Unconventional Oil and Gas Development and Agricultural Land-use in the U.S.

Yuelu Xu, West Virginia University, yuelu.xu@mail.wvu.edu

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Abstract

The rapid development of unconventional oil and gas (UOG) has raised public concerns about its land use and competition with agriculture. Using county-level data from 1997 to 2018, we find that on average, UOG development negatively affected crop acreage in the contiguous U.S. However, there exists significant regional heterogeneity. The relationship is positive in Southwestern region, U-shaped in Great Plains, and negative in Appalachia. There is significant difference in crop acreage between counties with and without UOG after 2008 in the contiguous U.S. and Great Plains. The reduction in crop acreage after 2008 was highest in Great Plains.

Key words: Unconventional oil and gas, Energy, Agriculture, Crop acreage

Introduction

Advances in horizontal drilling and hydraulic fracturing technologies have enabled energy producers in the U.S. to extract oil and gas from unconventional sources in a cost-efficient manner. The subsequent rise in unconventional production across the U.S. has transformed the energy markets. Between 2005 and 2018, the number of active unconventional oil and gas (UOG) wells grew more than tenfold (panel a, Figure 1). Meanwhile, the annual gross withdrawal of natural gas surged from 24 trillion cubic feet in 2000 to 41 trillion cubic feet in 2019, and the annual crude oil production doubled in 2019 relative to 2000 (panel b, Figure 1). Following the dramatic rise in domestic production, oil and gas prices in the U.S. have decreased significantly since 2007 (panel c, Figure 1). The growth in UOG production and associated infrastructure have significantly influenced regional incomes, employment, and land use (Weber and Hitaj, 2015; Tsvetkova and Patridge, 2016).

We use county-level data on active UOG wells and crop acreage from 1997 to 2018 to evaluate the net effect of UOG development on crop land-use decisions in the contiguous U.S. and several key shale regions. Individual shale regions considered include Appalachia (Ohio, New York, Pennsylvania, and West Virginia), Southwest region that covers shale plays under Arkansas, Louisiana, New Mexico, Oklahoma and Texas, such as Eagle Ford, Haynesville, Permian, Anadarko, and Barnett shale plays, and Great Plains that includes shale plays under Colorado, Kansas, Montana, North Dakota, and Wyoming, such as Bakken and Niobrara shale plays (Kaplan, 2019). Figure 2 plots the geographic distribution of the shale regions. We aggregate several shale play regions with similar geographical conditions and climates for crop production into three major areas to obtain workable sample sizes for regional analysis. The regions included in this study accounted for 70% and 60% of total U.S. shale gas and tight oil production, respectively, in 2018 (EIA, 2019).

Our results indicate that the impacts of UOG development on agricultural land use vary across regions. Overall, growth in UOG wells decreases crop acreages in the contiguous U.S, with each active UOG well reducing crop acreages by 5.2 acres in an average county. In Appalachia, an additional active UOG well decreases crop acreages by 4.5 acres. In Southwest, the relationship between UOG development and crop acreages is positive; one more active UOG well increases crop acreage by 2.6 acres. In Great Plains, there is a negative and diminishing marginal effect of UOG development on agricultural land use. On average, a county with upstream UOG production in Great Plains experienced 12,000 acres decrease in agricultural land after 2008. A similar difference is found for the change in crop acreages of UOG producing counties from pre to post 2008 in the contiguous U.S.; on average, the reduction in crop acreage is 4,586 acres in a county with UOG development after 2008 relative to a county without UOG development. However, this change in crop acreage is not detected in Appalachia and Southwest.

Background

Energy market growth and the development of UOG infrastructure can affect agricultural land use in several ways. First, upstream UOG development competes for land with the agricultural sector (Fitzgerald et al., 2020; Hitaj et al., 2014). The development of UOG may displace agricultural land because developing a new site for drilling requires corresponding infrastructure such as new roads for access, well pads for drilling, and pipelines for shipment. For example, Hitaj et al. (2014) note that large-scale drilling activities are accompanied by a significant reduction in irrigated acreages in Weld County, CO. Given that over a third of active farm and ranch land in the U.S. is located in shale counties (Hitaj and Suttles, 2016), the negative impact of UOG production on agricultural land use due to drilling and infrastructure development could be significant.

Second, upstream UOG and agriculture, to some degree, compete for factors of production, such as water and labor. Although water use in UOG production is significantly less than in irrigated agriculture, changes in the quantity or quality of water can affect farmers who use water for crop and livestock production during dry years and seasons. UOG water use can be particularly noticeable in small to midsize streams where withdrawals for UOG production represent a significant portion of stream discharge (Brantley et al., 2014; Barth-Niftilan, 2015; Hitaj et al., 2020). In addition, while water scarcity is not as prominent in the Appalachian region as in other UOG regions, like the Eagle Ford in Texas, potential contamination can threaten agricultural production. Competition for labor can also affect the regional agricultural sector as upstream UOG growth increases local wages and inflates low-skilled labor costs (Hitaj et al., 2014; Komarek, 2016). These factors may discourage farmers from continuing to invest in the agricultural sector.

Third, increased oil and gas supply and the associated decline in energy prices could have lowered agricultural production costs. Agricultural production in the United States is highly energy-intensive—energy-related expenses account for more than 50% of the total operating cost for key crops such as corn and wheat (Marshall et al., 2015). Fuels are used directly to operate farm machinery, power irrigation systems, and transport inputs/outputs to and from markets, as well as indirectly in the form of fertilizers and agricultural chemicals. Lower energy costs could encourage farmers to expand production acreage (Pfeiffer and Lin, 2014).

Furthermore, UOG development generates capital gains, including land appreciation (Weber and Hitaj, 2015) and revenues from royalties (Weber and Hitaj, 2015; Brown et al., 2016; Brown et al., 2019), which may affect agricultural production both positively and negatively. On one hand, lease and royalty payments from UOG development supplement farmers' incomes. Nationally, farmers received $2.3 billion in lease and royalty payments in 2011 (Hitaj, et al. 2014). These gains from energy markets may be used to invest in machinery, upgrade technology or acquire land to expand crop acreages (Weber and Key, 2014). On the other hand, capital gains from UOG development may lead to decreased agricultural acreages as the UOG revenues increase the opportunity cost of agricultural production (Hoy et al., 2018). Additional UOG income may encourage earlier retirement of older farmers. The average age of principal farm operators in the US has been rising in recent decades as retirements of older farmers outpace the inflow of younger farmers (Gale, 1994; Fried and Tauer, 2016). The accelerated retirements due to UOG capital gains may decrease the land used in crop production.

The net impact of the UOG development on agricultural land use is thus ambiguous. If the positive effect due to decreased energy-related costs and reinvestment of capital gains outweigh the negative impact of land displacement for infrastructure, increased competition for some inputs and the higher opportunity cost of agricultural production, then UOG development can lead to more cropland acreages and higher agricultural production. Otherwise, a decline in agricultural land use can be expected. Furthermore, the effects of UOG development on agricultural land use can be different across major UOG regions due to heterogeneities in geography, climates, labor markets and changes in land value associated with drilling activities (Weber and Hitaj, 2015).

Prior studies have investigated the potential impacts of UOG development on the agricultural sector in different shale plays. Results are overall mixed. Hoy et al. (2018) find no significant changes in land use of beef and dairy farms in UOG producing counties relative to non-UOG counties before and after 2007 in the Marcellus region. Allred et al. (2015) investigate land cover loss (rangelands, forestlands, croplands, and wetlands) due to oil and gas development in the U.S. and Canada in 2000-2012 using satellite vegetation and oil and gas well data. They show that the impact of oil and gas development on land cover loss is likely long-lasting since the recovery of previously drilled land is much slower than the loss of land during accelerated drilling. Using remote-sensing field-scale agricultural land cover data, Fitzgerald et al. (2020) find that drilling activities reduce crop cover and increase fallow acreage in North Dakota's Bakken Shale play. However, the negative impacts in some areas are temporary as producers put some of the removed lands back into crop production after the UOG well spud year.

