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Essays in the economics of energy development and disamenities

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DEDICATION

To my parents, John S. and Doris L. Rakitan, and my brother, John T. Rakitan.

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ABSTRACT

This dissertation consists of three essays broadly themed around evaluating the impact of energy infrastructure on local consumers and industries. Taken together, they characterize ways in which the presence of energy activity is reflected in local land and labor market conditions, with a particular focus on the deployment of wind energy generation and shale resource extraction.

The first chapter examines the relationship between the placement of wind energy infrastructure and house values and incomes in Iowa. The results suggest that income growth offsets some of the negative house-value effects commonly observed in the evaluation literature, but also that income gains reported in the literature are geographically distributed away from wind farm locations. I conclude that proximity to wind turbines does not increase the real incomes of local residents.

The second chapter applies a regional model to county-level wage, house value, employment and energy production data to characterize the economic impact of the U.S. shale boom of the mid-2000s. While the boom has been responsible for wage and employment gains in counties located within the bounds of U.S. shale oil and gas plays, the net effect on house values has been negative. Within the set of energy-producing counties, however, house value declines are mitigated during the boom period as willingness-to-pay for residential space can overcome some of the the negative impacts of energy industry activity. I conclude that shale energy extraction is a disamenity at the local level.

The third chapter extends the analysis of the impact of the shale boom by examining possible spillovers in agriculture. Using parcel-level data from North Dakota, I analyze rental rates to assess the extent to which oil industry activity affects the returns to agricultural land. While “on-shale” parcels lease at lower rates than parcels located outside the oil fields, I cannot reject the hypothesis that proximity to an oil well has no impact on returns to agricultural land. Since my data examine agricultural surface rents with no associated mineral rights, my results imply that fracking-related house value declines reported in the literature may be due to aesthetic and nuisance considerations rather than lasting local environmental damage.

CHAPTER 1. GENERAL INTRODUCTION

In the years between 2000 and 2015, the U.S. energy portfolio has undergone changes at the intensive and extensive margins. Total net power generation expanded by more than 185,000 megawatt hours over 15 years (EIA Monthly Energy Review; see Table A.1), while per-capita energy consumption in the U.S. averaged just over 13 MWh per person since 2010 (World Bank; see Table A.2). At the same time, renewable energy generation gained market share nation-wide from 9.4% in 2000 to 13.3% in 2015 (EIA Monthly Energy Review; see Table A.1), with wind energy and other non-hydro renewables growing from 2.1% to 7.2% of total net generation. Other intensive-margin changes are also apparent: the share of coal among fossil-fuel energy generation has declined over time, falling from 51.7% of energy produced in 2000 to 33.2% in 2015. While the share of energy generated from all fossil-fuel sources has declined by 3.9 percentage points, the share of energy generated from natural gas has grown from 15.8% to 32.7%, nearly on par with coal itself. As the U.S. energy portfolio has changed, new infrastructure has been deployed to generate power and recover fuel feedstocks. Components of this infrastructure, such as wind turbines and oil wells, are increasingly sited near areas of residential and commercial land use (Krupnick et al (2017)). Consequently, the welfare impacts of energy development have received increased attention in the economics literature.

Energy production has benefits and costs at global and local scales. For example, a coal-fired power plant in Iowa might produce electricity that can be sold in a different state while emitting greenhouse gases that contribute to climate change worldwide. At the same time, other air contaminants released by burning coal can create a health hazard in the immediate vicinity of the plant. With proper accounting of the net benefit of energy technologies, policy measures can be designed to maximize usable power while minimizing damages. In this dissertation, I contribute to our understanding of the net benefits of the changing U.S. energy portfolio by examining the local impacts of two of its components: the increase in wind energy generation capacity and the shale energy boom of the mid-2000s. Although these subjects have received treatment in the environmental and energy economics literature, I contribute to the stock of knowledge by examining incomes and land values together at consistent scales. By considering the effect of energy investment on both outcomes, I can more completely characterize the net benefit of energy investment in one analysis.

The first study, presented in Chapter 2, examines how large-scale wind farms affect area house value and wages using data from Iowa. Wind energy infrastructure is often associated with decreases in nearby property values and increases in local incomes. However, house value changes are often observed within viewing distances, while income changes have been measured at the county level. This raises the question of how the external net benefits of wind infrastructure are distributed over space. Additionally, because the direct and indirect effects of wind energy installations affect both incomes and house values concurrently, it is possible that there is a bias in benefit or cost estimates derived from either of these outcomes alone. Using restricted-access income tax return data from the Iowa Department of Revenue and address-level house value information, I estimate the impact of wind farms on both incomes and property values within 5 miles of the installation. I find that households in proximity with wind farms experience lower income and house value growth than households located farther away. Also, a wind farm's size is negatively related to house values and incomes. My results imply that the income gains reported in the prior literature are distributed far away from individual wind farms and that rural populations may consider larger wind farms as disamenities.

Chapter 3 presents the second study, which considers the land and labor market effects of the U.S. shale boom of the mid-2000s. The boom traded off possible environmental damage and negative quality-of-life impacts against income gains and rents captured by workers and property owners. Improved oil and gas recovery technology yielded a labor demand shock that raised wages, but might also have affected regional housing prices though impacts on environmental variables and worker inflow. If the labor shock is strong enough, housing prices will rise as more workers move closer to higher wages. If the environmental disamenity impacts are strong enough, housing prices will fall. Using the timing of the boom and variation in extraction rates as a treatment across 2,141 counties from 2000 to 2010, I find that boom-period oil and gas activity is associated with wage and employment increases of 3.9% and

4.4% respectively, while house values decrease by 1.5%. This suggests that the potential negatives of oil drilling dominate the benefit from the labor shock. My results imply a willingness to pay of between $160 and $425 for a 1% reduction in total energy produced in-county.

Chapter 4 presents a study examining the relationship between agricultural and the shale boom. While the economic literature has documented negative housing market impacts of the U.S. shale boom of the mid-2000s, the oil and gas industry's effect on agriculture have received less attention. On the one hand, oil and gas lease payments create wealth and supplement farm incomes; on the other hand, not all farm households own the rights to nearby minerals. Additionally, shale energy activity can bid up the prices of local agricultural inputs such as labor and transportation, and the threat of environmental damage may cause agricultural land to lose value. Using parcel-level data for North Dakota public lands, I estimate the changes in rental rates associated with the presence of shale energy activity. I find that leases for parcels within the Bakken shale generate lower returns than parcels outside the Bakken, but the presence of oil and gas wells does not produce a significant effect. My results suggest that the expected long-term consequences of the shale boom are relatively minor. In light of this finding, it is possible that the negative house-value impacts documented in previous studies come from the nuisance of shale well drilling rather than from long-term environmental consequences.

In the context of the U.S. energy portfolio, Chapters 3 and 4 contribute directly to the subset of the literature valuing the economic impacts of the shale boom that has produced large quantities of domestic oil and gas, while Chapter 2 contributes to the literature surrounding the challenges of deploying renewable energy technology. The concluding remarks of Chapter 5 include reflection upon the limitations of the studies in this dissertation and charts the course of future research.

References

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Chapter 1 Tables

Table 1.1: Changes in U.S. net electricity generation, 2000-2015

	2000	2015	Change
Total net generation (thousand MWh)	3,892.20	4,077.60	185.405
Renewables shares (%)			
Wind share	0.1%	4.7%	4.6
Non-hydro share	2.1%	7.2%	5.1
All renewables	9.4%	13.3%	3.9
Fossil fuel shares (%)			
Coal	51.7%	33.2%	-18.5
Natural gas	15.8%	32.7%	16.9
All fossil fuels	70.8%	66.9%	-3.9

Source: author's calculations with data from May 2017 EIA Monthly Energy Review, Table 7.2a.

Table 1.2: Per-capita U.S. electricity consumption

Year	kWh per capita	5-yr moving average
2000	13,671.05	-
2001	13,046.61	-
2002	13,296.18	-
2003	13,307.49	-
2004	13,388.59	13,341.99
2005	13,704.58	13,348.69
2006	13,583.27	13,456.02
2007	13,657.45	13,528.28
2008	13,663.43	13,599.46
2009	12,913.72	13,504.49
2010	13,394.05	13,442.38
2011	13,240.13	13,373.75
2012	12,954.90	13,233.24
2013	12,988.92	13,098.34
2014	12,972.73	13,110.15

Source: World Bank Data Tables (available online at http://data.worldbank.org/)

CHAPTER 2. ASSESSING THE EXTERNAL NET BENEFITS OF WIND ENERGY: THE CASE OF IOWA'S WIND FARMS

A modified version of this paper to be submitted to peer-reviewed journals

Timothy J. Rakitan

2.1 - Introduction

The placement of energy infrastructure has the potential to impact the well-being of nearby residents, which may partially offset the broader benefits of an expanding energy portfolio. In the economic literature, studies have considered the presence of oil and gas wells (e.g. Boxall, et al (2005); Gopalakrishnan and Klaiber (2012); Muehlenbachs, et al (2015)); natural gas pipelines (e.g. Hansen, et al (2006); Kask and Maani (1992)); and high-voltage transmission lines (e.g. Hamilton and Schwann (1995), Sims and Dent (2005)). These studies find evidence that house prices capitalize negative net welfare impacts from proximity to energy infrastructure.

Recently, hedonic and impact-evaluation methods have been applied to the case of wind energy generation installations, also called "wind farms." While several hedonic and contingent-valuation studies find zero or negative property value capitalization of wind farms' presence (e.g. Gibbons (2015), Hoen, et al (2010), Lutzeyer, et al (2016), Vyn and McCullough (2012)), other studies using input-output models find that construction of large-scale wind projects has positive effects on gross local product (e.g. Lantz and Tegen (2009), Slattery, et al (2011), Tegen, et al (2012)). Other studies using more traditional econometric approaches find that wind energy installation placement is associated with increases in per capita income and county-level employment (Brown, et al (2012), Weber, et al (2013)), as well as increases in tax bases and government revenue (De Silva, et al (2015), Kahn (2013)).

Taken together, this set of results—that rents often capitalize welfare losses while incomes and employment seem to rise in the presence of wind energy installations—prompts the question of whether the local external net benefits of wind energy infrastructure are positive or negative.[1] The federal government (along with the governments of 45 states and the District of Columbia) has funded various incentives for wind energy development, including subsidies in the form of wind energy production tax credits (Girardi (2014)). This makes the finding of decreased house values more puzzling, since that theory predicts that land rents should capitalize gains from subsidies. Novan (2015) points out that these subsidies may not be properly calculated in the first place, since they do not account for the costs of variability in wind energy generation. In particular, subsidies for wind energy generation may be too high; if the net local welfare impact is both negative and large, the inefficiency is greater still. To this end, I estimate the impact of large-scale wind farms on house values and income. I take a reduced-form, difference-in-differences approach using address-level data from Iowa. The high resolution of these data allows me to characterize the impact of wind energy infrastructure locally without having to rely on county aggregates. I test the hypothesis that wind farm placement affects both incomes and house values, comparing these outcomes for "treated" households located near wind farms with those from "control" households located farther away. The quasi-experimental research design "differences out" non-time-varying group effects, and both groups are composed of panels of households observed in 2002, 2008 and 2012.

To date, income studies have largely relied on aggregated data, while hedonic house price studies use data at the household level. By contrast, I observe both measures at the household level, which allows me to estimate both impacts at a consistent geographic scale. The data come from separate sources; house values were obtained from county assessors throughout Iowa, while income observations were derived from restricted-access income tax data used on-site at the Iowa Department of Revenue (IDR).[2] Variation in "exposure" to wind farms is both temporal and spatial; I control for wind farm age as well as generation capacity and turbine count.

[1] In this context, "external net benefits" refers to the overall welfare change experienced by those not party to a transaction. The term encompasses both spillovers and externalities.

[2] Iowa's state tax collection bureau.

I find no evidence that wind farm exposure significantly changes real income in rural Iowa. This result differs from the results documented in other studies. This is possibly due to my selection of geographic scale and to the high resolution of the income and house value data. By estimating house value and income impacts at consistent geographic scales, I provide a more complete characterization of the local net benefit of wind power. Additionally, the difference-in-differences study design allows me to difference out locational fixed factors that can confound an analysis conducted at the county level. Since I observe income directly, I also obtain an estimate that reflects the net effect of royalty payments and any gains in labor productivity due to wind energy infrastructure. A conservative interpretation of the study's results is that there are no substantial spillovers from wind farm placement in rural areas. As a matter of policy, this suggests that regions with low population densities are best suited to host wind farms, all else equal.

The remainder of the paper is organized as follows: the next section discusses selected literature and details the institutional and technological background of Iowa's wind energy landscape; Section 2.3 presents the economic theory underlying the study and the econometric methodology; Section 2.4 discusses data; Section 2.5 presents the results and Section 2.6 concludes.

2.2 - Literature

Since the mid-2000s, the state of Iowa has maintained the second-highest statewide wind energy generation capacity, and as of 2012 maintained the largest wind energy capacity share of any state in the U.S. at 30% (EIA 2012).[3] Iowa has more than 95 separate wind energy installations, with statewide nameplate generation capacity[4] of over 6.1 gigawatts. Most often turbines are sited on farmland or other exposed, relatively flat terrain with few buildings or trees to disrupt airflow. On average, the turbines in

[3] At the time of writing, this fact is still true; wind power in Iowa boasted at 33% share of statewide generation capacity in 2016 and 2017 (U.S. EIA, "State Energy Profiles: Iowa." Available at https://www.eia.gov/state/print.php?sid=IA).

[4] "Nameplate capacity" refers to the theoretical maximum power output of a turbine generator under an ideal set of conditions.

most of Iowa's wind farms are spread over 11,700 acres (about 18 square miles) per wind farm. This equates to approximately 103 acres per megawatt of nameplate capacity.[5] Areas of concentration are throughout the western half of the state, as well as along the northern tier. The spatial distribution of wind farms generally follows the geographic distribution of Iowa's greatest wind resource potential, visible in Figure 2.1. Average wind speeds at an altitude of 80 meters throughout Iowa's northwest fall between 7.5 and 9 meters per second.

The years between 2000 and 2014 saw a proliferation of wind farms throughout the state. Figure 2.2 describes statewide cumulative installed capacity starting in 1992. The large year-over-year capacity increases beginning in 2008 are clearly visible, with statewide capacity growing at approximately 125 megawatts per year from 2000 to 2007, accelerating to 650 megawatts per year between 2007 and 2013. During this time period, the state of Iowa also maintained two fully-transferable renewable energy production tax credits.[6] However, an analysis by the Iowa Department of Revenue finds that the policy has generated revenues for the state that partially offset its costs. Girardi (2014) estimates a projected property tax gain to the state of Iowa of approximately $958,000 between 2014 and 2015 due to these policies.

