) and (4) are for the dryland crops. For the irrigated crops, for a well drilled within 11-20 km radius of a township, revenue from the irrigated crops decreases by 2% if the well is drilled in any month of the year and revenue from the irrigated crops decreases by 7.6% if the well is drilled during April to September. Although we do not observe any significant effect within 21-30 km radius, irrigated crop revenue per acre increases because of increased use of hydraulic fracturing in the 31-40 km radius. For a well drilled in any month within 31-40 km radius of the township, irrigated crop revenue decreases by 1.3%, and if the well is drilled during April to September, irrigated crop revenue decreases by 2.8%. The effect disappears after 40 km. In case of dryland crop revenue per acre, no effect is observed except 11-20 km radius. Within 11-20 km radius if a well is drilled in any month, revenue from drland crops decreases by 9%, if the well is drilled during April to September, dryland crop revenue decreases by 7.6%. No significant effect is observed on dryland crop revenue after 20 km. These results are supportive of the conclusion that close proximity to hydraulic fracturing wells decreases irrigatecd crops' productivity.