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

**Abstract**

Using county-level data from 1997 to 2018, we examine the effect of unconventional oil and gas (UOG) industry growth on agricultural acreage in the U.S. We find that on average, each active UOG well reduces crop acreage by 3.3 acres in counties with UOG production. However, the impacts vary by region. The relationship is positive in Southwest, U-shaped in Great Plains, and negative in Appalachia. The difference in crop acreage change after 2008 between counties with and without UOG is significant 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 afforded access to oil and gas resources in the U.S. and transformed the energy markets. Between 2005 and 2018, the number of active unconventional oil and gas (UOG) wells in the U.S. grew more than tenfold (panel a, Figure 1). As a result, 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 affected 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 cropland use in the contiguous U.S. and several key shale regions. Three individual shale regions are considered in this study (Figure 2). The Appalachian region includes Marcellus and Utica plays in Ohio, Pennsylvania, and West Virginia. The Southwest region includes Eagle Ford, Haynesville, Permian, Anadarko, and Barnett shale plays in Arkansas, Louisiana, New Mexico, Oklahoma, and Texas. Finally, the Great Plains region includes Bakken, Niobrara and other shale plays in Colorado, Kansas, Montana, North Dakota, and Wyoming (Kaplan, 2019). We aggregate several shale play regions with relatively similar geographic 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). In addition to the three regions, we also examine the contiguous U.S., which includes UOG production outside the three combined regions.

Our results indicate that in UOG producing counties, each active UOG well reduces crop acreage by 3.3 acres, and that a county with UOG production lost 4,586 acres after 2008. However, the impacts of UOG development on agricultural land use vary across regions. In Appalachia, an additional active UOG well decreases crop acreages by 6.3 acres. In Southwest, the relationship between UOG development and crop acreages is positive; an additional 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. No change is detected for county crop acreages in Appalachia and Southwest before and after 2008.

## Background and related literature

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 UOG development may displace agricultural land because new sites for drilling require the corresponding infrastructure such as new access roads, well pads, and pipelines. For example, Hitaj et al. (2014) note that large-scale drilling activities reduce irrigated acreage 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, to some degree, upstream UOG and agriculture 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 some 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, agricultural production in the United States is highly energy-intensive and lower energy prices, as a result of greater oil and gas supply, can decrease production costs. Energy-related expenses account for more than 50% of the total operating cost for major crops such as corn and wheat (Marshall et al., 2015). Fuels are used directly to operate farm machinery, power irrigation systems, transport inputs/outputs to and from markets, and indirectly in the form of fertilizers and agricultural chemicals. Therefore, lower energy costs can increase production acreage (Pfeiffer and Lin, 2014).

Fourth, 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 acreage (Weber and Key, 2014). On the other hand, capital gains from UOG development may lead to decreased agricultural acreage 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 U.S. 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 effects due to decreased energy-related costs and reinvestment of capital gains outweigh the negative impacts of land displacement for infrastructure, increased competition for inputs and higher opportunity cost of agricultural production, then UOG development can lead to more cropland acreage 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:

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

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*. $\beta_i$ 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, which includes unobservable county-specific time-variant factors such as farmers' risk preferences that should be largely uncorrelated with the independent variables.

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 breakpoint of energy markets, the year 2008[1]:

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

where $\text{Year}_{2008}$ is a dummy variable that equals 1 for years after 2008 and 0 otherwise.

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[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.

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

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

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

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. $\alpha_4$ measures the average difference between crop acreage of counties with and without UOG wells after 2008.

The last specification investigates how crop acreage changes when a county initiates UOG production:

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

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

where $WellDummy_{it}$ equals 1 if the county has at least one active UOG well at time *t* and 0 otherwise. $\alpha_6$ measures the change in county acreage following initiation of UOG production.

In addition to using the full sample data for equations (1)-(5), we estimate equations (1)-(3) using subsamples of UOG-producing counties. For each regression, we use clustered standard errors at the agricultural statistic districts[2], to control for spatial correlation and heteroscedasticity (Stock and Watson, 2008).