The property tax gains experienced by the state of Iowa are related directly to the land upon which wind farms are sited. Studies in the academic literature substantiate the positive contributions of wind farms to public coffers. For example, De Silva, et al (2016) find a 0.02% drop in property tax rates and a 0.014% increase in per-student school district revenues associated with a 1% increase in wind

[5] As a point of reference, Denholm, et al (2009) find that U.S. wind energy installations usually require between 30 and 140 acres per megawatt of capacity.

[6] In 2005, the state of Iowa adopted two tax credits to subsidize renewable energy production in the state, aimed predominantly at large wind energy installations. Iowa's Wind Energy Production Tax Credit (WEP) is available as a non-refundable tax credit for eligible projects completed between July 1 2005 and July 1 2012 and paid in continuity for 10 years from the date of installation, while the Renewable Energy Tax Credit (RE) is available for wind farms brought on line beginning July 1, 2005 (Iowa Public Utilities Board). As of the 2013 tax year, the claimed WEP and RE tax credits totaled approximately $5.2 million. Credits are fully transferrable for state tax return purposes; the State of Iowa has ascertained that credits often trade below their face value (Girardi (2014)). Despite the potentially large dollar value of these payouts, only 1.3% to 3% of Iowa's total wind energy production was awarded the tax credit. As such, it does not appear that state-level incentives greatly altered Iowa's utility-scale wind energy development.

power capacity, while Kahn (2013) finds public schools in districts funded by green energy revenues spend approximately $1,300 more per student than comparable counties with no wind farms. Both studies use data from the Texas Panhandle region.

Other benefits documented in the literature include employment and wage gains in areas with greater wind penetration. In their Texas study, De Silva, et al (2016) estimate the per-capita income gains from an additional megawatt per capita of wind power capacity to be approximately $2,600, along with positive (but statistically insignificant) county-level employment increases in selected industries. Brown, et al (2012) also find evidence of per-capita income benefits, using county-average wind speed as an instrument for county-level wind power capacity. They estimate a benefit to per-capita income of $11,000 for each additional megawatt of capacity per capita, as well as employment gains of 0.5 jobs for each additional megawatt per capita. In addition, energy royalty payments and land rents can contribute to non-wage income growth in areas with large energy resources. Weber, et al (2013) document concentrated rural wealth creation from energy royalties paid to farm households. Their analysis includes mineral royalties from oil and gas rights ownership as well as energy rents paid to wind farm households; they note that rents are concentrated among relatively few landowners.

Wind farms can also generate negative local impacts. Public opposition to a large proposed wind farm in the waters of Cape Cod was driven in part by objections to the disruption of scenery (Eileen McNamara, "What really toppled Cape Wind's plans for Nantucket Sound," *Boston Globe*, Jan 30th, 2015). Wind farms have also been responsible for migratory bird kills and disruption of local ecosystems (Barclay, et al (2007)). Additionally, long-term exposure to low-frequency sounds attributed to wind turbine operation has been claimed to cause "wind turbine syndrome," a condition associated with developmental difficulties in children and mental anguish in adults (Pierpont (2006); Farboud, et al (2013)), although there are competing hypotheses regarding the underlying basis for these conditions (Rubin, et al (2014)). Less-severe annoyances may include interruptions to wireless communication technologies, including radio, television and cellular signals (Ángulo, et al (2013)). Despite these claims, the environmental economics literature contains mixed evidence of adverse impacts on consumers. Vyn and McCoullogh (2014), Hoen (2006), Hoen (2010) and Hoen, et al. (2014) have found no statistically or economically significant differences in residential house prices in the vicinity of wind power generation facilities in the U.S. and Canada. On the other hand, some evidence indicates that the negative impact of wind infrastructure may be more closely associated with visibility than health risk. Gibbons (2015), for example, finds evidence of a 4% drop in house values in the U.K. associated with proximity and visibility of wind turbines. Dröes and Koster (2014) find similar results, observing a 1.4% to 2.3% decreases in hedonic sales value for houses sited within 2 kilometers of a wind turbine in Denmark. Heitzelman and Tuttle (2012) also find a negative effect, and Jensen, et al (2014) are able to attribute a 3% residential house price drop to wind farms' visual disamenity, while "soundshed" disruption accounts for a property value decrease between 3% and 7%.

Other recent literature has used stated-preference methods to understand local sentiment about existing wind farms rather than using hedonic methods to characterize a willingness-to-pay to avoid the negative effects or gain access to amenities. In one such paper, Lutzeyer, et al (2016) utilize a choice experiment to gauge willingness-to-pay for off-shore wind energy in vacation-rental viewsheds, finding evidence that recreational renters would never pay more for a beach view interrupted by wind turbines. Walker, et al. (2014) point out that hedonic methods, which rely on observed sales of a fixed asset (e.g. a house, a plot of agricultural land), tend to over-sample high-population-density areas relative to low-population-density areas–however, the spacing requirements of wind energy production, along with other subjects the hedonic literature, often translates to turbines being located in low-density areas with large areas of available land. Walker, et al. (2014) turn instead to surveys and interviews to assess local perceptions about the property-value changes wrought by wind farms in two communities on Lake Erie in Ontario, Canada, finding that local residents perceive a loss in property value regardless of the available data. Similarly, Firestone, et al (2015) use a survey instrument to evaluate perceptions about the amenities and disamenities of a single turbine installed along the Delaware coast. They find the opposite result, however, reporting that locals evince positive attitudes toward the turbine's placement.

2.3 – Theory and Empirical Strategy

As described above, literature to date has documented that house values capitalize disamenities from wind energy while local wages and employment rise in counties with greater wind energy deployment. However, it remains unknown whether there exists a measurable real wage change associated with wind farm proximity; furthermore, if such a differential does exist, does it affect all households within a county or only households exposed to the disamenities of wind farms? If wind energy installations comprise a disamenity, the resulting negative land demand shock will drive down local real estate values, causing the value of houses near wind installations to appreciate more slowly than those of non-exposed houses. If the effect is large enough to prompt significant attrition from the local labor market, wages will rise. Alternatively, if wind energy constitutes a positive productivity shock, incomes of exposed households should rise faster than those of non-exposed households.

To capture this formally, I assume a spatial equilibrium where wages and rents adjust to local characteristics, following Roback's (1982) method. Locational fixed factors—including wind energy infrastructure—affect the utility of nearby households, and workers' choices of where to live bids rents and wages up or down accordingly. Workers are assumed to be freely mobile between regions and face competitive labor markets. Labor is supplied inelastically and paid a wage w. Workers live in households indexed by h. Each household maximizes utility U by consuming a numeraire x at a price of 1 and renting land K at price r subject to the budget constraint $w \geq x + rK$. The above implies that indirect utility will depend on both wages and rents.

Additionally, I assume utility depends on local characteristics, including exposure to wind farms. Households control their exposure to local characteristics by their choice of where to live. Given a change to location-specific factors, workers can move between regions to maximize indirect utility—workers bid up rents in more desirable regions while wages change to reflect local productivity and labor supply. Hence, wages and rents will be functions of local characteristics.

Figure 2.3 illustrates this mechanism in action. Consider two regions indexed by the variable ω that are identical but for wind farm exposure. Region $\omega = 0$ lacks a wind farm, while region $\omega = 1$ has one. Worker mobility implies that indirect utilities will equalize across markets, i.e. $V(w, r, 0) = V(w, r, 1) = \bar{V}$. If wind farms are a nuisance, utility in region 1 will be lower at all values of r and w than utility in region 0, i.e. $V(w, r, 1)$ will lie strictly to the southeast of $V(w, r, 0)$. Equilibrium occurs where $V(w, r, \omega)$ intersects the unit iso-cost line corresponding to numeraire production, given by $C(w, r) = 1$ in wage-rent space. Although utility is identical between regions, rents decline and wages rise in region 1 relative to region 0, implying an expanded budget set for region 0 consumers. That is, if wind farms are a disamenity, real incomes must rise to compensate workers located nearby them.

I operationalize the analysis above by examining the cross-sectional growth in wage and rent measures as functions of the wind farm exposure variable ω. Let y be the outcome of interest (either wages or rents) and define time period $t = 0$ as the time period during which no houses were exposed to wind farms and $t = 1$ as the time period in which $\omega = 1$ for some but not all households. The real income differential can be estimated by comparing the cross-sectional rates of growth of wages and rents.

The outcome of interest (i.e. incomes or house values) will be a function of local characteristics at time t as well as household characteristics. This suggests the reduced-form relation

$$\ln(y_{hct}) = \beta \cdot \omega_{ht} + \gamma \cdot z_h \cdot \omega_{ht} + \mu_h + \theta_{ct} + \epsilon_{hct} \quad (2.1)$$

where ω_{ht} is the wind farm exposure dummy, z_h is a measure of the intensity of house h's exposure to a wind farm, μ_h is a household fixed effect, θ_{ct} is a county-year effect and ϵ_{hct} is a normally-distributed iid error term. The error is assumed to be uncorrelated with county or household attributes. At $t=0$, $\omega_{ht}=0$, while $\omega_{ht}=1$ for some households at $t=1$. The logarithmic treatment of y follows Roback's (1982) formulation and allows the right-hand side coefficients to be interpreted in percent terms.

The house fixed-effect captures both house characteristics and characteristics of household occupants (such as human capital). Necessarily, wage and rent growth will be correlated with these characteristics, as well as with county-specific and time-specific factors. If these factors are unobserved, they will bias estimates These can be accounted for in first-differences. Following the time period definitions above, $\omega_{h(t=0)}=0$ for all households, implying

$$\ln(y_{hc(t=0)}) = \mu_h + \theta_{c(t=0)} + \epsilon_{hc(t=0)} \tag{2.2}$$

Similarly, the outcome at $t=1$ can be written

$$\ln(y_{hc(t=1)}) = \beta \cdot \omega_{h(t=1)} + \gamma \cdot z_h \cdot \omega_{h(t=1)} + \mu_h + \theta_{c(t=1)} + \epsilon_{hc(t=1)} \tag{2.3}$$

Differencing between time periods yields the expression

$$\begin{aligned} \ln(y_{hc(t=1)}) - \ln(y_{hc(t=0)}) &= \beta \cdot \omega_{h(t=1)} + \gamma \cdot z_h \cdot \omega_{h(t=1)} \\ &\quad + \mu_h + \theta_{c(t=1)} + \epsilon_{hc(t=1)} - (\mu_h + \theta_{c(t=0)} + \epsilon_{hc(t=0)}) \end{aligned} \tag{2.4}$$

Collecting terms yields the growth equation

$$\begin{aligned} \Delta_t \ln(y_{hc}) &\equiv \ln(y_{hc(t=1)}) - \ln(y_{hc(t=0)}) \\ &= \beta \cdot \omega_{h(t=1)} + \gamma \cdot z_h \cdot \omega_{h(t=1)} + \zeta_c + \nu_{hct} \end{aligned} \tag{2.5}$$

where $\zeta_c = (\theta_{c(t=1)} - \theta_{c(t=0)})$ and $\nu_{hct} = (\mu_h - \mu_h) + (\epsilon_{hc(t=1)} - \epsilon_{hc(t=0)})$. The specification in (2.5) differences out the household effect μ_h, while a county control ζ_c accounts for the influence of local characteristics that can affect regional growth.

The wind farm exposure parameters β and γ are identified if wind farm placement is uncorrelated with the error term $\epsilon_{hc(t=1)} - \epsilon_{hc(t=0)}$. That is, if unobserved shocks to household h's wage or rent growth also affect the probability of the existence of a wind farm of size z_h, then estimates of β and γ will be biased. However, this would also require that such shocks be uncorrelated with the county growth effect ζ_c as well as with the household effect μ_h, which has been differenced out in computing the growth rate of Equation (2.5).

To estimate Equation (2.5) econometrically, I specify:

$$\Delta_t \ln(y_{hc}) = \beta \cdot Treatment_h + \gamma \cdot Treatment_h \cdot Intenisty_h + \zeta_c \cdot County_{hc} + \epsilon_{hc} \qquad (2.6)$$

where y is income or house value; $Treatment_h$ is a dummy equal to 1 if house h is within 5 miles of a wind turbine, ζ_c is a fixed-effect that is nonzero if household h is in county c, and ϵ_h is the error term. Estimating the first-difference of house values and incomes “differences out” household-level fixed effects. The county fixed-effect ζ_c accounts for county-level factors that can affect the growth in wages or property values. The $Intensity_h$ measure decomposes the treatment effect across the household’s years of exposure to a wind farm ($Duration_h$), distance away from a wind farm ($Distance_h$), wind farm capacity in units of 100 MW ($Capacity_h$) and total turbines in the wind farm (in 100-count units) ($Turbines_h$). The coefficients have the interpretation of changes in the rate of growth of house values and incomes. If wind farm exposure is a disamenity, then increasing exposure intensity should be associated with lower house values and higher incomes.[7]

[7] Note that, in the case of distance, larger distances constitute lower intensity—therefore, if wind farm exposure is a disamenity, the expected sign of distance is positive.

The econometric specification in Equation (2.6) has the form of a difference-in-differences estimation. Differencing the outcome of interest between time-periods provides the first difference, accounting for house-level fixed effects, while wind farm exposure constitutes the second difference. By removing the influence of non-time-varying household-specific effects and controlling for county-specific time-varying factors, I minimize the potential for bias in the estimate of the effect of wind farm placement.

2.4 – Data

Wind turbine data come from the U.S. Geological Survey Data Series 817 (Diffendorfer, et al 2014). The dataset contains geo-coded location and attribute information for individual wind towers throughout the United States, including date of installation, generation capacity per turbine and total number of turbine towers within a given wind farm. Utility-scale wind farms in Iowa typically have 40 to 100 individual turbines, with a mean turbine count of 69.71. Average capacity per turbine has also increased over the years; the largest installation in Iowa as of 2012 was constructed in 1999 and contains 257 individual towers, although each one is only rated at 0.75 MW capacity. On the other hand, the wind farm having the greatest capacity (443.9 MW) was built in 2011 and has 193 individual turbines. Mean generation capacity for wind farms in Iowa is 112.55 megawatts. Iowa's wind farms are concentrated in the western and north portions of the state; Figure 2.4 shows this distribution visually, displaying county-level total turbine counts as of 2014.

The physical locations of houses used in the study were taken from the websites of assessors' offices in turbine-hosting counties. Using the wind turbine location data to determine turbine positions, houses were selected using area-frame sampling based on proximity to turbines and observed similarities of the parcels on which they were located. This initial dataset was refined to include addresses with dwellings. Houses with unclear location information were geo-located using ArcGIS software. The resulting dataset was used to determine exposure to wind energy by address. Once measures of wind farm size were associated with each house, the data were merged with value and income data by physical address. The control-group addresses were determined by locations with wind and topography characteristics comparable to wind farm locations but without a nearby wind farm. Once the addresses were associated with wind farms and their attributes, the data were matched against income and house value records.