We contribute to previous literature by expanding the study area to the contiguous U.S. and by comparing the results from major shale play regions. We also explicitly consider the effect of the structural change in the energy market break in 2008, which has been empirically identified as a breakpoint for UOG growth in prior literature in terms of oil and gas prices, UOG production, and the number of UOG wells (Mugabe et al., 2020, Huang and Etienne 2021). We examine aggregate crop acreage change that may be attributed to the growth in UOG at the county scale and consider the quadratic specification to account for a potential nonlinear relationship between regional UOG development and agricultural land use. The nonlinear relationship may occur because the initial UOG well development can have a larger marginal effect on infrastructure development than the subsequent new wells. The first wells in the area require marginally more infrastructure like well pads, pipelines, and access roads, than the subsequent wells. We further control for the factors that directly affect crop acreages, including region-specific crop prices, input costs, and climate.

Empirical Model

Following Miao et al. (2015) and Li et al. (2019), the empirical strategy is based on county-scale analysis that assures data availability, including land-use change, UOG development, climate variables, and input and output prices across multiple regions. We contrast the agricultural land-use change in counties with and without UOG wells. Five specifications are used for the contiguous U.S. and sub-regions. The first model examines the linear relationship between the UOG development and changes in agricultural land use:

(1) $$Acreage_{it} = f(OutputPriceIndex_{i,t-1}, Climate_{i,t}, FertilizerPrice_t, TimeTrend_t)$$

$$+\alpha_1 * UOGWells_{it} + \beta_i + e_{it},$$

where, the dependent variable is the aggregate annual planted crop acreage at the county scale.

$OutputPriceIndex_{i,t-1}$ is a lagged aggregate price index for eight crops in county i. $Climate_{it}$ includes annual precipitation and temperature in county i in year t. $FertilizerPrice_t$ denotes national fertilizer price. $TimeTrend_t$ controls the overall change in acreage due to unobservable factors that may change over time. $UOGWells_{it}$ denotes the number of active UOG wells in county *i* at time *t*. β_i is a county fixed effect to capture unobserved time-invariant features that can influence land-use decisions at the county scale. e_{it} is the error term.

In the second specification, both linear and quadratic terms are included to allow the marginal effect of an additional UOG well to differ depending on the number of existing wells. Initial growth in UOG requires land for infrastructure, including pads, access roads, and pipelines. However, after sufficient infrastructure is developed, additional wells require substantially less land for infrastructure. The empirical model is specified as:

$$(2)\quad Acreage_{it} = f(OutputPriceIndex_{i,t-1}, Climate_{i,t}, FertilizerPrice_t, TimeTrend_t) + \alpha_1 * UOGWells_{it} + \alpha_2 * {UOGWells_{it}}^2 + \beta_i + e_{it}.$$

The third specification investigates the marginal effects of UOG development on agricultural land use before and after the break point of energy markets, the year 2008[1]:

$$(3)\quad Acreage_{it} = f(OutputPriceIndex_{i,t-1}, Climate_{i,t}, FertilizerPrice_t, TimeTrend_t) + \alpha_1 * UOGWells_{it} + \alpha_3 * UOGWells_{it} * Year_{2008} + \beta_i + e_{it},$$

[1] We provide the robustness check for using alternative years (2007 and 2009) as the break point. Estimation results are overall robust to various years. Tables S1 - S4 in the Appendix A present the detailed estimation results using 2007 and 2009 as the break points.

where Year_{2008} is a dummy variable equaling 1 for years after 2008 and 0 otherwise.

The fourth specification examines the difference of crop acreages in counties with and without UOG development after 2008:

(4) $$Acreage_{it} = f(OutputPriceIndex_{i,t-1}, Climate_{i,t}, FertilizerPrice_t, TimeTrend_t)$$

$$+\alpha_4 * UOGDummy_i * Year_{2008} + \alpha_5 * Year_{2008} + \beta_i + e_{it}.$$

We include $UOGDummy_i$ in the regression equation, which equals one if the county had at least one UOG well during the sample period and 0 otherwise. α_4 measures the average difference between crop acreages of counties with and without UOG wells after 2008 given the additional control of $Year_{2008}$.

The last specification investigates how crop acreages change when a county enages in UOG production:

(5) $$Acreage_{it} = f(OutputPriceIndex_{i,t-1}, Climate_{i,t}, FertilizerPrice_t, TimeTrend_t)$$

$$+\alpha_6 * WellDummy_{it} + \beta_i + e_{it},$$

where $WellDummy_{it}$ equals 1 if the county has at least one active UOG well at time t and 0 otherwise. α_6 measures how crop acreage changes when a county starts UOG production.

In addition to using the full sample data, we estimate equations (1)-(3) using subsamples of UOG-producing counties. In estimating the models, we compute robust standard errors, clustered at the agricultural statistic districts[2], an aggregate geographical level relative to county, to allow

[2] Agricultural statistic districts are defined groupings of counties in each State, by geography, climate, and cropping

for spatial correlation and heteroscedasticity in the panel structure of the data (Stock and Watson, 2008).

Data and variables

The econometric analysis is based on a balanced panel of annual observations from 2,612 counties in the contiguous US from 1997 to 2018. The dependent variable is the combined planted acreage of eight major crops at the county level, including barley, corn, cotton, oats, peanuts, rice, soybeans, and sorghum.[3] Planted acreage data, obtained from National Agricultural Statistics Service (NASS), are constructed based on the County Agricultural Production Survey. County estimates for small grains are typically published in mid-February, while row crops estimates are released from early March through late June each year (U.S. Department of Agriculture, 2020). We consider counties that produced at least one of the eight major crops in at least one year during the selected period in the analysis.

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practices, which combine similar crop production counties together (USDA NASS, 2018). ASDs with shale play boudnaries are presented in Figure 2.

[3] Li et al. (2019) use ten major field crops as aggregated crop acreages; ten major field crops include barley, corn, cotton, oats, peanuts, rice, rye, soybeans, sorghum and wheat. These crops account for more than 85% of total cropland acreage in the US. Partially following Li et al. (2019), we use eight out of these ten major field crops as aggregated crop acreages in this work since county-level acreages of wheat and rye are not available after 2008 from USDA NASS.

Control variables considered are selected based on prior literature. Following Li et al. (2019), we include one-year lagged Laspeyres price index[4] as a proxy for the expected crop price to minimize the endogeneity concern. The Laspeyres price index is constructed using deflated state-level prices received by farmers with 1997 as the base year and corresponding production. The price index is defined as $\text{PriceIndex}_{it} = (\sum_{c=1}^{8} p_{cit} q_{ci1997}) / (\sum_{c=1}^{8} p_{ci1997} q_{ci1997})$, where p_{cit} is the received price of crop *c* in county *i* in year *t*; q_{ci1997} denotes the production of crop *c* in county *i* in the base year 1997, and $\text{t} \in \{1997, \ldots, 2018\}$.

Fertilizer costs account for a significant share of total operating costs (ERS, 2020). Therefore, the price of fertilizer is included as a control. We use the national index of fertilizer prices from USDA ERS with 2011 as the base year (ERS, 2019).