## Data and variables

[2] Agricultural statistic districts combine counties with similar crop production environments based on geography, climate, and cropping practices, (USDA NASS, 2018). ASDs with shale play boundaries are presented in Figure 2.

The econometric analysis is based on a balanced panel of annual observations from 2,612 counties in the contiguous U.S. from 1997 to 2018. We consider counties that produced at least one of the eight major crops in at least one year during the analysis period. The dependent variable is the combined county-level planted acreage of eight major crops, including barley, corn, cotton, oats, peanuts, rice, soybeans, and sorghum, obtained from the National Agricultural Statistics Service (NASS).[3] The NASS planted acreage data are constructed using 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 (U.S. Department of Agriculture, 2020).

Control variables are selected based on prior literature. Following Li et al. (2019), we include a one-year lagged Laspeyres price index[4] as a proxy for the expected crop price to minimize endogeneity. 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 for crop $c$ in county $i$ in year $t$; $q_{ci1997}$ denotes the production of crop $c$ in county $i$ in the base year 1997,

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[3] Li et al. (2019) use ten major field crops including barley, corn, cotton, oats, peanuts, rice, rye, soybeans, sorghum and wheat to represent aggregate crop acreage. We use eight crops because county acreages for wheat and rye are not available after 2008 from USDA NASS.

[4] We also considered alternative price indexes, including Passche and Fisher price indexes. Estimation results are consistent across different price index specifications. These results are available from the authors upon request.

and $t \in \{1997, \ldots, 2018\}$.

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 monthly-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 combined number of active unconventional oil and gas wells in a given county. The impacts of unconventional oil or gas well development on agriculture should be similar in terms of land use, labor, and royalty payments. We hence focus on the combined UOG activities in the analysis.[5] The well data are obtained from Enverus. Figure 2 shows the spatial distribution of active UOG wells in 2018. Five hundred and eighty-six counties produced UOG in forty-two states in 2018, up from two hundred and forty-two UOG counties in 1997.[6] Forty counties had more than 1,000 active UOG wells in 2018; Weld County, CO had the most UOG wells with 6,132.

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[5] Using UOG production could be another dimension to examine the impacts of UOG on crop acreages. However, we do not have access to UOG production data at the county level to conduct the analysis.

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

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 samples and subsamples of counties with UOG. Heterogeneities in crop production and UOG development across regions are evident. The average county crop acreage is the highest in Great Plains, followed by Appalachia and Southwest. Sixty percent 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[7]. We average the maximum percentages for each county during the sample period for each region. Overall, counties without UOG wells have greater shares of land in

[7] In Appendix B, we use a restricted sample to estimate the impact of UOG development on crop acreage. In the restricted sample, we drop the largest 20% of agricultural counties in terms of crop acreage that have never had UOG. Figure B1 shows the information corresponding to figure 4 with a restricted sample. The results using the restricted sample are largely consistent with those presented in the paper.

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 the Southwest.

## Estimation results and discussion

We first conduct the full sample analysis to compare the change in crop acreage across counties with and without UOG production[8]. 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), and the average effect of UOG development on county crop acreage in response to initial UOG production (equation 5).

Table 2 reports the estimation results. Model 1 for the contiguous U.S. shows that UOG development on average has a negative effect on the aggregate acreage. An additional active UOG well reduces 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 acreage, while after 2008, an additional active well reduced aggregate crop acreage by 16.1 acres (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 no statistical effect of initial UOG production on crop acreages in the contiguous U.S.

[8] We have also estimated the models separately for oil and gas wells. The results are slightly different from those reported in the paper. These results are available from the authors upon request.

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 do not have UOG resources. The shale play is largely located beneath the Allegheny Plateau with lower productivity soil (Hoy et al., 2018).

None of the regression results for Southwest show a statistically significant relationship between UOG development and crop acreage when all counties are considered (models 11-15). Since oil and gas production in the Southwest has a much longer history than in other regions, UOG-counties in the area may have already developed some of the necessary infrastructures for UOG production. As a result, additional infrastructure needs in this region may have been less substantial than in other regions. Also, the use of the full sample, which includes counties with and without active UOG wells, could dilute the impacts of UOG development on crop acreage, resulting in insignificant coefficients.