Income data come from records maintained by the Iowa Department of Revenue (IDR), the state's tax-collection bureau. These data are not publicly available, and the income analysis was conducted on-site at IDR. The records capture information from all Iowa state income tax returns filed electronically ("e-file"), as well as limited data captured from all paper returns filed in a timely fashion,[8] beginning in 2002.[9] Income data is aggregated to the household level and reflects the earnings of non-dependent taxpayers filing on the same tax return at the same address.[10] I observe household Adjusted Gross Income (AGI) for all households in the dataset, although I do not observe the particular sources of income by household, i.e. I cannot distinguish between wage and non-wage income. As a result, some of the income changes I observe may be due to changing returns on capital owned by the household, possibly including land leased to agriculture or energy. Control group sampling and the difference in differences approach mitigate these issues somewhat. Observations excluded from the final dataset include taxpayers

[8] Here, "timely" refers to January of the year following the year for which the return is filed. For example, a paper return for tax year 2007 filed by January of 2009 would be captured in IDR's files.

[9] Electronically filed tax returns have accounted for an increasing share of all returns filed in Iowa; internal data from IDR indicate an e-file share of 62.2% in 2004, increasing to 86.6% in 2011.

[10] The income of children or other residents who do not file as independent taxpayers is not considered.

with out-of-sate home addresses and those who did not file tax returns for tax years 2002, 2008 and 2012.

House values were obtained directly from county assessors' offices. House values are composed of the total assessed value of the land, dwelling and any improvements to buildings on a given parcel. Data in the sample reflect residential parcels containing single-family residences or rural dwellings. Assessed values have two distinct advantages over transaction-based observations: first, they provide a complete time series of values for individual properties regardless of whether the property is sold; and second, they are not subject to thin and selected samples. The local effects of nearby sales influence the assessor's valuation of non-transacted properties, meaning that the information contained in the price of transacted houses should be reflected in the assessor's valuation.[11]

One caveat is necessary: while most Iowa counties use electronic databases to record property values, many only began keeping electronic records after 2005. Additionally, many assessors who began maintaining electronic records in years after 2002 do not have complete records for years prior to the start of the electronic recordkeeping. Additionally, not all tax filers report a physical home address. As a result, the full sets of income observations and house value observations do not perfectly overlap. I estimate Equation (2.6) separately for each data set rather than condition on a household belonging to both datasets. From each dataset I obtain a panel of observations, i.e. households that appear in 2002, 2008 and 2012.

[11] Ma and Swinton (2012) examine the differences in amenity valuations from transaction prices and assessed-value data, concluding that assessed values do not accurately capture marginal willingness-to-pay for natural amenities, especially in a dynamic context. While this is potentially a concern in the case of wind energy infrastructure, I necessarily assume that the presence of wind energy has no interaction with the valuation of any other local amenities. Expansions of this research will use transaction-level data to examine to what extent this is the case.

Tables 2.1 and 2.2 report summary statistics stratified by geography. Control households are located more than five miles from any wind farm in the data set, while “Treated by 2012” households are located within five miles of a wind farm that began operation between 2002 and 2012, including the endpoint years. Table 2.1 reports statistics for the income dataset,[12] including household distance away from the nearest wind turbine regardless of treatment group status, contemporaneous years of exposure and treatment-intensity measures of capacity and turbine count. Table 2.2 reports statistics for house values and includes the same covariates.[13]

In 2002, incomes and house values in the control group are lower than households in the treatment group. However, control incomes grow quickly, ending higher than the treated group in 2012. The realized covariate measures differ somewhat between both data sets, but the summary statistics are similar. On average, “Treated by 2012” households in the income dataset are exposed to older wind farms of higher capacity and lower turbine counts than their counterparts in the house value dataset.

2.5 – Results

Tables 2.3 and 2.4 present the results of estimating the log-differenced specifications. All the estimations follow Equation (2.6) and include county fixed effects (ζ_c). The average treatment effect β is presented in column 1, while subsequent columns examine the effect of the treatment-intensity parameter γ. Superscripts denote the outcome of interest as wages (incomes) and rents (house values). The presence of wind farms does not significantly affect incomes or house values, although the signs of the treatment intensity coefficients (γ) suggest negative

[12] Percentile cutoffs are censored in Table 2.1 to preserve the confidentiality of income data.

[13] The samples were matched separately, which accounts for differences in covariate measurements.

impacts. *Distance* is an exception—it is negative for house values and positive for income. Though the estimate is not significantly different from zero, the pattern of signs is consistent with higher house values and lower incomes at close distances to a wind farm.

In addition, the joint effect of exposure and intensity (i.e. $\hat{\beta} + \widehat{\gamma_s} \cdot \bar{s}$, where $\bar{s}$ is the average intensity, $s \in \{Distance, Duration, Capacity, Turbines\}$) is also negative for incomes and house values. F-tests of the joint significance of β and γ_s cannot reject the null of no effect in Tables 2.3 and 2.4, although some of the specifications in Appendix B do yield joint significance. Changing the treatment radius does little for the significance of the income results. In contrast to the previous literature, house value effects remain insignificant across the differing radii.[14]

The general lack of significance is confirmed in the alternative specifications presented in Appendix B. While some of the coefficients in Tables B.1 and B.2 are significant, their signs are not intuitive (e.g. in model 8 in Tables B.1 and B.2, the turbine count coefficients are positive and significant while the capacity coefficients are negative and significant). Varying the start and end dates generally does not affect the significance of the intensity coefficient estimates. However, an additional mile of distance away from a wind farm between 2002 and 2008 is associated with a 1.6% increase in incomes (Table B.3). Additionally, the average effect on rents (β^r) is 0.065 and significant at the 5% level between 2004 and 2012 (Table B.6). Also in Table B.6, the marginal effect of an additional mile away from a wind farm is negative and

[14] Estimates with different treatment group radii are not reported. However, the marginal effects of capacity and turbine count become positive and significant for houses within 1 mile of a wind farm. While it is possible that larger wind farms bid up local rents through the capitalization of energy royalties, the lack of significant income effects suggests over the same area suggests that this could be due to sampling variation.

significant, counterintuitively suggesting that proximity to a wind farm is associated with increased house values.

In the context of the theory outlined in Section 3, this implies that wind farms do not comprise a disamenity for households within five miles of the wind farm.[15] That is, if the disamenity effect is significant, then either rents must fall or wages must rise, as depicted in Figure 2.3. As an alternative, the same theory predicts that gains to local productivity due to wind farm placement will shift the iso-cost curve to the right in Figure 2.3, leading to increased wages and rents. If the disamenity effect is great enough to countervail the productivity effect, workers will bid rents down as firms bid them up, and wages still rise.[16]

To this end, I find that the income increases documented in the literature at wider geographic scales (e.g. at the county level) do not appear here. For example, Brown, et al (2012) examine data at the county level, finding an implied benefit of approximately $11,000 per additional megawatt per capita over an eight-year span (i.e. $1,375 per year) attributable to wind energy throughout the United States.[17] This prompts the question of how county-level gains have occurred when households located nearby large wind farms do not appear to benefit directly over a similar timeframe. One possibility is that few energy royalty recipients reside close to the source of their royalties, or that royalty payments are concentrated among a small number of landowners (as reported in Weber, et al (2013)). Alternatively, economic development in wind-heavy regions may be tied to agricultural indicators; the study period considered by Brown, et al

[15] This does not rule out the possibility that households located immediately adjacent to (or within the boundaries of) wind farms are compensated for exposure, but the effect size may be too small to matter over a wider area.

[16] Even in the case that wind farms are a negative local productivity shock, the wage effect is ambiguous but rents must fall.

[17] The finding is not necessarily as large as it at first appears. In particular, this would require an additional megawatt per resident; at the mean county population of 45,200 in the data used by Brown, et al (2012), this implies that the $11,000 per megawatt per capita translates to $11,000 for 45,200 additional megawatts of installed capacity, or approximately $0.24 over eight years per individual megawatt.

(2012) includes years in which agricultural commodity prices were unusually high. While I also include data from these years, my data are at the household level, so I am able to observe within-county income variation. Brown, et al (2012) use county-average wind resource potential as an instrument for wind energy penetration. It is possible that regions with higher wind resource potential also host productive farmland, making incomes susceptible to agricultural commodity price changes. If there is unobserved heterogeneity that is correlated with county level wind resource potential, I have accounted for it with the county fixed effect ζ_c. Conservatively, my results suggest that the external net benefits of wind energy are not different from zero at the local level.

2.6 – Conclusion

I estimate the external net benefits of wind farm location by examining income and house value growth in rural Iowa. I use data at the address level, allowing me to difference out unobserved household-specific characteristics that may affect growth in both outcomes, and I account for local market activity with county fixed effects. My data are more detailed than others in the literature, and my estimation strategy allows me to distinguish the effect of wind farm placement from other local drivers of economic activity.

My results indicate that the external net benefits of wind farm placement are not different from zero. Neither incomes nor house values vary significantly with wind farm exposure. This result stands in contrast to results documented in the existing literature, which has found negative house value impacts and positive effects on income. I attribute this to the difference in geographic scales between the present study and others. For example, house value impacts have been shown to occur only within short distances of individual wind towers. At the same time, income gains may be distributed over so wide an area that their influence is too small to measure without precise information regarding land ownership.

Future work will address several of the gaps in the present analysis. For example, it remains unknown whether agricultural land capitalizes the disamenities of wind farm exposure as part of an option value. That is, if agricultural land were converted to residential use, would the disamenities of life near a wind farm be capitalized? Given the sparse population densities in areas with large wind farms, research into this question might provide an alternative to assessors' data in measuring cost-of-living as outlined in the theoretical framework. Additionally, assessed house values may reflect long-run trends in real estate prices, but do not necessarily represent an exact mutual valuation of a house and all its attributes as assumed in the traditional hedonic framework; this can possibly bias the marginal effect estimates toward zero. Expansions of this research will use parcel-level transactions for residential, rural and agricultural land to address both of these shortcomings.

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Chapter 2 Figures and Tables