Climate variables include precipitation and temperature. We include climate variables as they directly affect crop yields and farmers' land-use decisions (Pröbstl-Haider et al., 2016). Data on county-level annual average precipitation (in inches) and temperature (in degrees Fahrenheit) are obtained from the National Oceanic and Atmospheric Administration (NOAA) (National Oceanic and Atmospheric Administration, 2020).

We measure UOG development using the number of active UOG wells. Both oil and gas wells are included in the analysis. The well data are obtained from Enverus. Figure 2 shows the spatial

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[4] We considered alternative price indexes, including Passche and Fisher price indexes. Estimation results are consistnet regardless of the price index used.

distribution of active UOG wells in 2018. As can be seen, 586 counties produced UOG across 42 states in 2018, up from only 242 UOG counties in 1997.[5] Forty counties had more than 1,000 active UOG wells in 2018; Weld County, CO had the most UOG wells with 6,132.

Figure 3 presents the growth of active UOG wells from 1997 to 2018 by region. The Southwest has the longest history of UOG production relative to other areas. The number of active UOG wells in Southwest had already exceeded 3,000 in 1997, while in the same year Appalachia and Great Plains only had 4 and 521, respectively. With the rapid expansion of UOG development, by 2018, the number of active UOG wells increased to 11,230, 74,397, and 23,800 in Appalachia, Southwest, and Great Plains, respectively.

Table 1 reports summary statistics for the full sample and subsamples of counties with UOG. Heterogeneities in crop production and UOG development across regions are evident. The average county-level crop acreage is the highest in Great Plains, followed by Appalachia and Southwest. Meanwhile, 60% of counties in Southwest have had at least one active UOG well during the sample period, the highest across the three regions. Of the counties with UOG development, the average number of UOG wells is 41, 93, and 86 during the sample period, in Appalachia, Southwest, and Great Plains, respectively.

Figure 4 presents the percentage of cropland relative to total county acreage for counties with and without UOG wells. To conserve space, we average the maximum percentages for each county during the sample period for each region. Overall, counties without UOG wells devoted greater

[5] Pre-2004 UOG wells were mainly experimental and R&D projects.

shares of land to agricultural production than counties with UOG. Figure 5 presents the aggregate county crop acreages by region from 1997 to 2018, along with the number of active UOG wells. The crop acreage grew in Great Plains over the sample periods but declined in Southwest.

Estimation results and discussion

We first conduct the full sample analysis to compare how crop acreages had changed between counties with and without UOG production. We consider specifications with linear (equation (1)) and quadratic (equation (2)) effects, a structural break in 2008 (equation (3)), the overall differences in crop acreage after 2008 between UOG and non-UOG counties (equation (4)), as well as the average effect of UOG development on crop acreage after it begins to produce UOG relative to a non-UOG county (equation (5)).

Table 2 reports the estimation results. Focus first on the contiguous U.S. Model 1 shows that UOG development on average, negatively affects the aggregate acreage in the U.S. during the sample period; an additional active UOG well reduces the cropland by 5.2 acres. No quadratic effect is detected between crop acreage and UOG production (model 2). Before 2008, the UOG development had no impact on crop acreages; in contrast, an additional active well resulted in a 16.1-acre reduction in aggregate crop acreage after 2008 (model 3). Model 4 shows that the average crop acreage in a county with UOG is 4,586 acres less than non-UOG counties after 2008. Model 5 shows that the shift from non UOG production to UOG production in a county did not affect crop acreages in the contiguous U.S.

In Appalachia, an additional UOG well decreases crop acreage by 4.5 acres (model 6). None of the other regression results shows a significant effect of UOG on crop acreage. This finding is consistent with Hoy et al. (2018), who find little change in total farmland acres in drilling relative to non-drilling counties in the Marcellus region. A possible explanation is that most agricultural counties in Appalachia usually do not have UOG resources; the shale play is largely located beneath the Allegheny Plateau characterized by soil with lower productivity (Hoy et al., 2018). Although UOG wells may affect cropland use in the few individual counties with drilling activities, on aggregate such effect disappears.

None of the regression results for Southwest shows a statistically significant relationship between UOG development and crop acreages when all counties are considered. Since UOG production in Southwest has a much longer history than in other regions (figure 3), UOG-counties in the area may have already developed the necessary infrastructure for UOG production. In other words, counties with no UOG production from 1997 to 2018 in Southwest may not possess any oil and gas in their nature. Hence, using the full sample, which includes both counties with and without active UOG wells, could dilute the impacts of UOG development on crop acreages and cannot reflect the true relationship for the Southwest region.

Estimation results for Great Plains are reported in models 16-20. Consistent with Fitzgerald et al. (2020), we find that UOG development overall negatively affects crop acreages in the region. An additional active UOG well, on average, decreases cropland by 13.1 acres. The quadratic term is positive and significant, although the magnitude of the coefficient is small. In other words, the impact of UOG development on crop acreage in Great Plains may be U-shaped. Model 18 suggests that the net effect of an additional active UOG well on crop acreages after 2008 is 12.4-acre reduction. In addition, a county with UOG development has 12,731 acres less cropland than a county without UOG development after 2008 (model 19). The begin of UOG production does not have a significant impact on crop acreages in Great Plains (model 20).

To obtain a more focused picture of how UOG production has affected crop acreage, we estimate equations (1)-(3) using data for counties that have hosted upstream UOG industries during the sample period. Non-UOG counties are excluded from the analysis. Table 3 reports the estimation results, which are overall consistent with the full sample analysis. Model 1 indicates that one more active UOG well will decrease crop acreages by 3.3 acres in an average county with UOG production. The effects of drilling activities after 2008 are negative and significant; model 3 suggests that an additional active UOG well after 2008 decreases crop acreage by 13 acres at the county level in the contiguous U.S.

The results for Appalachia (model 4) suggest a negative and significant relationship between UOG development and aggregate crop acreage in counties with UOG. An additional active UOG well decreases aggregate crop acreage by 6.3 acres. The negative relationship between the UOG development and agricultural land use in counties with UOG production is consistent with findings in Xiarchos et al. (2017), who show that shale development is associated with farmland loss in shale counties. Model 6 shows that there is no statistical differences in the effect of additional UOG well on crop acreages before and after 2008, which is consistent with result using the full sample.

Model 7 in table 3 indicates that in Southwest, an additional unconventional well leads to a 2.6-acre increase in aggregate crop acreages in counties with UOG production. The quadratic effect is negative, but insignificant (model 8). Model 9 suggests no significant change in the relationship between UOG wells and crop acreage before versus after 2008. Notably, Southwest is the only region out of the three considered in this study with unconventional oil and gas production before the momentous rise of UOG that started around 2008.

In Great Plains, the overall impact of active wells on crop acreages is negative, with an additional well decreases cropland by 10.2 acres on average (model 10). The quadratic term is significant in model 11, suggesting that the UOG development has a negative and diminishing marginal impact on crop acreage in Great Plains counties. Model 12 shows that one more active UOG well before (after) 2008 increases (decreases) crop acreages by 46.9 (56.7) acres.

The results presented above indicate that the effects of UOG development on county crop acreages vary by region in terms of signs and magnitudes. The relationship between UOG development and crop acreage is negative and linear in the contiguous U.S. and Appalachia. In Appalachia, the effects of infrastructure development and windfall income from UOG production dominate the reinvestment effects, leading to reduced crop acreages. Weber and Hitaj (2015) conclude that UOG development results in greater land appreciation in the Marcellus Shale than in the Barnett Shale (Texas) because more farmers in the Appalachia region own mineral rights. Also, windfall income in Appalachia may discourage agricultural production instead of supporting reinvestment in expanding crop acreage.