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 acreage 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 UOG development in Great Plains has a declining negative marginal effect on crop acreage. Model 18 suggests that the net effect of an additional active UOG well is a 12.4-acre reduction in crop acreages after 2008. In addition, a county with UOG development has 12,731 acres less cropland than a county without UOG development after 2008 (model 19). There is no statistically significant change in crop acreage following initial UOG production (model 20).

Next, we examine the effect of UOG growth on crop acreage using equations (1)-(3) and the subsample of counties that have engaged in upstream UOG production. 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 an additional active UOG well decreases crop acreages in the U.S. on average by 3.3 acres. Model 3 suggests that an additional active UOG well after 2008 reduces crop acreage by 13 acres. Hence, UOG wells have a larger marginal effect on acreage post-2008 than pre-2008. This result is plausible because pre-2008 UOG wells were mostly experimental and exploratory, while the growth of the UOG industry post-2008 required corresponding extension expansion of infrastructure.

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 no statistical differences in the effect of additional UOG well on crop acreages before and after 2008, which is consistent with the full sample result. Again, a possible explanation for the lack of significance may be that most UOG production takes place in counties with little crop acreage in the Appalachian region.

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 decreasing 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 acreage by 46.9 (56.7) acres.

The results indicate that the effects of UOG development on county crop acreages vary by region in terms of signs and magnitudes. 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 acreage decline 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, a 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 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, and/or the negative effect of UOG income on engagement in agricultural production. The acreage trend from 2007 to 2018 in Great Plains (Figure 5) shows that croplands in Great Plains decreased dramatically in 2008 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. 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 the Southwest. Although UOG development may have led to land appreciation, the effect may have been smaller than if the landowner also owned the mineral rights.

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 the 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 price index coefficient is positive as expected but lower than reported in Li et al. (2019), 3.45 (model 1-5, table 2) versus 4.48. 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

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.

Crop planting decisions affect farmers' welfare, commodity 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. We find that overall UOG development has a negative impact on crop acreages in the contiguous U.S. The impact, however, varies considerably across regions. UOG development negatively affects agricultural land use in Appalachian counties where crop production is present. On the other hand, a positive relationship between the number of active UOG wells and crop acreage is found in the Southwest. The negative impact of UOG development on crop acreage in the Great Plains diminishes with an increase in the number of active UOG wells.

Several 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 developments 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 incorporate more disaggregated data, which may provide further insights into how UOG development affects agricultural land use. Third, although we include various control variables in the analysis, we are unable to account for many other factors that also affect crop acreage at the county level. Such variables include, among others, farmers risk preference and demographic factors. So long as these variables are uncorrelated with the key explanatory variables, the coefficient estimates for UOG variables should be consistent. Future studies may wish to consider other variables to more accurately document the change in crop acreages.

Finally, we investigate the impact of UOG development on crop acreage using the number of active UOG wells and do not account for permitted but inactive wells. Permitted but inactive wells include wells that have not yet been drilled as well as wells that have been drilled but have not been fractured. Fracturing is a necessary step that follows initial drilling in UOG production. The number of drilled but unfractured UOG wells has been growing in recent years in the U.S. (Mugabe et al., 2021). Although drilled but unfractured wells are not active in terms of oil and gas production, these wells require land for well pads, access roads and associated infrastructure, including pipelines in preparation for fracturing and production of oil and gas. Permitted but undrilled wells do not yet occupy land the way drilled but unfractured wells do. However, infrastructure preparation, including access roads and pipelines ahead of well drilling, can affect land use. Hence, the inclusion of drilled and undrilled permitted wells may uncover a larger effect of UOG development on agricultural acreage than observed in this study using active wells. Conditional on UOG well permitting data availability, future research should consider the impact of well permitting on land use.