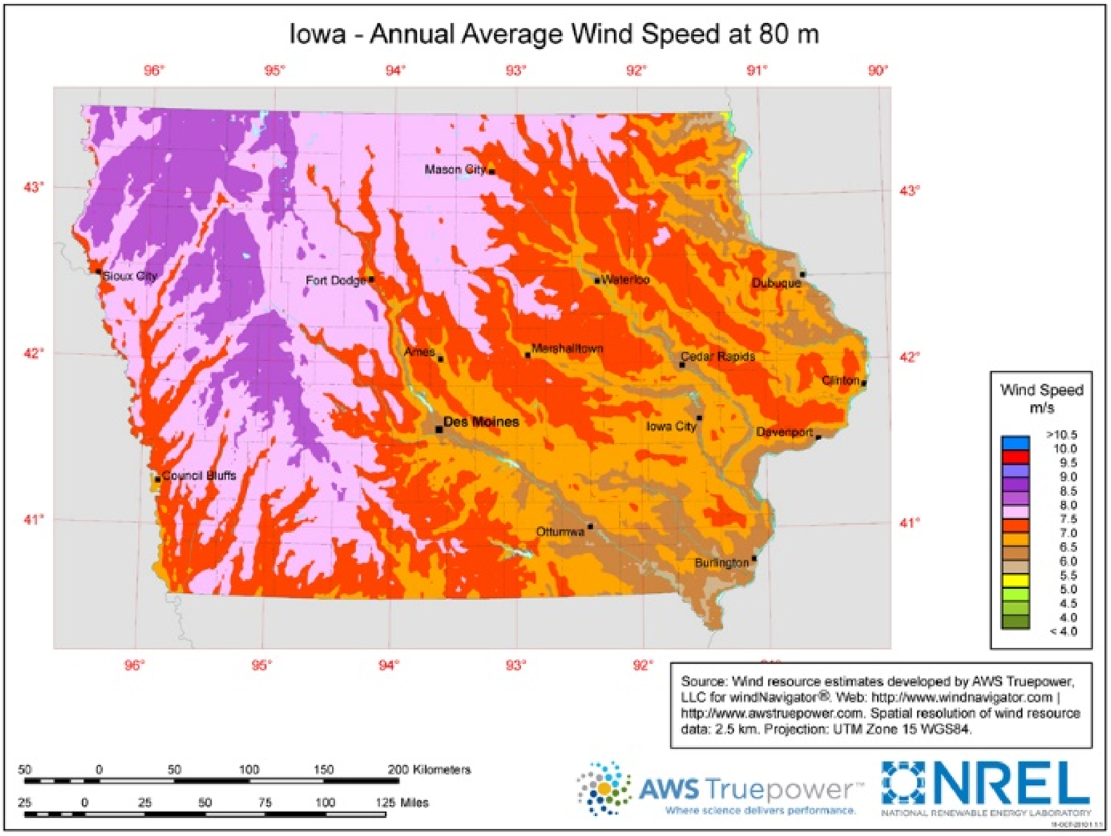

Figure 2.1: a map of Iowa's wind resource potential

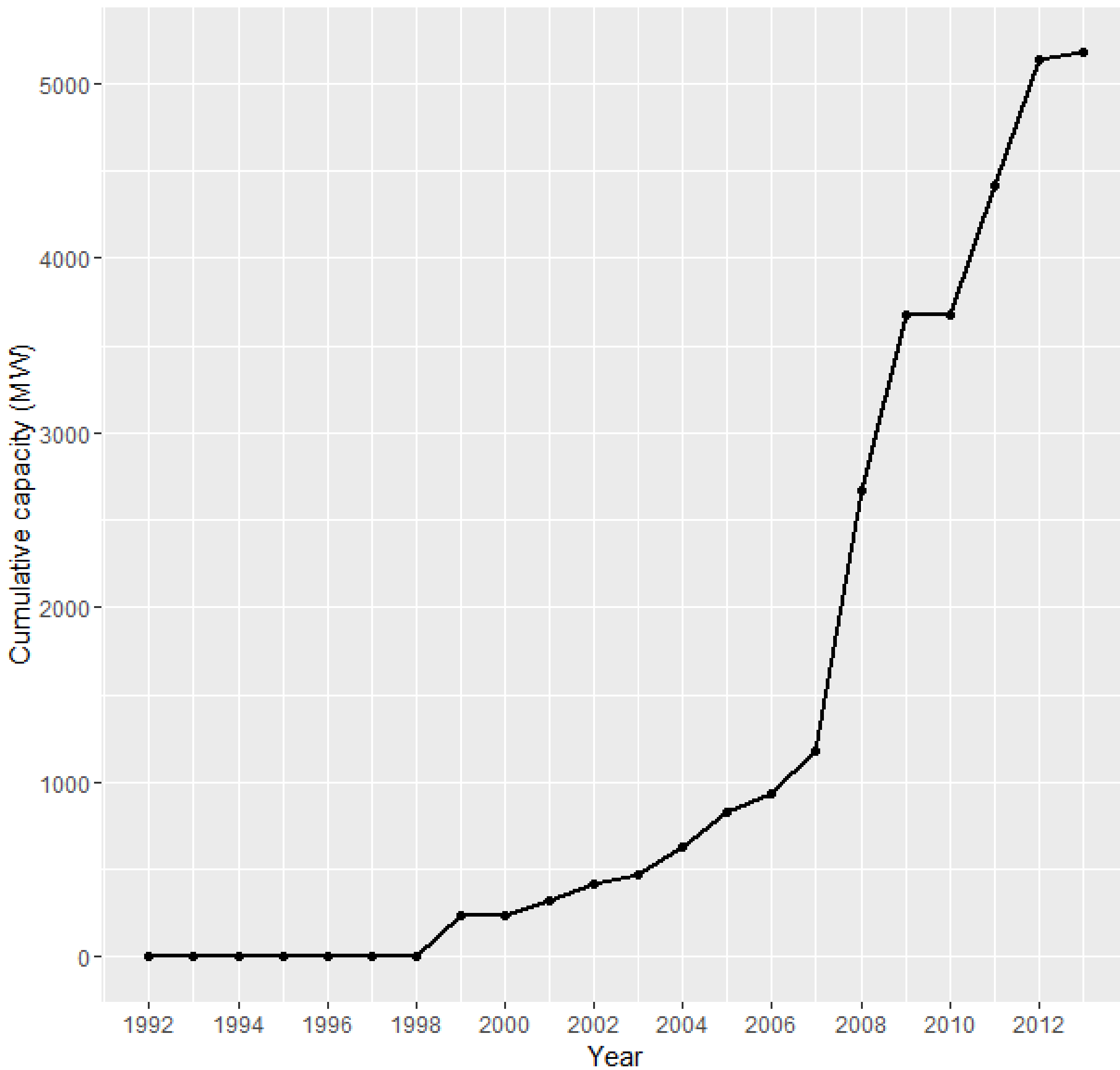

Figure 2.2: Cumulative wind power capacity installed in Iowa, 1992 to 2012

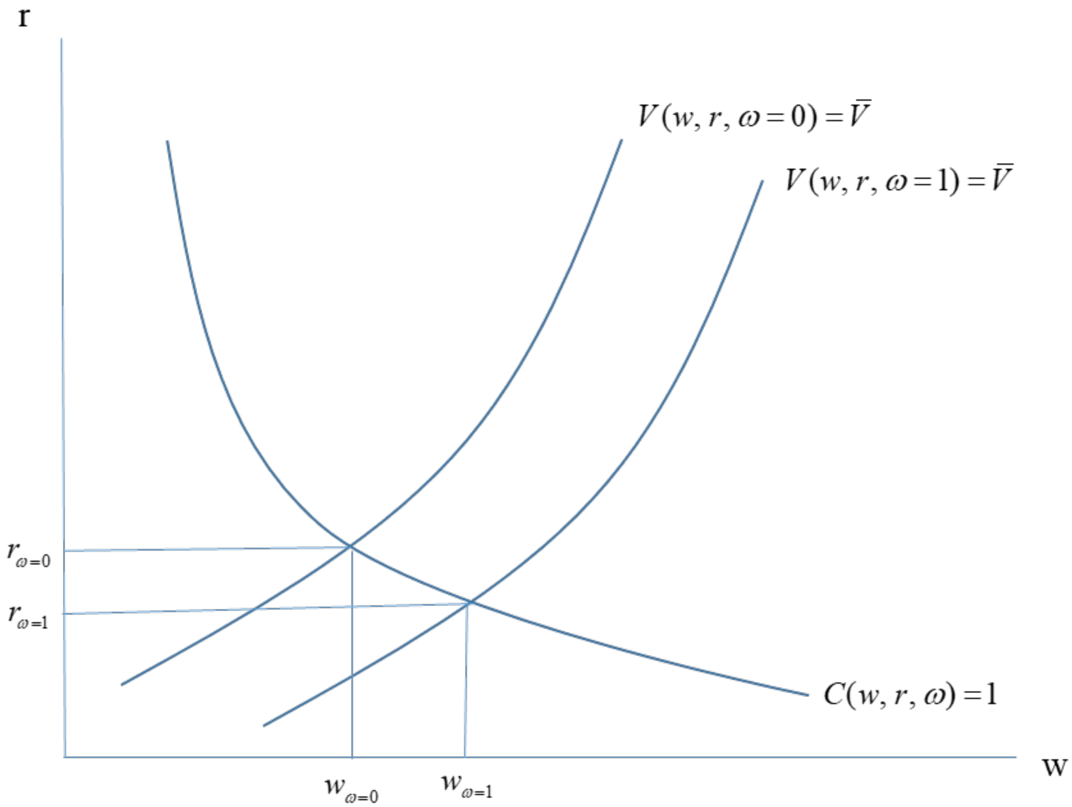

Figure 2.3: Local wage and rent differential when wind farm exposure is a disamenity

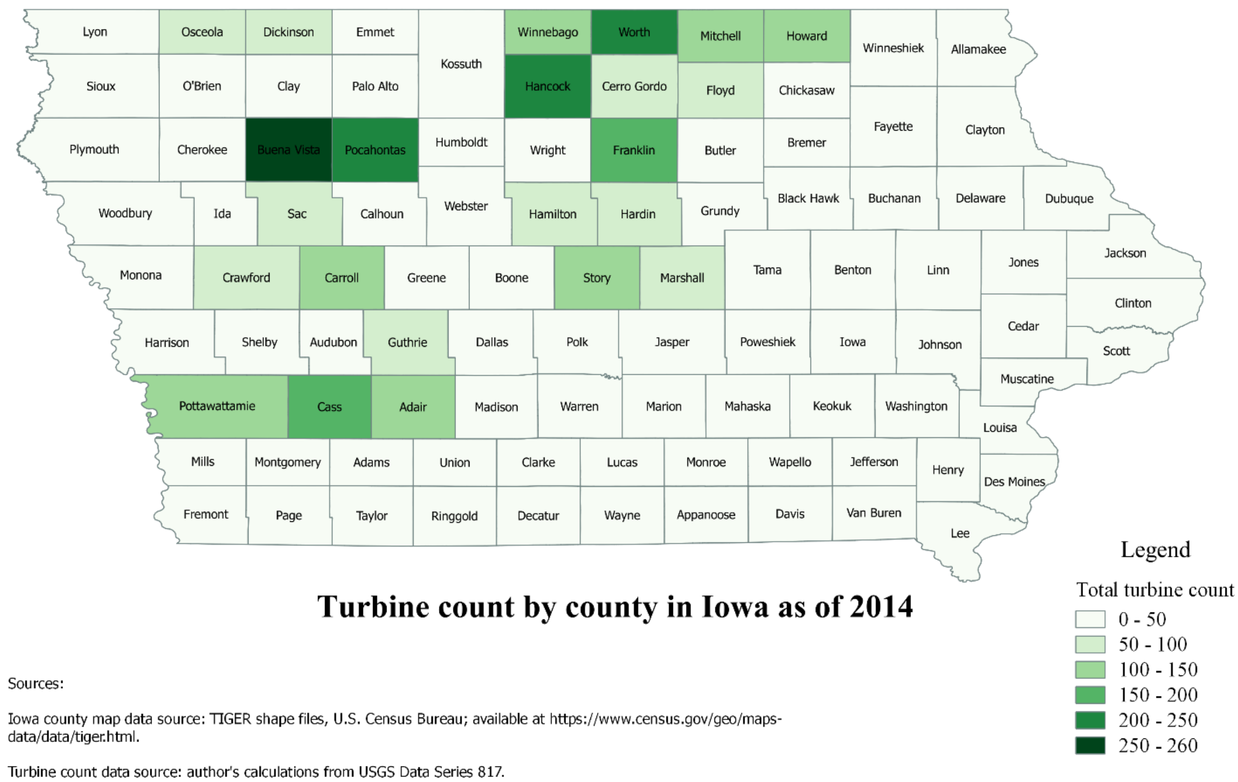

Figure 2.4: Iowa wind turbine counts by county

Table 2.1: Summary statistics – Income dataset

Year	Treatment group	Variable	Mean	Std Dev	10th Pctl†	90th Pctl†	Observations
2002:							
	Control	Household Income	$42,471.73	33844.3	$12,800.00	$75,800.00	152
		Distance (miles)	10.477	4.138	5.653	16.491	152
		Duration (Years)	0	0	0	0	152
		Capacity (100 MW)	0	0	0	0	152
		Turbines (100 count)	0	0	0	0	152
	Treated by 2012	Household Income	$49,804.51	33995.77	$17,800.00	$79,200.00	267
		Distance (miles)	2.418	1.447	0.405	4.156	267
		Duration (Years)	0	0	0	0	267
		Capacity (100 MW)	0	0	0	0	267
		Turbines (100 count)	0	0	0	0	267
2012:							
	Control	Household Income	$123,158.68	348059.87	$16,600.00	$220,800.00	152
		Distance (miles)	10.480	4.144	5.653	16.491	152
		Duration (Years)	0	0	0	0	152
		Capacity (100 MW)	0	0	0	0	152
		Turbines (100 count)	0	0	0	0	152
	Treated by 2012	Household Income	$94,352.11	196041.74	$19,243.00	$169,775.00	267
		Distance (miles)	2.418	1.447	0.405	4.156	267
		Duration (Years)	3.873	2.607	0	7	267
		Capacity (100 MW)	0.915	0.624	0.016	1.5	267
		Turbines (100 count)	0.592	0.431	0	1	267

†Observations censored by rounding

Table 2.2: Summary statistics – House values dataset

Year	Treatment group	Variable	Mean	Std Dev	10th Pctl	90th Pctl	Observations
2002:							
	Control	House value	$58,508.02	40,249.27	$12,840.00	$111,780.00	91
		Distance (miles)	8.068	5.904	5.526	10.24	91
		Duration (years)	0	0	0	0	91
		Capacity (100 MW)	0	0	0	0	91
		Turbines (100 count)	0	0	0	0	91
	Treated by 2012	House value	$98,246.57	44,649.23	$50,609.00	$155,115.00	968
		Distance (miles)	2.93	1.251	0.758	4.107	968
		Duration (years)	0	0	0	0	968
		Capacity (100 MW)	0	0	0	0	968
		Turbines (100 count)	0	0	0	0	968
2012:							
	Control	House value	$96,279.23	77,882.24	$26,110.00	$164,290.00	91
		Distance (miles)	8.068	5.904	5.526	10.24	91
		Duration (years)	0	0	0	0	91
		Capacity (100 MW)	0	0	0	0	91
		Turbines (100 count)	0	0	0	0	91
	Treated by 2012	House value	$121,480.24	56,624.22	$60,085.00	$193,650.00	968
		Distance (miles)	2.93	1.251	0.758	4.107	968
		Duration (years)	2.99	2.452	0	7	968
		Capacity (100 MW)	0.895	0.709	0.016	1.5	968
		Turbines (100 count)	0.603	0.468	0.01	1	968

Table 2.3: Income growth, 2002 to 2012

Parameter	*Dependent variable: change in log income* (1)	(2)	(3)	(4)	(5)
Treated by 2012 (β^{w})	-0.084	-0.003	-0.025	0.03	-0.023
	(0.135)	(0.175)	(0.164)	(0.159)	(0.157)
Distance (miles) (γ^{w}_{dist})		0.015			
		(0.022)			
Duration (years) (γ^{w}_{dur})			-0.017		
			(0.027)		
Capacity (100 MW) (γ^{w}_{cap})				-0.131	
				(0.086)	
Turbines (100 count) (γ^{w}_{turb})					-0.123
					(0.131)
Joint effect:	-	0.033	-0.09	-0.089	-0.095
Joint significance:	No	No	No	No	No
County FE:	Yes	Yes	Yes	Yes	Yes
Observations	419	419	419	419	419
R2	0.1041	0.1055	0.1049	0.1075	0.1055

Note: *p<0.1; **p<0.05; ***p<0.01

Table 2.4: House value regressions, 2002 2012

Parameter	*Dependent variable: change in log house value*				
	(1)	(2)	(3)	(4)	(5)
Treated by 2012 (β^r)	-0.066	-0.120*	-0.03	-0.056	-0.057
	(0.052)	(0.070)	(0.058)	(0.052)	(0.053)
Distance (miles) (γ^r_{dist})		-0.009			
		(0.007)			
Duration (years) (γ^r_{dur})			-0.005		
			(0.004)		
Capacity (100 MW) (γ^r_{cap})				-0.008	
				(0.010)	
Turbines (100 count) (γ^r_{turb})					-0.011
					(0.015)
Joint effect:	-	-0.146	-0.044	-0.063	-0.063
Joint significance:	No	No	No	No	No
County FE:	Yes	Yes	Yes	Yes	Yes
Observations	1,059	1,059	1,059	1,059	1,059
R2	0.183	0.188	0.184	0.184	0.184

Note: *p<0.1; **p<0.05; ***p<0.01

APPENDIX A: CHAPTER 2 ADDITIONAL TABLES

In additional specifications, capacity and turbine count become significant only when both are included (see model 8 in Tables A.1 and A.2). Effect sizes and signs are similar for both income growth and house value growth. Capacity coefficients are negative, implying a 1.4% income decrease and a 0.84% house value decrease per megawatt. Applying these growth rate differences to base-year control-group averages yields an income difference of $595 per megawatt and a house value difference of $491 per megawatt. Turbine results are similar. Using control-group incomes, the estimated 2.1% income gain reported in Table A.1 is approximately equivalent to $892 per additional turbine. House value differences are similar—using the base-year control-group house values, the 1.4% house value gain is equivalent to $819 per turbine. House values also grow more slowly within 5 miles of a wind farm, although the implied loss of 0.0034% (approximately $2, using control-group base-year house values) per year is not economically significant.

Use of alternative endpoint years also has little effect on growth rates (see Tables A.3 – A.6). While the 2002-2008 growth estimations reported in Tables A.3 and A.4 use the same data as the estimations presented in Chapter 2, the 2004-2012 growth estimations use an expanded dataset that overlaps substantially with the original data. In particular, a larger number of house value observations are available beginning in 2004, and sampling variation in tax filers led to a greater number of data points between 2004 and 2012. While treatment intensity measures are not significant in Table A.5, the treatment effect β^w is significant, implying a loss of 30% relative to control group income growth. House value growth over the same period is negatively related to distance, implying that treated houses lose 7% in house value growth per additional mile away from a wind farm. Duration of exposure is also negative and significant; growth of treated houses is 2% lower per additional year of exposure.