In Great Plains, the relationship between crop acreage and UOG development is generally negative. However, the decline in acreage in response to UOG development is diminishing. These results are consistent with findings in Fitzgerald et al. (2020), who document that drilling activities in Bakken Shale have had a significant negative but declining effect on agricultural land use. These results are reasonable for a region that required significant infrastructure development to support UOG growth. In Great Plains, lack of adequate infrastructure is evident even today as a substantial quantity of natural gas is flared (Tan and Barton, 2015). Initial UOG development requires significant land resources for well pads, access roads, and pipelines. However, subsequent growth with additional drilled wells requires marginally less land. The negative relationship between acreage and UOG growth suggests that in this region, capital reinvestment and cheap energy and fertilizer effects are dominated by additional land requirements for UOG growth, higher costs of inputs like labor, or the negative effect of UOG income on engagement in agricultural production. The trend from 2007 to 2018 in Great Plains (Figure 5) shows that croplands in Great Plains decreased dramatically in 2008 with the rise of UOG production and rebounded afterward (from 2007 to 2012), followed by a similar U-shaped pattern from 2013 to 2016.

The results for Southwest differ from other regions. We find a positive relationship between the number of UOG wells and crop acreage for counties with UOG development in Southwest, suggesting that the marginal expansion in acreage due to UOG growth is increasing. Two factors may help explain why the results for Southwest differ from other regions. First, compared to Appalachia and Great Plains, split estates where different parties own surface and underground mineral rights are more common in Southwest. Although UOG development may have led to land appreciation, the effect may have been smaller than if the landowner also owned the mineral right. Indeed, Weber and Hitaj (2015) document only modest land appreciation in the Barnett shale (Texas), due to shale gas development compared to the Marcellus region where split estates are less prevalent. The limited land appreciation and windfall income from UOG development may have encouraged farmers to expand crop acreage in Southwest, instead of early retirement. Meanwhile, split estates may facilitate a more active growth in the upstream UOG sector because of landowners' smaller bargaining power. Greater expansion in UOG production could, in turn, generate revenues, including land leases, that support further cropland expansion if additional income is at least partially invested in the agricultural sector. Such capital reinvestment can have a positive effect on acreage and on-farm asset values.

Second, Southwest has a longer history of significant fossil fuel production, including UOG, than other regions (Figure 3). Recent UOG production growth in Southwest has required relatively less additional infrastructure as oil and gas production was present for many decades and some infrastructure had been in place. Although the region had experienced a substantial expansion in UOG production over the past two decades, the cropland losses due to UOG infrastructure development may be substantially less than in Great Plains and Appalachia.

The results for other control variables in tables 2 and 3 are comparable to prior analyses of crop acreage in the U.S. Crop prices significantly increase crop acreages. The coefficient for the Laspeyres price index found in this study, around 3.45 (model 1-5, table 2), is lower than 4.48

reported by Li et al. (2019). The difference may be due to the inclusion of eight crops in this study as opposed to ten in Li et al. (2019). The coefficient estimates for the fertilizer price index are negative as expected and consistent with those reported in Li et al. (2019).

Conclusion

Expansion of UOG development in the U.S. has significantly affected the agricultural sector. This study analyzes how county crop acreages have changed due to UOG production during 1997-2018. Unlike previous studies that mainly focus on individual shale regions, we provide a comprehensive analysis of this relationship in the contiguous U.S. and across three major UOG production regions. In addition to the linear relationships in previous studies (Xiarchos et al., 2017; Hoy et al., 2018; Fitzgerald et al., 2020), we allow for the possible nonlinear effects of UOG development on crop acreage and also consider the effect of the structural break in UOG production.

We find that overall UOG development has a negative impact on crop acreages in the contiguous U.S. Crop acreage in UOG counties showed a smaller declining trend during the sample period compared to the sample with all counties. The impact, however, varies considerably across regions. Using the data from only UOG-producing counties, we find that additional UOG development exerts a negative and positive linear effect on crop acreage in Appalachia and Southwest, respectively. The relationship between UOG wells and crop acreages is nonlinear in Great Plains, which is U-shaped. The results also show that in Great Plains and in the combined U.S. data, counties with UOG experienced a significant decrease in crop acreages after 2008 relative to counties without UOG.

Agricultural land-use changes directly affect farmers' welfare, crop supplies, and ecosystem services (Blanco-Canqu et al., 2015; Malin and Demaster, 2016). Our results highlight that policies concerning agricultural land-use change due to UOG development need to be region-specific and account for the possible nonlinearities. UOG development negatively affects local agricultural land use in Appalachia, while a positive relationship between the number of active UOG wells and crop acreages is found in Southwest region. The negative impact of UOG development on crop acreage in Great Plains diminishes with increase in the number of active UOG wells.

Three limitations of this study should be mentioned. First, the decision-making regarding crop acreage is complex and our findings could be transitory with the rapid development in energy and crop markets. Second, due to the use of county-level data, we are unable to identify some important farm-level characteristics such as oil and gas right ownership, lease, and royalty payments. Future research should, where possible, incorporate more disaggregated data, which may provide further insights on how UOG development causes changes in land use. Third, we investigate the impact of UOG development on crop acreages using the number of active UOG wells. Permitted wells, which include both undrilled and active wells, are not considered. Although undrilled wells do not necessarily occupy land, the preparation of infrastructure including access roads and pipelines, may compete for resources including land and labor with agriculture. Hence, analysis of permitted wells may uncover a larger effect of UOG development on agricultural acreage than observed in this study using active wells. Conditional on the availability of well permitting data, future research should consider the relationship between well permitting and land use.

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Table 1. Summary statistics, 1997-2018

	UOG and Non-UOG counties combined															
	U.S. (# of county=2,612)				Appalachia (# of county=222)				Southwest (# of county=390)				Great Plains (# of county=372)			
VARIABLES	Mean	SD	Min.	Max.	Mean	SD	Min.	Max.	Mean	SD	Min.	Max.	Mean	SD	Min.	Max.
Aggregate crop acreage (1,000 acres)	65.8	93.5	0	840.2	50.7	61.6	0	281.3	33.9	59.2	0	397.8	87.8	99.4	0	840.2
# of active UOG wells (count)	12	116.8	0	6132	11	83	0	1523	58	235.2	0	3532	17	175.4	0	6132
Dummy for active UOG wells	0.2	0.4	0	1	0.3	0.5	0	1	0.6	0.5	0	1	0.2	0.4	0	1
Fertilizer price index (base year 2011)	64.6	26.7	31.9	119.2	64.6	26.7	31.9	119.2	64.6	26.7	31.9	119.2	64.6	26.7	31.9	119.2
Avg. annual precipitation (inch)	3.1	1.2	0.1	10.2	3.6	0.6	2.2	6.7	2.9	1.6	0.2	7.9	2.1	0.9	0.5	7.4
Avg. annual temperature (ºF)	54.5	7.7	33.9	77.1	50.1	30	40.1	57.1	63.3	5.5	42.3	77.1	49.7	6.4	33.9	66.1
Laspeyres price index (base year 1997)	1.3	0.5	0.5	2.8	1.4	0.5	0.7	2.6	1.2	0.4	0.5	2.2	1.4	0.5	0.7	2.8
	Only UOG counties															
	U.S. (# of county=459)				Appalachia (# of county=63)				Southwest (# of county=239)				Great Plains (# of county=74)			
VARIABLES	Mean	SD	Min.	Max.	Mean	SD	Min.	Max.	Mean	SD	Min.	Max.	Mean	SD	Min.	Max.
Aggregate crop acreage (1,000 acres)	26.2	43.1	0	319.6	22.9	32.5	0	182	23.3	40.7	0	280.3	32.7	50.7	0	319.6
# of active UOG wells (count)	69	271.4	0	6132	41	152.1	0	1523	93	290.9	0	3532	86	386.0	0	6132
Fertilizer price index (base year 2011)	64.6	26.7	31.9	119.2	64.6	26.7	31.9	119.2	64.6	26.7	31.9	119.2	64.6	26.7	31.9	119.2
Avg. annual precipitation (inch)	2.9	1.4	0.1	7.9	3.7	0.6	2.4	6.7	3.0	1.4	0.2	7.9	1.8	1.1	0.5	7.4
Avg. annual temperature (ºF)	57.9	9.3	34.2	77.1	50.1	2.6	43.6	56.7	64.3	4.8	44.8	77.1	46.6	6.8	34.2	65.5
Laspeyres price index (base year 1997)	1.3	0.4	0.5	2.8	1.3	0.5	0.7	2.6	1.2	0.4	0.5	2.2	1.4	0.5	0.7	2.8
	Results of t-test mean comparison between counties with and without UOG															
	U.S.				Appalachia				Southwest				Great Plains			
VARIABLES	Mean	SD			Mean	SD			Mean	SD			Mean	SD		
Aggregate crop acreage (1,000 acres)	48.03***	47.78			38.80***	20.69			28.67***	22.25			68.80***	26.00		
Avg. annual precipitation (inch)	0.271***	19.96			-0.0893***	-4.50			-0.275***	-9.09			0.385***	15.74		
Avg. annual temperature (ºF)	-4.161***	-50.16			0.023	0.24			-2.812***	-23.37			3.895***	22.62		
Laspeyres price index (base year 1997)	0.0191***	3.77			0.0423**	2.67			-0.0239**	-2.91			0.0142	1.02		