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## Table 1. Summary statistics, 1997-2018

| | UOG and Non-UOG counties combined | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | U.S. ( # of counties=2,612) | | | | Appalachia (# of counties=222) | | | | Southwest (# of counties=390) | | | | Great Plains (# of counties=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 counties=459) | | | | Appalachia (# of counties=63) | | | | Southwest (# of counties=239) | | | | Great Plains (# of counties=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 | | |

Clustered standard errors in parentheses *** $p<0.01$, ** $p<0.05$, * $p<0.1$

## 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 |

Clustered 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 |

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

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

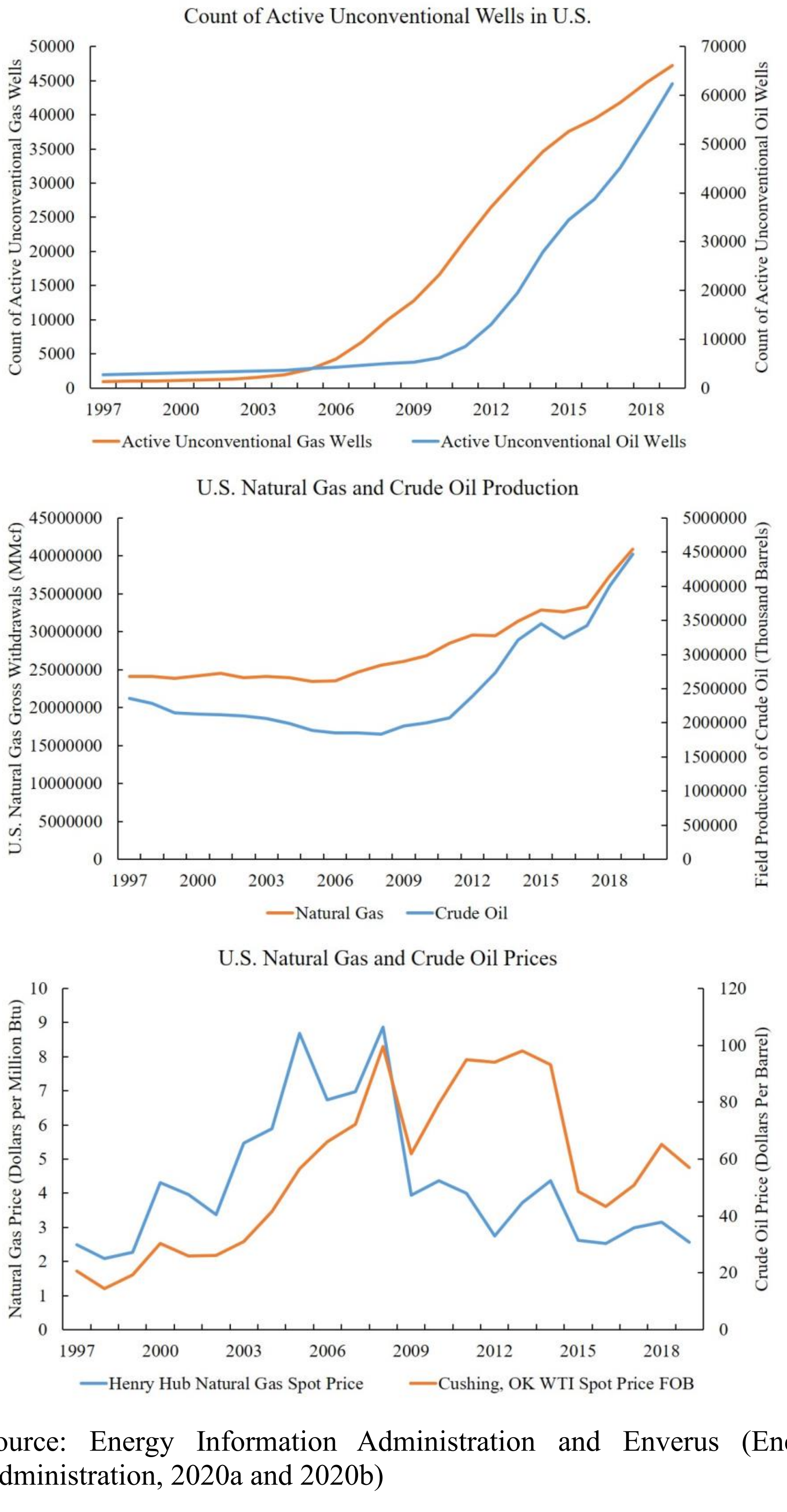
| | Dependent variable = aggregate crop acreage (1000 acres) | | | | | |
|---|---|---|---|---|---|---|
| VARIABLES | (1) | (2) | (3) | (4) | (5) | (6) |
| | | U.S. | | | Appalachia | |
| Lagged Laspeyres price index | 2.9329*** | 2.9237*** | 3.1729*** | 3.7120*** | 3.7346*** | 3.7487*** |
| | (0.9532) | (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 |