Table A.1: Income growth, 2002 to 2012 (additional specifications)

	Dependent variable: change in log income		
Parameter	(6)	(7)	(8)
Treated by 2012 (β^w)	0.023	-0.016	0.295
	(0.165)	(0.166)	(0.183)
Duration (years) (γ^w_{dur})	0.004	-0.004	-0.055
	(0.035)	(0.037)	(0.039)
Capacity (100 MW) (γ^w_{cap})	-0.14		-1.395***
	(0.114)		(0.452)
Turbines (100 count) (γ^w_{turb})		-0.109	2.091***
		(0.183)	(0.716)
Joint effect:	-0.089	-0.095	0.043
Joint significance:	No	No	10%
County FE:	Yes	Yes	Yes
Observations	419	419	419
R2	0.1075	0.1055	0.1193

Note: *p<0.1; **p<0.05; ***p<0.01

Table A.2: House value growth, 2002 to 2012 (additional specifications)

	Dependent variable: change in log house value		
Parameter	(6)	(7)	(8)
Treated by 2012 (β^r)	-0.007	0.001	0.039
	(0.061)	(0.061)	(0.054)
Duration (years) (γ^r_{dur})	-0.011	-0.013	-0.034***
	(0.011)	(0.012)	(0.013)
Capacity (100 MW) (γ^r_{cap})	0.017		-0.896***
	(0.031)		(0.238)
Turbines (100 count) (γ^r_{turb})		0.036	1.465***
		(0.048)	(0.402)
Joint effect:	-0.024	-0.016	0.018
Joint significance:	No	No	5%
County FE:	Yes	Yes	Yes
Observations	1,059	1,059	1,059
R2	0.185	0.185	0.191

Note: *p<0.1; **p<0.05; ***p<0.01

Table A.3: Income growth, 2002 to 2008

	Dependent variable: change in log income							
Parameter	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Treated by 2008 (β^w_{2008})	-0.08	-0.051	-0.02	0.039	-0.018	0.218	-0.015	12683***
	(0.081)	(0.083)	(0.088)	(0.19)	(0.083)	(0.222)	(0.089)	(0.425)
Distance (miles) (γ^w_{dist})		0.016*						
		(0.009)						
Duration (years) (γ^w_{dur})			-0.043			-0.065	-0.003	-0.037
			(0.037)			(0.041)	(0.045)	(0.098)
Capacity (100 MW) (γ^w_{cap})				-0.097		-0.171		-0.104
				(0.129)		(0.139)		(0.29)
Turbines (100 count) (γ^w_{turb})					-0.318		-0.309	-0.15
					(0.196)		(0.239)	(0.508)
Joint significance:	No	No	No	No	10%	No	No	No
County FE:	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	419	419	419	419	419	419	419	419
R2	0.1103	0.1152	0.1128	0.1117	0.1165	0.1167	0.1165	0.1169

Note: *p<0.1; **p<0.05; ***p<0.01

Table A.4: House value growth, 2002 to 2008

Parameter	*Dependent variable: change in log house value* (1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Treated by 2008 (β^r_{2008})	0.021	0.016	0.028	0.058	0.06	0.085**	0.089**	0.053
	(0.022)	(0.021)	(0.024)	(0.041)	(0.049)	(0.041)	(0.045)	(0.081)
Distance (miles) (γ^r_{dist})		-0.005						
		(0.005)						
Duration (years) (γ^r_{dur})			-0.013			-0.016	-0.016	-0.016
			(0.012)			(0.010)	(0.010)	(0.010)
Capacity (100 MW) (γ^r_{cap})				-0.026		-0.038*		-0.205
				(0.025)		(0.023)		(0.301)
Turbines (100 count) (γ^r_{turb})					-0.041		-0.062	0.282
					(0.046)		(0.040)	(0.523)
Joint significance:	10%	No	10%	No	No	10%	10%	No
County FE:	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	1,059	1,059	1,059	1,059	1,059	1,059	1,059	1,059
R^2	0.066	0.068	0.067	0.066	0.066	0.069	0.069	0.069

Note: *p<0.1;**p<0.05;***p<0.01

Table A.5: Income growth, 2004 to 2012

Parameter:	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Dependent variable: change in log income							
Treated by 2008 (β^{w})	-0.308**	-0.209	-0.321*	-0.313*	-0.331**	-0.321*	-0.3*	0.088
	(0.156)	(0.18796)	(0.17813)	(0.16877)	(0.16523)	(0.17806)	(0.18088)	(0.2132)
Distance (miles) (γ^{w}_{dist})		0.017						
		(0.01974)						
Duration (years) (γ^{w}_{dur})			0.004			0.005	-0.018	-0.11*
			(0.03193)			(0.04911)	(0.05606)	(0.06657)
Capacity (100 MW) (γ^{w}_{cap})				0.007		-0.002		-1.441***
				(0.08157)		(0.1287)		(0.46927)
Turbines (100 count) (γ^{w}_{turb})					0.066		0.126	2.542***
					(0.12245)		(0.21846)	(0.83056)
Joint significance:	5%	No	10%	10%	No	10%	No	10%
County FE:	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	448	448	448	448	448	448	448	448
R2	0.0624	0.0644	0.0625	0.0624	0.0629	0.0625	0.0631	0.0764

Note: *p<0.1; **p<0.05; ***p<0.01

Table A.6: House value growth, 2004 2012

Parameter	*Dependent variable: change in log house value* (1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Treated by 2008 (β^r)	0.065**	0.159***	0.157***	0.106*	0.115**	0.187***	0.187***	0.183***
	(0.026)	(0.047)	(0.054)	(0.056)	(0.057)	(0.066)	(0.067)	(0.067)
Distance (miles) (γ^r_{dist})		-0.071***						
		(0.027)						
Duration (years) (γ^r_{dur})			-0.023**			-0.022*	-0.022*	-0.023
			(0.011)			(0.012)	(0.012)	(0.017)
Capacity (100 MW) (γ^r_{cap})				-0.03		-0.023		-0.086
				(0.040)		(0.034)		(0.569)
Turbines (100 count) (γ^r_{turb})					-0.054		-0.036	0.102
					(0.061)		(0.056)	(0.933)
Joint significance:	5%	1%	5%	5%	5%	10%	10%	10%
County FE:	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	1,824	1,824	1,824	1,824	1,824	1,824	1,824	1,824
R2	0.098	0.104	0.1	0.098	0.098	0.1	0.1	0.1

Note: *p<0.1; **p<0.05; ***p<0.01. Table A.6 presents estimates of the house value specifications of Equation (2.6) using data from 2004 to 2012. Due to variation in electronic recordkeeping by county assessors, additional observations are available during this time period—the estimates in Table A.6 use this expanded data set. Marginal results are similar when the data set is restricted to the set of overlapping addresses from the 2002 base year, but joint significance is lost for most of the specifications under this restriction.

CHAPTER 3. THE LAND AND LABOR MARKET IMPACTS OF THE U.S. SHALE BOOM

A modified version of this essay to be submitted for publication in a peer-reviewed journal

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3.1 - Introduction

The U.S. shale boom of the mid-2000s traded off possible environmental damage and negative quality-of-life impacts against income gains and rents captured by workers and property owners. Hedonic house-price studies have found negative impacts capitalized into house prices (e.g. Muehlenbachs et al (2015)), while studies of wages and employment have documented a positive and significant labor demand shock in areas with shale resources (e.g. Brown (2014), Komarek (2015)). At the same time, possible human and animal health impacts may be related to the industrial chemicals used the hydraulic fracturing methods that enabled the boom (e.g. Bamberger and Oswald (2015), Hill (2012)). On the other hand, municipalities can also gain revenue due to expansion of the property tax base, leading to greater provision of public amenities and school district funding (Marchand and Weber (2015), Weber and Hitaj (2015)).

The value of shale energy resources drives both land and labor market responses to the change in the value of the shale resource. To date, however, the land and labor market impacts of the boom have not been studied simultaneously.[18] Using the timing of the boom and variation in extraction rates as a treatment across 2,141 counties from 2000 to 2010, I examine the concurrent effects of the shale boom on land and labor markets. I find that boom-period oil and gas activity is associated with employment and wage increases of 4.4% and 3.9% respectively, while house values decrease by 1.5%. Comparisons with non-energy-producing counties show that oil and gas producing counties have higher wage and employment levels than non-producers, although median house values are systematically lower. Additionally, I use Roback's (1982) method to generate measures of the willingness to pay for shale

[18] Jacobsen (2016) provides an exception to this statement; however, my analysis provides a more in-depth treatment of the economics that drive land and labor market changes.

energy activity. My results imply a willingness to pay between $160 and $425 for a 1% reduction in total energy produced in-county.

Total energy (in BTUs) produced from onshore oil and gas resource extraction increased 1.23 times nationwide between 2000 and 2010, with 218 counties experiencing value growth of over $20 million between 2000 and 2011 (USDA 2014). Precise directional drilling and high-volume slickwater hydraulic fracturing comprise the technological advancement credited with enabling the boom (Brown (2014); Zuckerman (2014)). Oil and gas resources trapped within layers of shale rock are often difficult to recover. Economically meaningful volumes of the resource are often spread over a large area and cannot be recovered by relying on geologic pressure alone, as in conventional oil drilling (Hyne (2010)). Hydraulic fracturing methods use large volumes of water laden with fine sand particles and industrial chemicals, pumped at immense pressure to fracture the shale rock within an oil or gas well. The pressure and chemicals break up and wear down the rock, and the sand particles serve to prop open the fractures and allow geologic pressure to expel the trapped minerals. Horizontal drilling methods allow firms to expose greater surface areas within a shale play, allowing a single well to recover minerals over a wider geographic area, sometimes as far as two miles away from the well pad. This increase in well productivity, combined with the relatively high oil and natural gas prices of the mid-2000s, made the exploitation of on-shore U.S. shale resources economically viable, with the first of the boom-period drilling beginning in Texas prior to 2005 (Brown (2014); Zuckerman (2014)).

The geography of oil and gas extraction is determined by resource location. Inputs to the exploitation of shale resources are able to locate in areas with greater resource endowments, meaning that local labor and land market conditions will depend on resource availability. Theory predicts that an increase in productivity should stimulate derived demand for production inputs. In the case of the shale energy boom, areas with no shale resources will not experience this shock, while areas within an oil or gas play will experience differential intensity of the shock based on local mineral endowments. I exploit these differences to examine the impacts of the shale boom on the welfare of oil counties.

I consider two primary research questions: first, what was the impact on land and labor markets in shale energy counties; and second, is the implicit value of energy extraction positive or negative? While the labor demand shock associated with the increase in economically recoverable oil and gas reserves would be expected to lead to increased wages and employment, are enough permanent workers attracted by high wages and job opportunities to bid up land rents? If the boom provided sufficient funding to develop well-functioning institutions and attract consumers for purposes beyond mineral recovery, house values in producing areas should rise relative to house values in non-producing areas. On the other hand, if traffic congestion (Rahm et al (2015)), increased crime rates (James and Smith (2017)), oil spills (Vengosh et al (2014) and water contamination (Olmstead et al (2013)) from shale activity generate costs in excess of the local benefits, house values will remain low and only increase within shale counties if labor demand stimulates excessive in-migration.

The remainder of this study is organized as follows: the next section reviews selected literature; Section 3 describes the theory underlying the empirical analysis; Section 4 discusses econometric specifications; Section 5 describes the data used to measure the shale boom's impacts on land and labor markets; Section 6 discusses results and Section 7 concludes.

3.2 – Literature

The theoretical motivation for this study is taken in part from the urban and regional economics literature concerned with the valuation of local amenities, including Roback (1982) and Rosen (1979). I also draw on the growth frameworks of Glaeser et al (1995) and Shapiro (2006). To date, these methods have not been applied to understanding the shale boom, although they have been used to value the presence of local industry and infrastructure (see, for example, Artz et al (2007) and Kim and Orazem (2016)). A large portion of the existing analyses uses hedonic methods. Boxall et al (2005) apply the hedonic method to houses near to sour gas wells in Alberta, Canada, finding that the marginal sour gas well within 4km of a house is associated with a value loss of approximately C$2,100. Gopalakrishnan and Klaiber (2012) apply the method to shale gas wells in Washington County, Pennsylvania; in a similar but more-expansive study, Muehlenbachs et al (2016) exploit the drilling moratorium imposed by the state of New York to conduct a propensity-score matched difference in differences study of house values along the New York-Pennsylvania border. Both studies find significant price effects in local housing markets, houses located within 2 kilometers of a shale gas well experiencing a 22% to 24% price drop relative to non-exposed houses. However, Weber and Hitaj (2015) find positive impacts of drilling presence on agricultural land in Texas and Pennsylvania, while Weber et al (2016) find that shale activity has increased both house values and the property tax base in Texas.

Weber (2012) and others have examined the employment effects of the boom, finding significant employment growth equivalent to 1.5% of pre-boom employment and wage effects equivalent to 2.6% of pre-boom levels throughout Colorado, Texas and Wyoming. Feyer et al (2017) estimate an employment increase of 0.85 jobs per million dollars of new oil and gas produced, as well as significant wage increases within 100 miles of new production. Komarek (2015) exploits the fracking moratorium imposed by New York, finding employment gains of 3% and wage gains of 8% in the Marcellus and Utica shales of Pennsylvania, Ohio and West Virginia relative to the New York portion of the Marcellus shale. Some authors have considered the possibility of U.S. mineral booms leading to "resource curse" scenarios, in which labor in non-resource sectors is effectively rationed. A study by Allcott and Keniston (2015) examines historical resource booms in the oil and gas sector and find significant positive spillovers with the manufacturing sector. Komarek's (2015) study of the Marcelllus and Utica shales finds no evidence of resource curse behavior, i.e. there were employment and wage gains in the non-traded goods sectors (e.g. construction, transportation), but no "crowding out" of the traded-goods sectors, e.g. manufacturing.

A common potentially confounding factor in the literature is the issue of endogenous energy extraction. Fleming et al (2015) point out that unobserved heterogeneity in local institutions can affect both the amount of energy extracted and local labor and land market conditions. Convenient instruments include known geologic distribution of oil and gas resources, which Weber (2012) uses to calculate the proportion of county-level surface area situated within the boundaries of an active oil or gas play. Proven reserve measures are also well suited to serving as instruments for extraction activity; however, reserve estimates can evolve over time, and county-level reserve estimates are not widely available. In my analysis below, I account for these possibilities with a difference-in-differences study design using region and year fixed-effects. The present study contributes to the literature by considering a wider geographic region than similar studies and by considering the simultaneous clearing of land and labor markets. I describe this in greater detail in the next section.