Table 2. Estimation results for all counties, 1997-2018

	Dependent variable = aggregate crop acreage (1000 acres)									
VARIABLES	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
			U.S.					Appalachia		
Lagged Laspeyres price index	3.4468***	3.4500***	3.4870***	3.3463***	3.4575***	4.5198***	4.5141***	4.5286***	5.8908***	4.4817***
	(0.7762)	(0.7764)	(0.7793)	(1.0158)	(0.7807)	(0.7506)	(0.7577)	(0.7497)	(0.9194)	(0.7891)
Fertilizer index	-0.0372***	-0.0373***	-0.0381***	-0.0349***	-0.0364***	-0.0885***	-0.0884***	-0.0887***	-0.1029***	-0.0865***
	(0.0112)	(0.0112)	(0.0112)	(0.0129)	(0.0111)	(0.0189)	(0.0190)	(0.0189)	(0.0192)	(0.0192)
Precipitation	-0.6115***	-0.6097***	-0.6132***	-0.6401***	-0.6083***	-0.7631*	-0.7620*	-0.7635*	-0.9936**	-0.7640*
	(0.2248)	(0.2246)	(0.2247)	(0.2240)	(0.2237)	(0.3871)	(0.3883)	(0.3873)	(0.3944)	(0.3894)
Temperature	0.0905*	0.0900*	0.0904*	0.0886*	0.0868*	0.3951**	0.3948**	0.3950**	0.3968**	0.3899**
	(0.0478)	(0.0478)	(0.0478)	(0.0474)	(0.0480)	(0.1674)	(0.1676)	(0.1674)	(0.1689)	(0.1682)
# of active UOG wells	-0.0052***	-0.0075***	0.0111			-0.0045*	-0.0033	0.0477		
	(0.0016)	(0.0027)	(0.0090)			(0.0025)	(0.0049)	(0.2153)		
# active UOG wells (quadratic)		0.0000					-0.0000			
		(0.0000)					(0.0000)			
# of active UOG wells * after 2008			-0.0161*					-0.0522		
			(0.0094)					(0.2146)		
County with UOG or not * after 2008				-4.5856***					0.4706	
				(1.1506)					(1.3062)	
After 2008				0.7443					-2.5254***	
				(0.7146)					(0.8335)	
UOG well dummy					-0.4685					0.5037
					(1.0302)					(1.3399)
Time trend	-0.1654**	-0.1633**	-0.1631**	-0.1730*	-0.1764**	0.0106	0.0095	0.0108	0.1405	-0.0129
	(0.0685)	(0.0689)	(0.0685)	(0.0934)	(0.0697)	(0.0808)	(0.0826)	(0.0809)	(0.0856)	(0.0911)
Constant	62.9623***	62.9750***	62.9291***	63.1888***	63.2102***	33.2178***	33.2332***	33.2230***	32.5950***	33.5658***
	(2.6974)	(2.6985)	(2.6994)	(2.6609)	(2.7202)	(9.3580)	(9.3657)	(9.3577)	(9.5179)	(9.4117)
Observations	54,831	54,831	54,831	54,831	54,831	4,662	4,662	4,662	4,662	4,662
R-squared	0.0061	0.0062	0.0063	0.0081	0.0053	0.0342	0.0343	0.0343	0.0367	0.0329
Number of counties	2,611	2,611	2,611	2,611	2,611	222	222	222	222	222

Robust standard errors in parentheses *** p<0.01, ** p<0.05, * p<0.1

Table 2. Estimation results for all counties, 1997-2008 (continued)

	Dependent variable = aggregate crop acreage (1000 acres)									
VARIABLES	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)
	Southwest					Great Plains				
Lagged Laspeyres price index	2.3701*	2.3141	2.4537*	2.5604*	2.2985*	6.7288***	6.8785***	6.9875***	5.4134**	6.6719***
	(1.3630)	(1.3787)	(1.4152)	(1.3513)	(1.3657)	(1.7051)	(1.7039)	(1.6946)	(2.0963)	(1.7181)
Fertilizer index	-0.0258	-0.0253	-0.0271	-0.0290	-0.0284	-0.1207**	-0.1224**	-0.1269***	-0.0994*	-0.1166**
	(0.0194)	(0.0195)	(0.0192)	(0.0183)	(0.0185)	(0.0466)	(0.0466)	(0.0468)	(0.0503)	(0.0468)
Precipitation	1.0801**	1.0764**	1.0761**	1.0687**	1.0611**	-4.9119***	-4.8950***	-4.8704***	-4.6551***	-4.7987***
	(0.4903)	(0.4909)	(0.4899)	(0.4915)	(0.5017)	(1.2967)	(1.2920)	(1.2888)	(1.2856)	(1.2832)
Temperature	-0.0151	-0.0182	-0.0151	-0.0143	-0.0138	0.1176	0.1010	0.1077	0.0671	0.0557
	(0.1262)	(0.1264)	(0.1264)	(0.1313)	(0.1217)	(0.1905)	(0.1883)	(0.1889)	(0.1753)	(0.1909)
# of active UOG wells	0.0020	0.0047	0.0056			-0.0131***	-0.0297***	0.0602***		
	(0.0014)	(0.0042)	(0.0056)			(0.0031)	(0.0062)	(0.0206)		
# active UOG wells (quadratic)		-0.0000					0.0000***			
		(0.0000)					(0.0000)			
# of active UOG wells * after 2008			-0.0035					-0.0726***		
			(0.0051)					(0.0205)		
County with UOG or not * after 2008				-1.9302					-12.7308***	
				(2.4658)					(3.7995)	
After 2008				1.0871					3.8874	
				(2.1191)					(2.6345)	
UOG well dummy					2.0902					-3.3650
					(1.6333)					(5.3544)
Time trend	-0.6451***	-0.6539***	-0.6424***	-0.6156***	-0.6527***	0.3809	0.3943	0.3934	0.2515	0.3461
	(0.1702)	(0.1719)	(0.1693)	(0.1555)	(0.1716)	(0.2975)	(0.2988)	(0.2985)	(0.4442)	(0.2976)
Constant	38.0143***	38.2743***	37.9486***	37.8137***	37.4242***	87.0077***	87.6931***	87.1816***	90.0618***	90.3547***
	(7.5755)	(7.6080)	(7.6030)	(7.8002)	(7.3119)	(10.0428)	(9.9559)	(9.9942)	(9.9303)	(10.1379)
Observations	8,190	8,190	8,190	8,190	8,190	7,812	7,812	7,812	7,812	7,812
R-squared	0.0638	0.0640	0.0638	0.0642	0.0642	0.0221	0.0237	0.0232	0.0258	0.0177
Number of counties	390	390	390	390	390	372	372	372	372	372