Clustered 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 |

Clustered 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)**

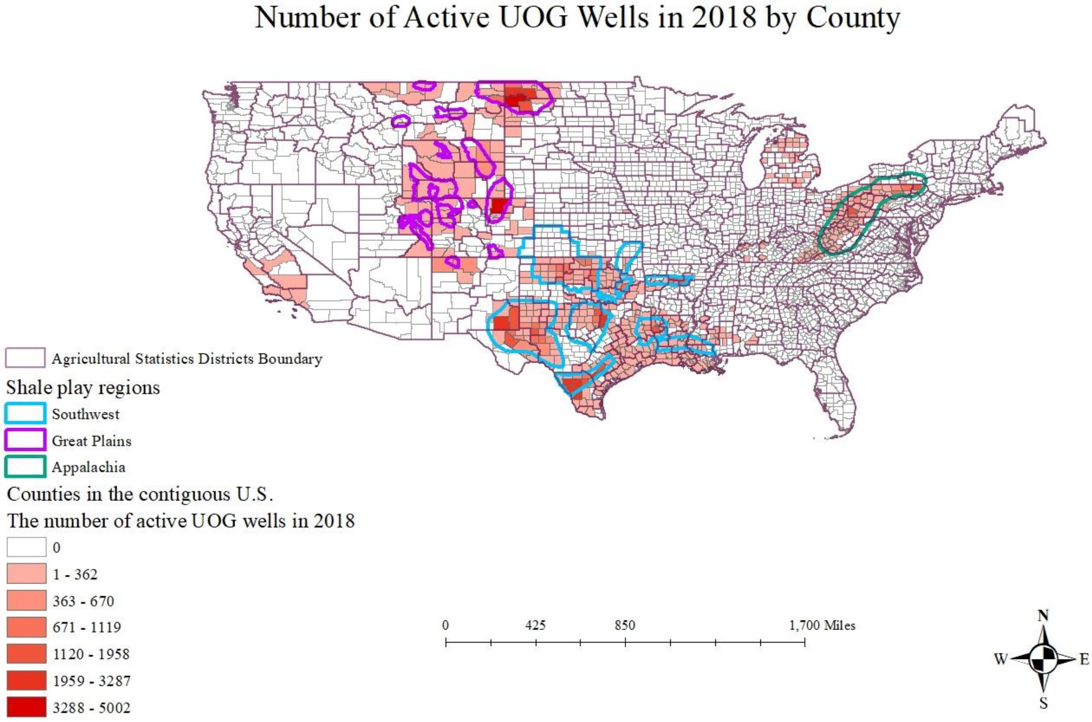



**Figure 2. Counties with active UOG wells in 2018 with agricultural statistics districts and shale play region boundaries**