3.3 – Theory

I motivate my analysis with a model developed by Roback (1982) and extended into a dynamic context by Shapiro (2006). Both models describe land and labor markets clearing in a spatial equilibrium, suggesting reduced-form econometric specifications that generate a measure of the implicit price of a local characteristic.

The premise of the model is that firms and consumers can chose their locations to maximize their payoffs subject to wages, rents and the local quality of life. In equilibrium, consumers' indirect utility and firms' indirect unit costs will be equated across regions. Let areas of residence be indexed by c. Assuming utility in region c depends on rental of land K at rate r_c, a quality-of-life metric Z_c and consumption of a numeraire and subject to wage w_c, indirect utility will be $V(r_c, w_c, Z_c)$. Free mobility implies that consumers will distribute themselves spatially such that $V(r_c, w_c, Z_c) = \bar{V}, \forall c$. Treating all three arguments as dependent on time and differentiating yields the growth of indirect utility:

$$V_r \frac{\partial r_c}{\partial t} + V_w \frac{\partial w_c}{\partial t} + V_Z \frac{\partial Z_c}{\partial t} = \frac{\partial \bar{V}}{\partial t} \tag{3.1}$$

In (3.1), V_j is the partial derivative of indirect utility with respect to argument j. Following Shapiro's (2006) formulation, I normalize utility growth to zero. Then, Equation (3.1) can be rearranged to yield

$$\frac{V_Z}{V_w}\frac{\partial Z_c}{\partial t} = \frac{-V_r}{V_w}\frac{\partial r_c}{\partial t} - \frac{\partial w_c}{\partial t} \tag{3.2}$$

Equation (3.2) has the interpretation that the growth rate of quality of life Z_c accounts for the difference of the growth rates of rent and wages. Equation (3.2) can be modified further to arrive at the more empirically tractable formulation

$$\frac{V_Z}{V_w}\frac{Z_c}{w_c}\frac{1}{Z_c}\frac{\partial Z_c}{\partial t} = \frac{-V_r}{V_w}\frac{r_c}{w_c}\frac{\partial r_c}{\partial t}\frac{1}{r_c} - \frac{\partial w_c}{\partial t}\frac{1}{w_c}$$
$$\Leftrightarrow \tag{3.3}$$
$$\frac{V_Z}{V_w}\frac{Z_c}{w_c}\frac{\partial \ln(Z_c)}{\partial t} = \frac{r_c K_c^*}{w_c}\frac{\partial \ln(r_c)}{\partial t} - \frac{\partial \ln(w_c)}{\partial t}$$

where $\frac{-V_r}{V_w}$ is equivalent to the utility-maximizing land demand K_c^* by Roy's Identity. The quotient $\frac{r_c K_c^*}{w_c}$ is the consumer budget share of land in region c, which I will denote κ_c; similarly, $\frac{V_z}{V_w}\frac{Z_c}{w_c}$ is the implied budget share of the quality-of-life measure Z_c. In particular, Equation (3.3) indicates that the quality-of-life contribution to consumer welfare growth is equivalent to the difference between the growth in cost of living $\kappa_c \frac{\partial \ln(r_c)}{\partial t}$ and growth in ability to pay $\frac{\partial \ln(w_c)}{\partial t}$. Assuming that quality-of-life growth is a linear function of characteristics X_{ct}, this is

$$\Delta QOL_{ct} \equiv \kappa \frac{\partial \ln(r_c)}{\partial t} - \frac{\partial \ln(w_c)}{\partial t} = \theta' X_{ct} + \epsilon_{ct} \tag{3.4}$$

where ϵ_{ct} is a random error term.

In Roback's (1982) original formulation, wages and rents adjust across space according to local characteristics. The marginal willingness-to-pay for any local characteristic s is given by

$$MWTP_s \equiv \frac{V_s}{V_w}\frac{1}{w} = \kappa_c \frac{d \ln(r_c)}{ds} - \frac{d \ln(w_c)}{ds} \tag{3.5}$$

Now assume that the arguments of (3.5) are implicit functions of time and that a spatial equilibrium holds in each time period t. The marginal willingness to pay can then be differenced between time periods. Let the marginal willingness to pay for characteristic s at time t be given by $MWTP_{st}$. Then,

$$\begin{aligned} MWTP_{s,t+1} - MWTP_{st} &= \kappa \frac{d\ln(r_{c,t+1})}{ds} - \frac{d\ln(w_{c,t+1})}{ds} - \left(\kappa \frac{d\ln(r_{ct})}{ds} - \frac{d\ln(w_{ct})}{ds}\right) \\ &= \kappa\left(\frac{d\ln(r_{c,t+1})}{ds} - \frac{d\ln(r_{ct})}{ds}\right) - \left(\frac{d\ln(w_{c,t+1})}{ds} - \frac{d\ln(w_{ct})}{ds}\right) \\ &\equiv \kappa\left(\Delta_{t+1}\frac{d\ln(r_{ct})}{ds}\right) - \left(\Delta_{t+1}\frac{d\ln(w_{ct})}{ds}\right) \end{aligned} \qquad (3.6)$$

Dividing Equation (3.6) through by Δt and taking the limit as Δt approaches 0, the discrete differences of the logarithmic derivatives of r and w with respect to s become the second derivatives $\frac{d^2\ln(r_{ct})}{dsdt}$ and $\frac{d^2\ln(w_{ct})}{dsdt}$.[19] The same result obtains in Shapiro's (2006) formulation. Growth in quality of life has the form $\kappa_c \frac{\partial\ln(r_{ct})}{\partial t} - \frac{\partial\ln(w_{ct})}{\partial t}$, which is then specified as a linear function of county characteristics X_{ct}. Differentiating with respect to any element of X_{ct}, denoted here by s, yields $\kappa_c \frac{\partial^2\ln(r_{ct})}{\partial t\partial s} - \frac{\partial^2\ln(w_{ct})}{\partial t\partial s}$.

The analysis above indicates that the influence of any characteristic s on growth in quality-of-life is approximately equivalent to the growth in marginal willingness to pay for a unit of s. This equivalence suggests two empirical techniques to examine the growth in quality of life. First, it is possible to directly estimate Equation (3.4); and second, it is also possible to estimate the wage and rent effects as a system with panel data and subsequently test whether marginal willingness to pay has changed significantly throughout the panel.

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[19] To see this, consider that $\Delta_{t+1}\frac{d\ln(r_{ct})}{ds}$ is the discrete approximation to the cross-derivative $\frac{d^2\ln(r_{ct})}{dsdt}$ for a one-unit change in t. Treating $\frac{d\ln(r_{ct})}{ds}$ as the time-t realization of a rent function that is continuous and differentiable in both time and the local characteristic, the difference $\Delta_{t+1}\frac{d\ln(r_{ct})}{ds}$ is equivalent to the expression $\frac{1}{\Delta t}\left(\frac{d\ln(r_{ct})}{ds}(t+\Delta t) - \frac{d\ln(r_{ct})}{ds}(t)\right)$. Taking the limit as $\Delta t \to 0$ yields the cross-derivative; the same argument holds for $wage_{ct}$.

3.4 – Econometric Specification

I estimate reduced-form econometric specifications that allow me to characterize the wage, rent and employment impacts of the shale boom. Additionally, I can use the estimated parameters to calculate marginal willingness to pay for a change in county-level energy production. I use both equation-by-equation OLS and Seemingly-Unrelated Regression to obtain coefficient estimates, which I then combine according to Equation (3.5) to obtain MWTP estimates for an individual year. Using system OLS allows me to obtain a standard deviation for the cross-equation combination in Equation (3.5). Per theoretical specification, wages and rents are treated in logarithmic form. I also estimate auxiliary regressions to examine the effect of the shale boom on wages and employment on an industry basis. Finally, I compare the computed marginal willingness to pay results from equation-by-equation OLS and SUR estimation to a direct estimation of the change in marginal willingness to pay for energy extraction by county, which I obtain by regressing the right-hand side of Equation (3.6) on oil and gas production measures and panel-varying controls.

Identification of shale boom effects comes from geography and timing. In particular, counties with areas that overlap an oil play, to which I will refer as producing counties, have the ability to host oil and gas production enterprises while counties located outside the play (non-producing counties) cannot. In a difference-in-differences context, producing counties and "boom" counties are the treatment groups, while non-producing counties form the control group; a county with strictly positive oil production in 2000, 2010 or any of the intervening years is considered a producing county. In estimating the effect of the shale boom, non-boom producing counties become the controls. The timing of the shale boom in the years between 2000 and 2010 motivates a convenient "before" and "after" distinction.[20] I will refer to the years after the start of the shale boom as the boom period.

[20] While it is generally agreed that the shale boom began in the mid-2000s, the exact start date varies by shale play. Additionally, booms are often relatively short-lived (Allcott and Keniston (2015), Fleming et al (2015)); using data from 2010 allows me to consider effects during the boom period itself rather than during a post-boom equilibrium.

As described in Section 3.2, Fleming et al (2015) point out that there may be unobserved heterogeneity among counties that can affect the response to a change in resource value. This argues for including a county fixed-effect in the empirical specification. Similarly, there may be state-level shocks, such as legislation or regulation, that affects the propensity of shale developers to exploit the resource in county *c*, suggesting that state-level controls may be necessary. Finally, macroeconomic shocks affect all counties, suggesting the need for a time fixed-effect. Let y_{cst} denote the outcome of interest (wages, rents or employment) for county c in state s at time t, and let $boom_{ct}$ be an indicator variable equal to 1 if county c experiences the effects of the boom at time t. I specify the reduced-form relation

$$\ln(y_{cst}) = \phi \cdot boom_{ct} + \mu_c + \eta_{st} + \delta_{ct} + \epsilon_{cst} \tag{3.7}$$

where $\phi \cdot boom_{ct}$ is the treatment effect, μ_c is unobserved county variation, η_{st} is a state-by-year fixed effect, δ_{ct} is a county-specific year fixed-effect and ϵ_{cst} is the error term, which I assume to be i.i.d. normal with mean zero conditional on county characteristics. During the pre-boom period (denoted by $t = 0$), $boom_{c0} = 0$ for all counties and Equation (3.7) can be written as

$$\ln(y_{cs0}) = \mu_c + \eta_{s0} + \delta_{c0} + \epsilon_{cs0}$$

During the boom period (i.e. $t = 1$), Equation (3.7) becomes

$$\ln(y_{cs1}) = \phi \cdot boom_{c1} + \mu_c + \eta_{s1} + \delta_{c1} + \epsilon_{cs1}$$

Differencing between time periods yields the growth equation

$$\Delta \ln(y_{cs}) \equiv \ln(y_{cs1}) - \ln(y_{cs0}) = \phi \cdot boom_{c1} + \left(\mu_c - \mu_c\right) + \zeta_s + \left(\delta_{c1} - \delta_{c0}\right) + \nu_{cs} \tag{3.8}$$

where $\zeta_s = (\eta_{s1} - \eta_{s0})$ and $\nu_{cs} = \epsilon_{cs1} - \epsilon_{cs0}$. I approximate the difference $\delta_1 - \delta_0$ by $\beta' X_{ct}$, a panel-varying vector of county-level characteristics and their changes over time, and I use a state-level dummy variable to control for ζ_s. Fully specified, this leads to

$$\Delta \ln(y_{cs}) = \phi \cdot boom_{c1} + \beta' X_{ct} + \zeta_s + \nu_{cs} \tag{3.9}$$

which I estimate using two-stage least squares.

To obtain the parameter estimates necessary to characterize marginal willingness to pay for local energy extraction, specify the system of equations

$$\ln(rent_{ct}) = \alpha^r + \phi^r_{prod} \cdot producer_c + \delta \cdot D2010_t + \psi^r_{prod} \cdot producer_c \cdot D2010_t + \theta' X_{ct} + \epsilon^r_{ct}$$

$$\ln(wage_{ct}) = \alpha^w + \phi^w_{prod} \cdot producer_c + \delta^w \cdot D2010_t + \psi^w_{prod} \cdot producer_c \cdot D2010_t + \gamma' X_{ct} + \epsilon^w_{ct} \quad (3.10)$$

where $producer_c$ is an oil-and-gas producing county dummy, $D2010_t$ is a dummy for the year 2010 (effectively a "post-boom" dummy), X_{ct} is a vector of county-level controls and ϵ^r_{ct} and ϵ^w_{ct} are error terms. The coefficient δ captures the overall change in outcomes in the post-boom time-period while the coefficient ψ_{prod} is the additional effect associated with a county being located within an oil or gas play. County-level controls in X_{ct} include panel-varying measures of characteristics, including high-school graduation rates, population and poverty rates, that may influence rents and wages.

As specified, Equation (3.10) does not control for potential regional differences that can affect rents and wages in geographically distant shale plays. This is not trivial: for example, structural differences between counties within the Bakken and Eagle Ford shale plays—such as state-level policies, local institutions and legal factors like the prevalence of split-estates[21]—may be associated with different reactions to increased oil and gas activity. To account for these differences, I specify

$$\begin{aligned}\ln(rent_{ct}) &= \alpha^r + \lambda^r \cdot region_c + \phi^r_{prod} \cdot producer_c \\ &\quad + \delta^r \cdot D2010 + \psi^r_{prod} \cdot producer_c \cdot D2010_t + \theta' X_{ct} + \mu_{ct}\end{aligned}$$

$$\begin{aligned}\ln(wage_{ct}) &= \alpha^w + \lambda^w \cdot region_c + \phi^w_{prod} \cdot producer_c \\ &\quad + \delta^r \cdot D2010 + \psi^w_{prod} \cdot producer_c \cdot D2010_t + \gamma' X_{ct} + \nu_{ct}\end{aligned} \quad (3.11)$$

where the $region_c$ indicator accounts for region-specific, time-invariant effects. I estimate versions of Equation (3.11) using state-by-year and county dummies.

[21] "Split estate" is the term given to real property for which ownership of the mineral rights and surface use rights is "split" between separate entities. Boslett et al (2016) point out that increases in mineral estate value can bias estimates of environmental damage from house value data because the mineral asset's value can offset value losses due to environmental concerns.