Robust standard errors in parentheses *** p<0.01, ** p<0.05, * p<0.1

Table 3. Estimation results for counties with UOG, 1997-2018

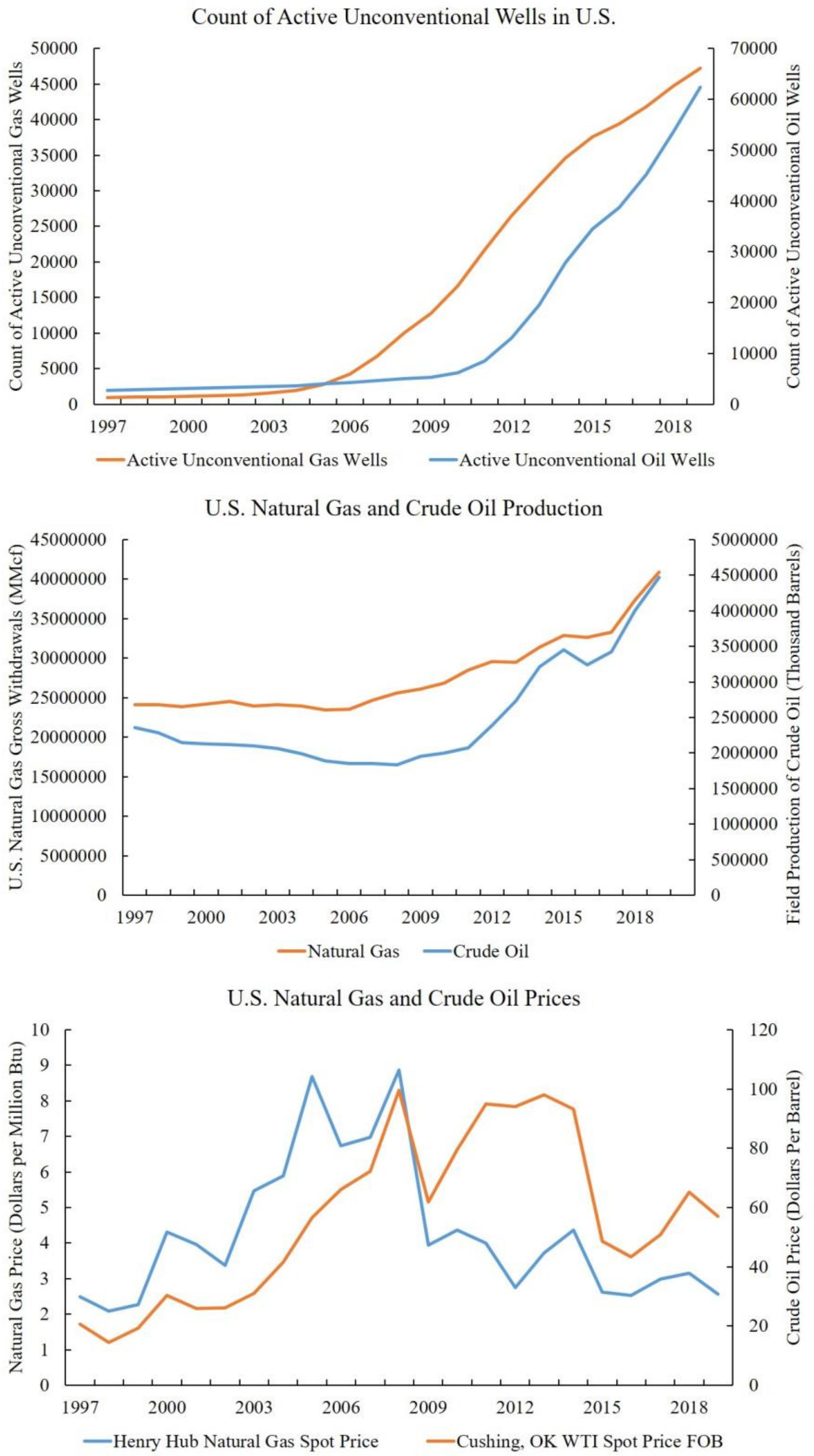
	Dependent variable = aggregate crop acreage (1000 acres)					
VARIABLES	(1)	(2)	(3)	(4)	(5)	(6)
	U.S.			Appalachia		
Lagged Laspeyres price index	2.9329***	2.9237***	3.1729***	3.7120***	3.7346***	3.7487***
	(0.9532)	(0.9431)	(0.9539)	(0.9702)	(1.0091)	(0.9173)
Fertilizer index	-0.0705***	-0.0704***	-0.0751***	-0.0913***	-0.0918***	-0.0924***
	(0.0158)	(0.0159)	(0.0154)	(0.0273)	(0.0277)	(0.0258)
Precipitation	0.0017	-0.0002	-0.0126	-0.4752	-0.4822	-0.4792
	(0.3402)	(0.3385)	(0.3409)	(0.3197)	(0.3378)	(0.3196)
Temperature	0.1317	0.1323	0.1319	0.2873	0.2879	0.2865
	(0.0866)	(0.0864)	(0.0867)	(0.1713)	(0.1707)	(0.1710)
# of active UOG wells	-0.0033*	-0.0028	0.0099	-0.0063**	-0.0074	0.0570
	(0.0019)	(0.0029)	(0.0075)	(0.0023)	(0.0043)	(0.1969)
# active UOG wells (quadratic)		-0.0000			0.0000	
		(0.0000)			(0.0000)	
# of active UOG wells * after 2008			-0.0130*			-0.0633
			(0.0077)			(0.1965)
Time trend	-0.3098**	-0.3120**	-0.2986*	0.1399*	0.1439*	0.1413*
	(0.1543)	(0.1570)	(0.1528)	(0.0693)	(0.0772)	(0.0686)
Constant	23.2707***	23.2474***	23.0583***	9.9143	9.8832	9.9640
	(5.1255)	(5.1170)	(5.1384)	(8.8212)	(8.7889)	(8.7994)
Observations	9,639	9,639	9,639	1,323	1,323	1,323
R-squared	0.0434	0.0434	0.0445	0.0734	0.0735	0.0735
Number of county	459	459	459	63	63	63

Robust standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1

Table 3. Estimation results for counties with UOG, 1997-2018 (continued)