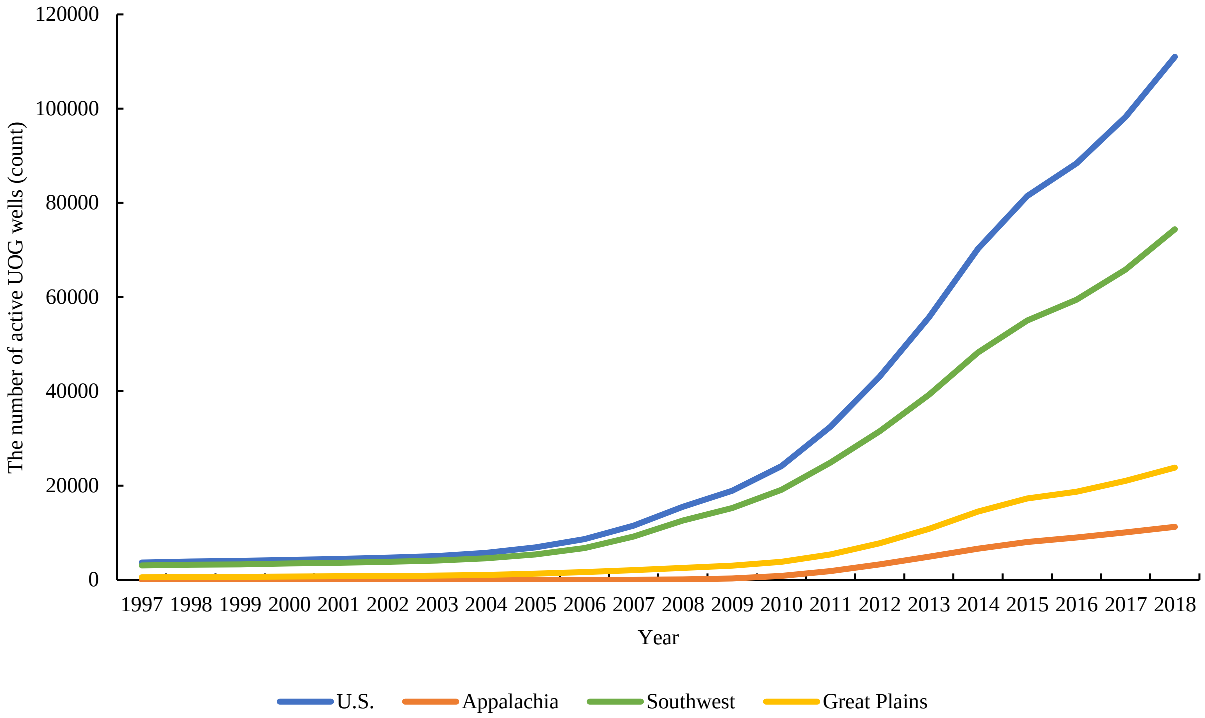



**Figure 3. The number of active UOG wells over time by region, 1997-2018**

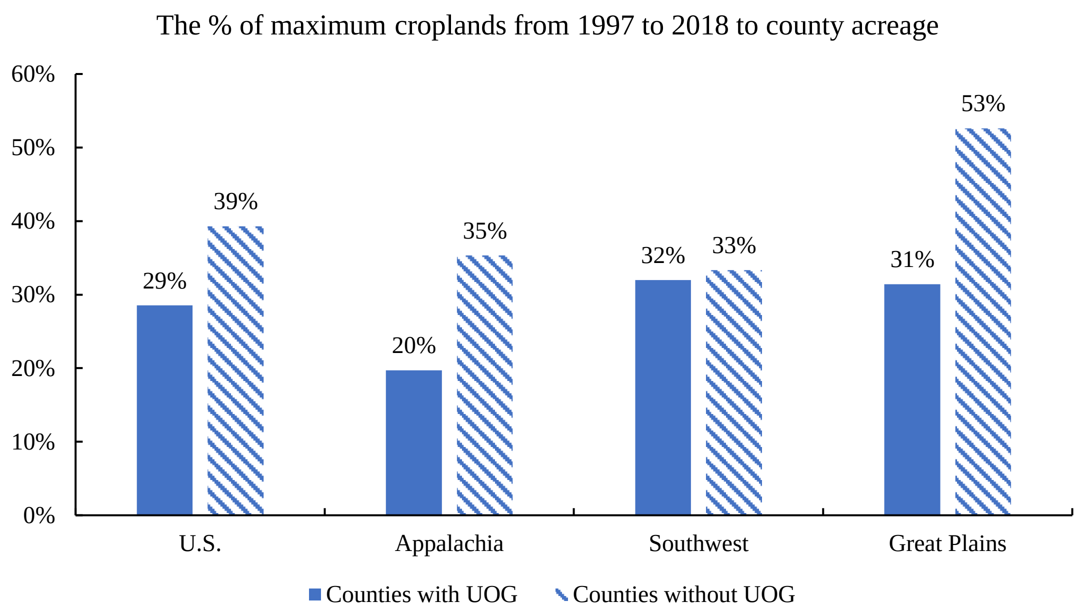



**Figure 4. Maximum observed crop