The specification in (3.11) can be further modified to account explicitly for total energy extraction. In particular, the effect of the shale boom on rents and wages may change with total volume of oil and gas produced or the number of new wells constructed or completed. I use the total heating energy produced in millions of BTUs (British Thermal Units) of a county's combined oil and gas produced at time t. To operationalize the treatment intensity estimations, I estimate the modified version of Equation (3.11) given by

$$\begin{aligned} \ln(rent_{ct}) = {} & \alpha^r + \lambda^r \cdot region_c + \phi^r_{prod} \cdot producer_c + \phi^r_{BTU} \cdot producer_c \cdot \ln(BTU_{ct}) \\ & + \delta^r \cdot D2010_t + \psi^r_{prod} \cdot producer_c \cdot D2010_t + \psi^r_{BTU} \cdot producer_c \cdot D2010_t \cdot \ln(BTU_{ct}) \\ & + \theta' X_{ct} + \mu_{ct} \end{aligned}$$

$$\begin{aligned} \ln(wage_{ct}) = {} & \alpha^w + \lambda^w \cdot region_c + \phi^w_{prod} \cdot producer_c + \phi^w_{BTU} \cdot producer_c \cdot \ln(BTU_{ct}) \\ & + \delta^w \cdot D2010_t + \psi^w_{prod} \cdot producer_c \cdot D2010_t + \psi^w_{BTU} \cdot producer_c \cdot D2010_t \cdot \ln(BTU_{ct}) \\ & + \gamma' X_{ct} + \nu_{ct} \end{aligned}$$

(3.12)

to obtain the effect of a percent change in BTUs extracted.

In addition, I also directly estimate Shapiro's (2006) formulation of quality-of-life growth by county and region. Let κ_c be the budget share of housing for consumers in county c as specified in Section 3.3.[22] I estimate the change in quality of life as

$$\begin{aligned} \kappa_c \cdot \Delta_{t+1} \ln(rent_{ct}) - \Delta_{t+1} \ln(wage_{ct}) = {} & \alpha + \lambda \cdot region_c + \phi_{prod} \cdot producer_c \\ & + \phi_{BTU} \cdot \Delta_{t+1} \ln(BTU_c) + \psi_{BTU} \cdot \ln(BTU_{ct}) \\ & + \Gamma' X_{ct} + \eta_{ct} \end{aligned} \qquad (3.13)$$

The left-hand side of Equation (3.13) is equivalent to the expression $\kappa_c \cdot \left(\ln(rent_{c1}) - \ln(rent_{c0})\right) - \left(\ln(wage_{c1}) - \ln(wage_{c0})\right)$, using the time period conventions described above.[23] Necessarily, I assume that both $rent_{ct}$ and $wage_{ct}$ are affected by contemporaneous measures

[22] I obtain the budget share from Bureau of Labor Statistics Consumer Expenditure Survey estimates, which are disaggregated by region. If county c is in region n, I use region n's share estimate for county c.

[23] This construction assumes κ to be constant over time. I use the year-2000 budget share below, since it is quite close to the 2010 budget share, on average.

of shale energy activity and their changes over time—i.e. growth in quality-of-life is a function of both the levels and the changes in a panel of county characteristics.

The marginal willingness to pay (MWTP) for a change in energy production as specified in Equation (3.5) can be calculated from estimated coefficients. Leveraging the difference-in-differences study design, I calculate MWTP for the years 2000 and 2010 as well as the difference between them. Formally, these are:

$$\widehat{MWTP}^{2000}_{\%\Delta BTU} = \kappa_c \cdot \hat{\phi}^r_{BTU} - \hat{\phi}^w_{BTU}$$

$$\widehat{MWTP}^{2010}_{\%\Delta BTU} = \kappa_c \cdot \left(\hat{\phi}^r_{BTU} + \hat{\psi}^r_{BTU}\right) - \left(\hat{\phi}^w_{BTU} + \hat{\psi}^w_{BTU}\right) \tag{3.14}$$

$$\Delta\widehat{MWTP}_{\%\Delta BTU} = \kappa_c \cdot \hat{\psi}^r_{BTU} - \hat{\psi}^w_{BTU}$$

In addition, since my analysis considers the effects of the shale boom in both land and labor markets, I must account for linkages between industries. That is, a labor demand shock in the mining industry may have different effects across the suite of non-mining industries in oil and gas producing counties. I estimate variations of the auxiliary regressions

$$\begin{aligned} \ln(wage_{cit}) &= \alpha_i^w + \phi_i^w \cdot producer_c + \delta_i^w \cdot D2010_t + \psi_i^w producer_c \cdot D2010_t + \gamma_i' X_{ct} + \nu_{cit}^w \\ \ln(empl_{cit}) &= \alpha_i^e + \phi_i^e \cdot producer_c + \delta_i^e \cdot D2010_t + \psi_i^e \cdot producer_c \cdot D2010_t + \pi' X_{ct} + \nu_{cit}^e \end{aligned} \tag{3.15}$$

to examine the impact of the shale boom on wages and employment by industry. In the presence of a labor demand shock brought on by the shale boom, wage and employment increases in mining and related sectors are to be expected—however, a sufficiently large shock to the return on labor may drive up wages across multiple sectors and cause increased employment in other industries through spillovers or increased demand for goods and services.

3.5 – Data

Data come from multiple sources; summary statistics are presented in Tables 3.1 through 3.6. All data vary at the county level except expenditure shares, which vary at the regional level. Wage and employment data are annual estimates taken from the Bureau of Labor Statistics (BLS) Quarterly Census of Employment and Wages (QCEW). County employment levels are BLS annual estimates. The wage observations are county-level average annual wage per worker, calculated as the total wages paid within the county divided by estimated annual average employment. Both measures are available disaggregated by industry as well as aggregated; I estimate Equations (3.9) through (3.13) with fully aggregated wage and employment data, while Equation (3.15) uses industry-specific data at the 2-digit NAICS code level. It should be noted that oil and gas producing counties tend toward lower populations than non-producers in both 2000 and 2010, visible in Table 3.2. It is therefore not surprising that total employment levels follow a similar pattern.

House value observations come from the 2000 Decennial Census and the 2010 American Community Survey (ACS), which replaced the Census as a means to collect house value data in 2005. Census house value observations are taken from the 2000 representative-sample results (Census SF-3 data) and describe county-average median value of owner-occupied housing. The same metric appears in the 2010 ACS 5-year estimates, which uses a weighted moving average process across county-level surveys since 2005. House prices are higher in non-producing counties both before and after the shale boom, although this can be attributed to other factors, e.g. non-producing counties are also more populous and have greater urban influence than non-producing counties.

I use BLS Consumer Expenditure Survey (CES) estimates of housing expenses to compute average budget shares (κ in the exposition above). CES estimates disaggregated to the level of the four Census regions (West, Midwest, South and Northeast) are available, and I use these to compute κ as the ratio of the total estimated expense on housing to estimated average annual expenditures for each region and assign the appropriate regional value to each county. On average, housing comprises between 31% and 33% of total expenditures, with some variation across regions.

To measure oil and gas production, I use the county-level oil and gas production series published by the USDA's Economic Research Service. The series reports gross barrels of oil and thousands of cubic feet of natural gas produced on-shore annually for all counties in the continental United States. While the series does not distinguish shale versus non-shale production, data from the Energy Information Administration highlights that major shale plays in the U.S. are responsible for over 90% of domestic on-shore oil and gas production growth in recent years.[24] The data series includes an indicator of whether or not the change in total value of a county's mineral resources extracted exceeds $20 million; I use this indicator to denote whether a county is a "boom" county.[25] Table 3.3 summarizes these measures, and a visual representation of the geographic distribution of thermal energy growth is presented in Figure 3.1. Table 3.4 reports the distribution of outcomes of interest by boom county. As noted above, I compute the total BTUs produced (in millions) using the EIA's conversion rates based on 2014 consumption rates. Some counties may produce large volumes of natural gas but negligible amounts of oil; computing BTU production allows me to observe a consistent measure of potential energy for all counties. The summary statistics show similar maximal production of oil between 2000 and 2010, and mean production increases by only 37,089 barrels (approximately 4.4%), although the standard deviation grows during this time-period. Mean natural gas production, however, shows a greater proportionate increase of approximately 4,856 million cubic feet (approximately 35.3%), with growth in maximal county-level production and standard deviation. This suggests that the advent of directional drilling/hydraulic fracturing technology affected counties with existing oil infrastructure.

I follow Weber (2012) in using two-stage least squares to avoid bias of estimated coefficients due to unobserved heterogeneity in counties. In particular, I use the percent of a county's surface area that overlaps the shale geography to instrument for a county's status a "boom" county, which is the same strategy followed by Weber (2012). In my results below, I report the first-stage F-test and Wu-Hausman endogeneity test statistic along with estimated parameters. County surface areas come from the U.S.

[24] See https://www.eia.gov/petroleum/drilling/

[25] This generally follows the strategy taken by Weber (2012) and Jacobsen (2016).

Census Bureau's TIGER GIS shapefile repository,[26] while shale geography shapefiles were taken from the U.S. Energy Information Administration's shale oil and gas maps webpage.[27]

Additionally, I include county-level measures of education, poverty and the logarithm of population as controls. Education includes the percentage of county populations with a high school degree and percent with a college degree, while poverty is the percent of a county's population with wages below the federal poverty line. I do not consider unemployment rates. I take these data from the American Community Survey and Census tables. I also use USDA Rural-Urban Continuum Codes (RUCC) and Natural Amenities Scale to characterize how rural a county is. RUCC values vary from 1 to 9, with 1 representing an urban county with a population of at least 1 million and 9 representing a county of less than 2,500 people and not adjacent to a metropolitan area.[28] Similarly, the Natural Amenities Scale is an index that ranks counties based on the physical characteristics that influence quality-of-life, including climate, topography and water area.[29] These measures are not time-varying, and thus will have the same average values in both 2000 and 2010. On average, we can see that oil-producing counties are less populated, less urban, less educated and less wealthy than non-producing counties, but with greater natural amenities.

My analysis includes 2,141 counties, 1,114 of which have nonzero BTU production between 2000 and 2010. Counties were chosen based on the presence of state-level oil production; as an example, since North Dakota is home to several oil and gas producing counties, all counties in North Dakota were sampled for the dataset. However, I do not capture all oil and gas producing counties in the United States. I use data from the following states: Alabama, Arkansas, Arizona, Colorado, Illinois, Indiana, Kansas, Kentucky, Louisiana, Maryland, Michigan, Missouri, Mississippi, Montana, North Dakota, Nebraska, New Mexico, Nevada, New York, Ohio, Oklahoma, Pennsylvania, South Dakota, Tennessee, Texas,

[26] The data are publically available at https://www.census.gov/geo/maps-data/data/tiger-line.html

[27] See https://www.eia.gov/maps/maps.htm#shaleplay

[28] See https://www.ers.usda.gov/data-products/rural-urban-continuum-codes/documentation.aspx

[29] See https://www.ers.usda.gov/data-products/natural-amenities-scale/

Utah, Virginia, West Virginia and Wyoming. These overlap or are adjacent to the shale regions responsible for the majority of U.S. on-shore oil and gas production between 2000 and 2010.

3.6 – Results

Estimation results are presented in Tables 3.7 through 3.12. Tables 3.7 and 3.8 report the IV results with associated OLS comparisons. I estimate the specifications in Equations (3.10) through (3.13) independently (equation-by-equation) and as a system. Marginal results from equation-by-equation estimations appear in Table 3.9. Full marginal effects are presented in Appendix C, along with SUR estimation results, selected industry-specific wage and employment results and alternative measures of rent (gross monthly rent, mobile home value).

The results reported in Table 3.7 suggest that the shale boom had positive and significant effects on boom counties relative to non-boom producing counties. The boom county coefficient in the wage IV specification corresponds to a 22.8% wage gain over 10 years in boom counties, while boom county employment increased approximately 4% per year between 2000 and 2010. Similarly, median house values rise by 1.8% per year. These rates of growth closely parallel Weber's (2012) results of 1.5% employment growth and 2.6% annualized wage gain. The first-stage F-statistics are reasonably high, and the Wu-Hausman test rejects the null hypothesis of consistent OLS for all three IV specifications. Comparing the growth equation results reported in Table 3.7 with the equation-by-equation panel estimation reported in Table 3.8, the interaction between the boom county dummy and the boom-period indicator (Year = 2010) is not significant in either the OLS or IV specifications.

However, there is still evidence of a positive labor demand shock. As reported in Table 3.9, a 1% increase in BTUs produced in 2000 is associated with a wage increase of approximately 0.5% within the set of producing counties. The additional effect of production in 2010 is 0.6% for a 1% BTU increase. Employment increases by 0.6% per additional BTU percentage in 2010; the production effect on employment in 2000 is not statistically different from zero. In contrast to the IV growth-equations reported above, house value is negatively related to production, with the median house value decreasing by 0.5% for each 1% change in BTUs produced in 2000. While the effect of production in 2010 is not statistically different from zero unless county fixed effects are specified, the effects production in both years together are jointly significant in specifications with state fixed effects. Production in 2010 is associated with a median house value increase of 0.4%. In principle, this is not enough to offset the base year effect; however, given the small size of the difference, it may not be of any practical significance.

The results of the difference series estimation of Equation (3.13) are presented in Table 3.10. Of greatest interest is the coefficient associated with $\Delta \ln(BTU)$, i.e. the effect of the percent change in total energy produced between 2000 and 2010. A unit increase in growth rate of energy production (listed under Δ log BTU in Table 3.10) is associated with a decrease of 0.004 in the rate of quality of life growth. Multiplied by average on-shale annual wages in 2010, the implied dollar value of the decrease in quality of life is approximately \$106 per worker. The implication is that oil-producing counties with the highest proportionate increases in energy production also experience the greatest decreases in quality of life. Among producing counties, lower production is associated with higher growth in quality of life—this is largely due to lack of wage growth in low-production counties. However, a 1% increase in pre-boom production is associated with a 0.005 percentage-point increase in quality of life growth.

The treatment-on-treated effects from the panel specifications are presented in Table 3.11, along with the total effect of producing-county status and log BTU production. I calculate these as the linear combination of treatment coefficients weighted by observed treatment measures for each row in the data set. Formally, this is equivalent to computing the linear combination

$$\hat{\phi}_{prod} \cdot producer_c + \hat{\phi}_{BTU} \cdot OGC_c \cdot \ln(BTU_{ct}) + \hat{\psi}_{prod} \cdot producer_c \cdot D2010_t + \hat{\psi}_{BTU} \cdot OGC_c \cdot D2010_t \cdot \ln(BTU_{ct})$$

for each county c. Averaging over producing counties in the second period ($t = 2010$) yields the total effect, while the treatment-on-treated effect is given by subtracting the average over producing counties in the first period, i.e. calculating only the $\hat{\psi}$ terms in the expression above.