	Dependent variable = aggregate crop acreage (1000 acres)					
VARIABLES	(7)	(8)	(9)	(10)	(11)	(12)
	Southwest			Great Plains		
Lagged Laspeyres price index	3.3321***	3.2092***	3.4717***	-0.8299	-0.0655	0.3403
	(1.1640)	(1.1602)	(1.2249)	(3.2660)	(3.3956)	(3.0762)
Fertilizer index	-0.0508**	-0.0497**	-0.0531**	-0.1172**	-0.1257**	-0.1420**
	(0.0224)	(0.0225)	(0.0219)	(0.0500)	(0.0516)	(0.0544)
Precipitation	0.4714	0.4617	0.4638	-2.6432	-2.6149*	-2.5457
	(0.3317)	(0.3337)	(0.3341)	(1.5464)	(1.5154)	(1.5103)
Temperature	-0.0153	-0.0302	-0.0144	0.1523	0.1182	0.1276
	(0.1108)	(0.1120)	(0.1111)	(0.1989)	(0.1970)	(0.1971)
# of active UOG wells	0.0026*	0.0067*	0.0064	-0.0102***	-0.0211***	0.0469**
	(0.0014)	(0.0037)	(0.0057)	(0.0030)	(0.0052)	(0.0166)
# active UOG wells (quadratic)		-0.0000			3e-06***	
		(0.0000)			(0.0000)	
# of active UOG wells * after 2008			-0.0037			-0.0567***
			(0.0049)			(0.0172)
Time trend	-0.6719***	-0.6940***	-0.6669***	0.1573	0.2008	0.2062
	(0.2125)	(0.2143)	(0.2112)	(0.4649)	(0.4654)	(0.4710)
Constant	29.8171***	30.9271***	29.6544***	38.0633***	39.0990***	37.9789***
	(7.3189)	(7.4674)	(7.3517)	(8.2311)	(8.2480)	(8.2201)
Observations	5,166	5,166	5,166	1,554	1,554	1,554
R-squared	0.0818	0.0828	0.0820	0.0669	0.0738	0.0736
Number of county	246	246	246	74	74	74

Robust standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1



Source: Energy Information Administration and Enverus (Energy Information Administration, 2020a and 2020b)

Figure 1. Active unconventional wells in the U.S. from 1997 to 2018 (top panel); U.S. natural gas and crude oil production from 1997 to 2019 (middle panel); U.S. natural gas and crude oil price from 1997 to 2019 (bottom panel)

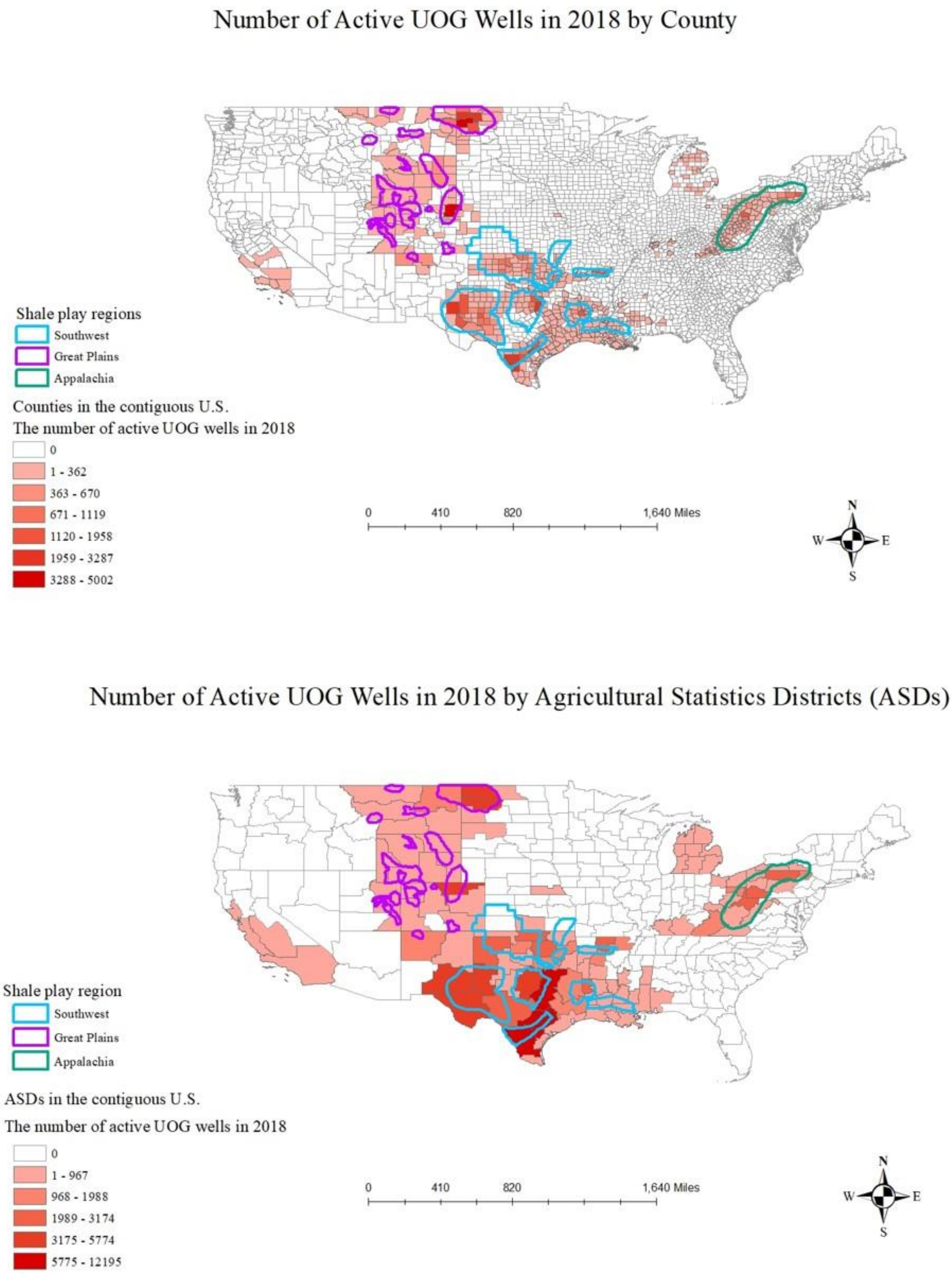


Figure 2. Counties with active UOG wells in 2018 and shale play region boundaries (top panel); ASDs with active UOG wells in 2018 and shale play region boundaries (bottom panel)