acreage from 1997 to 2018 as a percentage of total county acreage.**

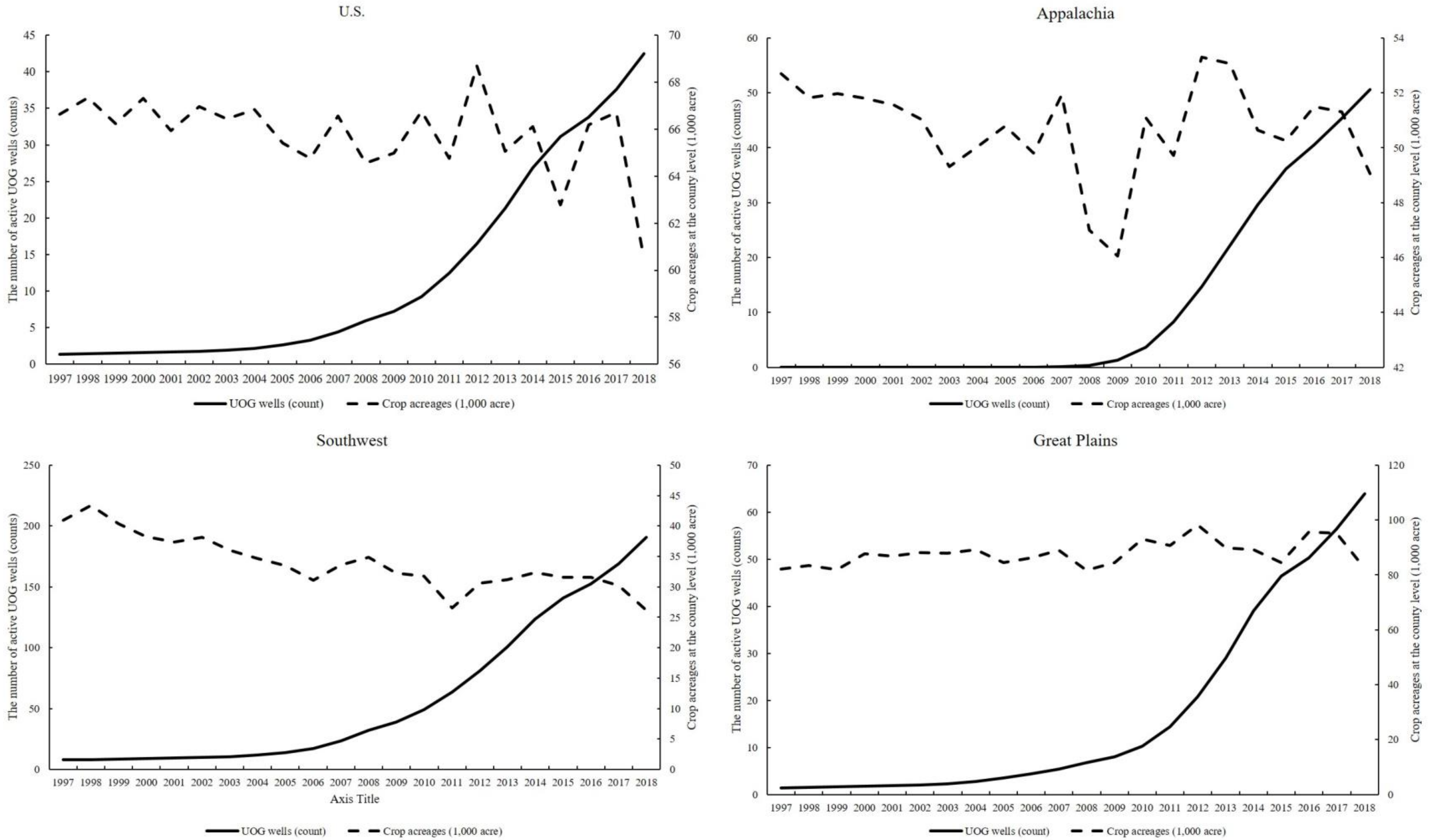



**Figure 5. Average county crop acreage and the number of active UOG wells by region**