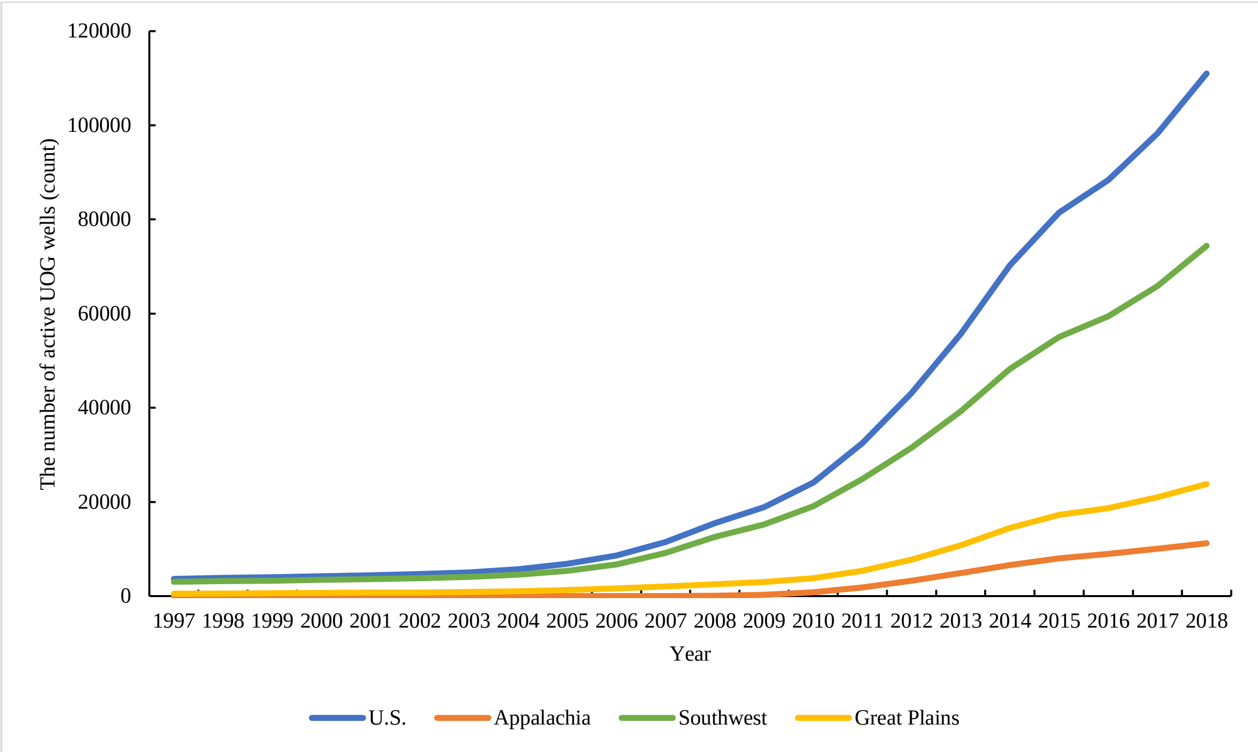


Figure 3. The number of active UOG wells over time by region, 1997-2018

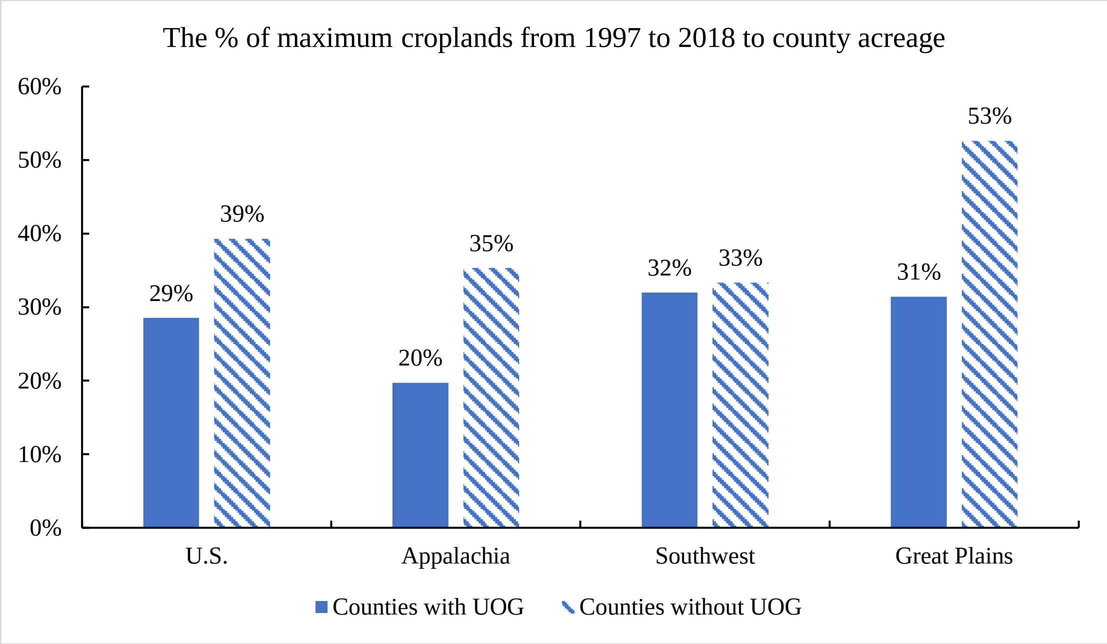


Figure 4. The percentage of maximum croplands from 1997 to 2018 to county acreages

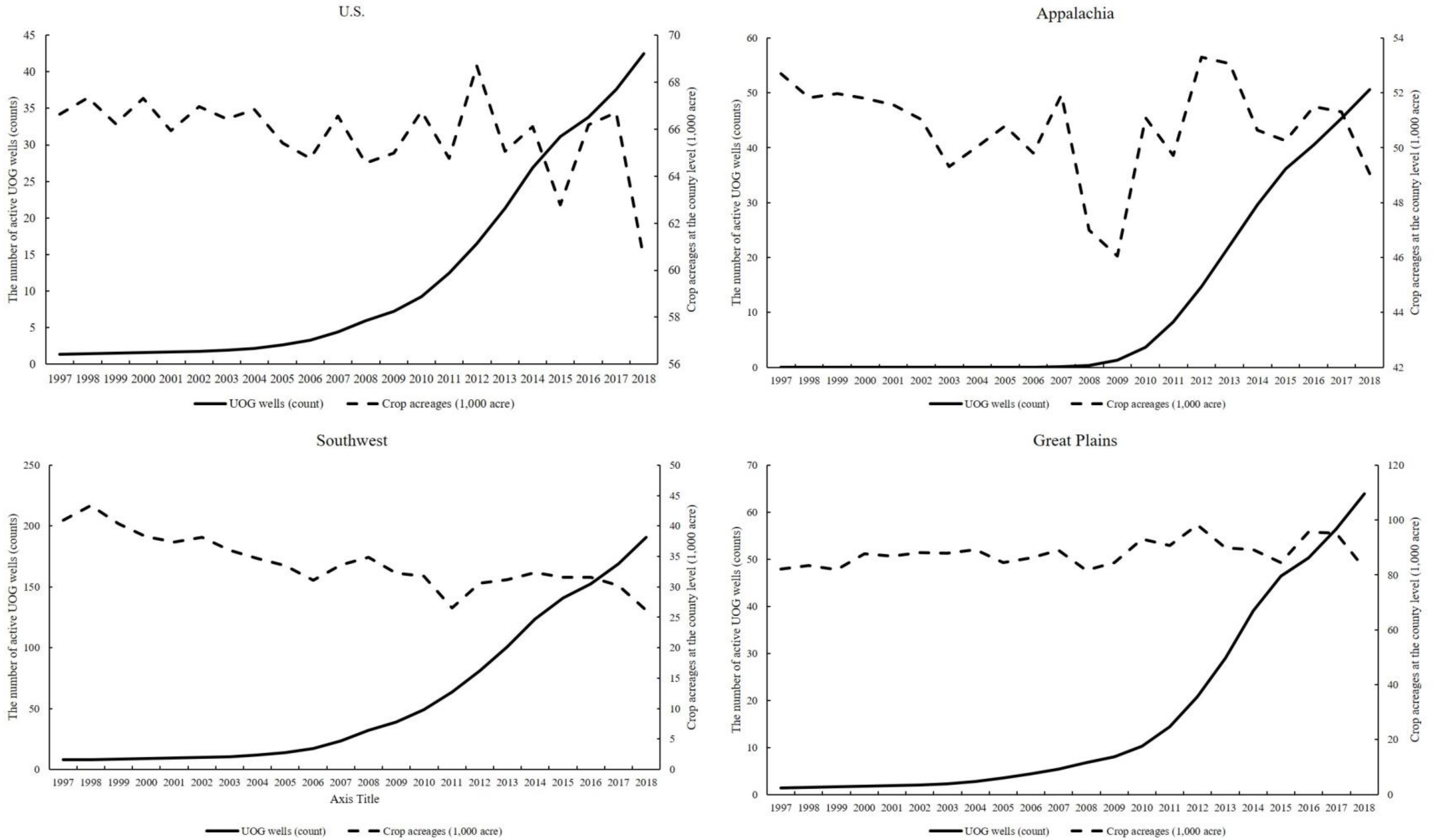


Figure 5. Average aggregate crop acreage and the number of active UOG wells at the county level by region (1,000 acres)