The effects reported in Table 3.11 can be interpreted as the average percent change in wages, median house values and employment given a county's shale activity. The average treatment effect (Average Treatment-on-Treated) characterizes the changes in the ex-post time-period attributable to belonging to the treatment group. This is a 3.7% to 3.9% wage increase, a house value decline of 1% to

1.5% and an employment increase of 4.1% to 4.4% in the shale boom period. The total effect of oil and gas production activity includes the average treatment effect, decomposing the panel variation in wages, house values and employment in energy-producing counties by total energy content produced (in millions of BTUs). The discrete difference-in-differences specification (column 3) measures a 6% wage increase, a 9.2% decline in house values and a 4.5% increase in employment relative to counties with no oil and gas production activities. The effects listed in column 4 of Table 3.11 account for the influence of county-level energy production. Including the log of million BTUs produced yields increases of 7.1% and 5.3% for wages and employment respectively, and a decline in median house value of 9.7%.

These positive wage and employment effects suggests the shale boom did indeed stimulate an increase in labor demand, but the negative ATT and joint effects on house values suggest that the disamenties associated with living near shale boom activity outweighed the prospective gains of in-migration. Anecdotal evidence of the temporary nature of oil work suggests that few workers would consider a permanent relocation, but if so, alternative rental measures must be bid up—if workers are not buying real estate, they may be renting it. Panel estimation of alternative rent measures reveals that neither mobile home values nor gross monthly rents are greatly affected (see Appendix, Table C.5).

The changes in the local willingness to pay for BTU production are summarized in Table 3.12. Coefficient estimates are similar for the equation-by-equation and SUR regressions, as expected, but the SUR regression allows for calculation of the standard error of a linear combination of variables across equations. Panel A of Table 3.12 reports the percentage marginal willingness to pay for a 1% increase in BTUs produced, complete with standard errors where applicable. Panel B of Table 3.12 presents the monetized version of these results.[30]

Specifications with county-level controls show a positive willingness to pay for additional energy production in 2000 while the state-level control specification yields a negative MWTP. The result is only significant for the estimation using state-level controls. The magnitudes are not unreasonable: for the

[30] The equation-by-equation columns of Table C.9 follow Roback's (1982) MWTP calculation, combining coefficients without accounting for cross-equation correlation—consequently, the results reported in these columns have neither standard errors nor number of counties associated with them.

year 2000, using state-level controls yields an estimate of $163 to avoid a 1% increase in county BTU extraction, while the county-control specification yields a $36 benefit from additional oil production. In 2010, however, high growth in incomes relative to growth in house values yields a willingness to pay of between $262 and $194 to avoid a 1% increase in BTUs produced. Both state- and county FE specifications yield significant t-statistics in 2010, indicating that the gap between wages and house values is larger after the beginning of the shale boom than prior to it. The difference-series MWTP calculation is identical to the reported coefficient for Δ log BTU in Table 3.10.

3.7 – Conclusion

The U.S. shale energy boom has been associated with large increases in returns to labor, demand for labor at all wages and changes in the return on land. The analysis above characterizes and quantifies these effects, implying that the main economic impacts in energy-producing counties stem from high wages and labor demand overcoming workers' reticence to locate themselves in the less-hospitable regions known for oil and natural gas production. I find evidence that real estate values in energy-producing counties decrease relative to non-energy counties, although counties with higher levels of shale activity experienced smaller median house value declines than low-producing counties.

While instances of property value increases due to shale resource exploitation are reported in the literature (e.g. Weber and Hitaj (2014)), my results suggest that energy rents are not systematically capitalized into residential real estate values. There exists the possibility that, while there may be some resource rents capitalized into house values in areas with greater energy production, the distribution of this capitalization is limited to houses in close proximity with oil and gas wells and may be correlated with unobservables such as split ownership of surface and mineral rights. According to Fitzgerald (2014), however, large portions[31] of oil and gas rights in the U.S. are held by absentee owners. While this may be beneficial for wealth creation in the communities in which mineral rights owners live (Brown et al (2016),

[31] Fitzgerald (2014) reports that, as of 2012, the production-weighted proportion of mineral leases held in-county in Colorado, Louisiana, Montana, New Mexico, North Dakota, Ohio, Oklahoma, Pennsylvania, Texas, Utah, West Virginia and Wyoming was approximately 36.5%.

Hitaj (2016), it also implies that the majority of land transactions will not include the mineral estate. Additionally, I use the median home value in my analysis, which will not be greatly affected if a small number of housing units capitalize oil and gas royalties into property values.

My estimates of the shale boom's wage and employment effects are consistent with the established literature, suggesting that local labor trends identified in the Eagle Ford, Marcellus and Niobrara shales (Brown (2014), Komarek (2015), Weber (2012)) are indicative of a general trend. These measures do not distinguish workers' long-run home, however; rather, I use data that describe labor market metrics by employment location. This necessarily means that I observe wages paid to non-resident employees, and I am not able to isolate the returns to labor captured by local residents.[32] Although this precludes me from claiming implications for local wealth, I am still able to interpret the wage changes as informing the quality of life.

The significant negative willingness-to-pay for additional BTU production in 2010 indicates that the shale boom is responsible for creating disamenity at the local level. On the one hand, this may be due to the compendium of fracking-related maladies identified in the literature, including traffic congestion, noise, industrial chemical spills, methane leakage, unsightly infrastructure and perceived threats to water quality (Krupnick et al (2017)). On the other hand, this might also be an indication of expectations about the transient nature of the energy boom. Employment may be both lucrative and plentiful during the boom period, but if workers expect that their fortunes will be short-lived, they will perceive minimal incentive to make the investment of re-locating into oil boomtowns (see Jaquet (2014) for an overview). While there still may be some upward pressure on land rent due to limited in-migration, the expectation of a short boom period may cause rental bids to be "shaded down" as a hedge against the possibility of employment termination. This may be especially true in areas like the Bakken region, where low housing stocks and lack of urban amenities make permanent re-location costly.

[32] In theory, this is not an issue—assuming that resident labor and non-resident labor are perfectly substitutable inputs vis-à-vis the jobs created by the shale boom, there is no reason to suspect that worker residence is related to selection into energy jobs.

One caveat bears mention, however—the IV results presented above attribute positive house value growth impacts to the shale boom, while OLS results are in general insignificant or negative. This could potentially be the result of the restricted dataset used to estimate the IV results—namely, non-boom producing counties were used as controls for boom counties in the IV estimations, while OLS results used the full set of counties. In addition, IV estimation of the wage, house value and employment effects of a percent change in BTUs failed the weak instruments test.

Further study may reveal longer-lasting effects of the shale boom. For example, Allred et al (2015) identified negative impacts to ecosystem services from expanded shale energy development, and various studies have found evidence of negative environmental impacts local to shale energy infrastructure (Olmstead et al (2012)). The immediate effects captured by hedonic studies (e.g. Boxall et al (2005), Gopalakrishnan and Klaiber (2012)) may not reflect correct information about the long-run environmental consequences of shale energy development. An expansion of the present study might use repeat sales of land across a variety of uses—including residential, commercial and agricultural—to examine whether structural environmental changes have occurred that affect the return on land.[33] Another extension of the present study might characterize the changes in the distribution of incomes and house values in response to more permanent infrastructure changes, such as existing oil and gas wells or pipelines, perhaps leveraging local information on land reclamation from capped wells.

[33] A number of studies (Gayer, et al (2000, 2002), Gayer and Viscusi (2002)) use Bayesian updating to examine the response of house values to information regarding hazardous waste sites and brownfield cleanups.

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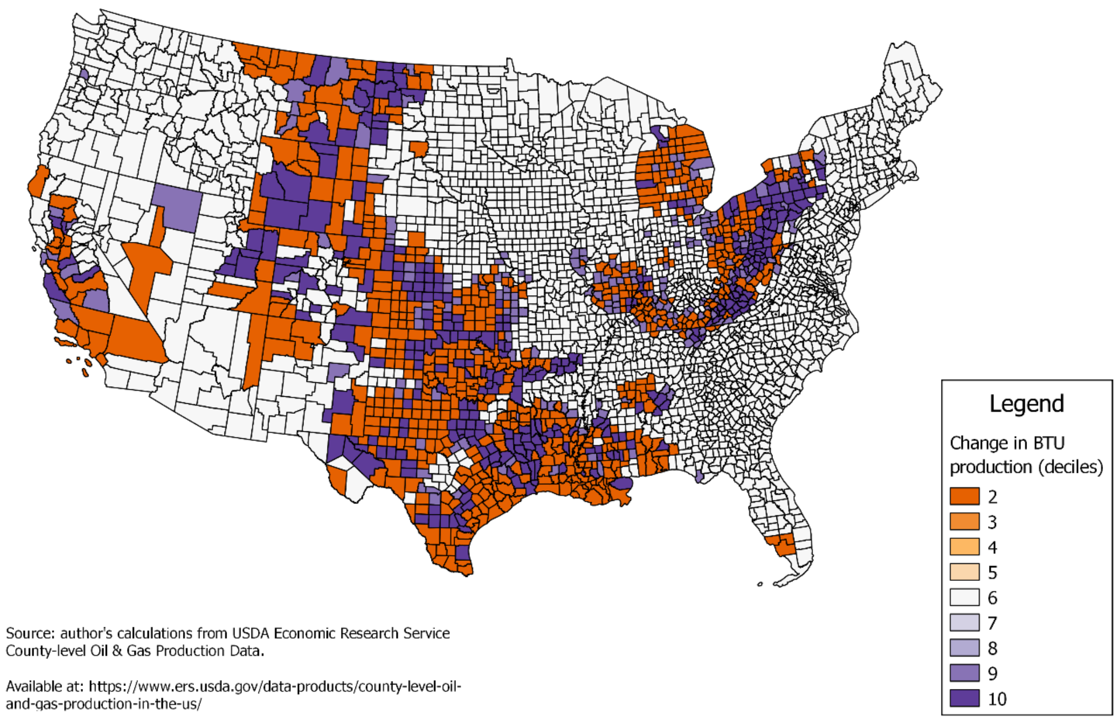
Chapter 3 Figures and Tables



Note: Deciles 4-6 experience approximately zero change; counties in the top decile gained between 0.46 and 795.6 trillion BTUs, while counties in the lowest decile lost between 0.94 and 414 trillion BTUs as drilling geography shifted between 2000 and 2010.

Figure 3.1: Growth in U.S. county-level energy output, 2000-2010

Table 3.1: Regional distribution of counties

Region	Non-producer	Producer
Midwest	450	344
Northeast	91	60
South	385	594
West	101	116
Observations:	1,027	1,114

Table 3.2: Summary Statistics - outcomes of interest

Year	2000		2010	
County type	Non-producer	Producer	Non-producer	Producer
Wage ($/year)				
mean	$23,742.67	$23,996.28	$32,044.62	$33,773.01
sd	6100.658	5660.479	8141.276	7564.976
min	$12,945.00	$12,642.00	$16,294.00	$15,831.00
max	$77,196.00	$54,648.00	$108,634.00	$73,067.00
Median house value ($)				
mean	$81,676.53	$66,676.48	$131,395.42	$101,400.90
sd	40774.659	27581.815	80731.717	43743.782
min	$22,500.00	$20,800.00	$19,400.00	$33,900.00
max	$497,000.00	$297,900.00	$827,300.00	$489,800.00
Employment level				
mean	29,980.68	25,036.48	29,428.26	23,801.01
sd	121,872.94	93,875.64	114,135.42	88,454.50
min	61	19	37	40
max	2,371,728.00	1,612,079.00	2,041,915.00	1,724,278.00
Observations:	1,027	1,114	1,027	1,114

Table 3.3: Summary statistics - oil and gas production by boom-county status

Year	2000			2010		
	Non-boom	Boom	All producers	Non-boom	Boom	All producers
BBL of oil produced (total barrels)						
mean	740,475.33	1,228,681.93	833,821.84	527,087.00	2,325,305.76	870911.593
sd	2,596,139.47	3,233,846.69	2,734,763.87	1,978,787.52	5,348,840.00	3019321.119
min	0	0	0	0	0	0
max	41,362,916.00	26,369,132.00	41,362,916.00	33,168,800.00	46,192,752.00	46192752
Million cubic feet of natural gas						
mean	11,752.92	22,285.81	13,766.84	7,775.48	64,510.08	18623.299
sd	42,525.32	52,464.01	44,763.52	32,082.88	130,628.03	67681.393
min	0	0	0	0	0	0
max	706,343.70	448,281.67	706,343.70	506,159.22	1,198,145.30	1198145.298
Total BTU produced (millions)						
mean	16,376,756.43	30,036,165.72	18,988,474.72	11,050,297.98	79,803,136.59	24196038.22
sd	50,886,166.41	63,233,995.60	53,706,253.96	38,061,315.10	140,151,780.36	75129968.08
min	0	0	0	0	0	0†
max	734,886,896.71	480,234,920.10	734,886,896.71	526,378,747.59	1,275,894,974.94	1275894975
Observations:	891	223	1,114		891	1,114

†The minimum BTU observation is zero due to a gap in the USDA's dataset--a single boom_county did not report data for 2010. The second-lowest value is 425700 million BTUs.

Table 3.4: Summary Statistics - outcomes of interest by boom county status

Year		2000		2010	
County type		Non-boom	Boom	Non-boom	Boom
Wage ($/year)					
	mean	$23,970.05	$24,107.25	$33,290.38	$35,814.54
	sd	5770.324	5181.352	7294.801	8328.571
	min	$12,642.00	$13,771.00	$15,831.00	$21,828.00
	max	$54,648.00	$45,220.00	$73,067.00	$67,859.00
Median house value ($)					
	mean	$67,606.88	$62,740.85	$101,518.65	$100,902.82
	sd	27300.063	28473.652	42028.139	50467.283
	min	$24,100.00	$20,800.00	$36,600.00	$33,900.00
	max	$281,600.00	$297,900.00	$469,600.00	$489,800.00
Employment level					
	mean	24,165.11	28,722.40	22,857.64	27,791.52
	sd	84,785.59	125,426.59	81,883.86	112,217.53
	min	50	19	40	64
	max	1,612,079.00	1,418,422.00	1,724,278.00	1,239,313.00
Observations:		891	223	891	223

Table 3.5: Summary Statistics - county-level characteristics

Year		2000		2010	
County type		Non-producer	Producer	Non-producer	Producer
House expenditure share (proportion)					
	mean	0.315	0.315	0.336	0.337
	sd	0.014	0.012	0.012	0.01
	min	0.305	0.305	0.326	0.326
	max	0.347	0.347	0.36	0.36
Population					
	mean	80,074.08	66,742.38	87,667.71	71,507.28
	sd	265,664.98	190,179.32	278,729.29	209,788.08
	min	444	356	460	286
	max	5,376,741.00	3,400,578.00	5,194,675.00	4,092,459.00
Poverty rate (%)					
	mean	12.259	13.955	13.33	14.345
	sd	5.95	5.914	5.772	5.501
	min	2.1	2.9	1.1	0
	max	53.5	45.7	51.7	41.6
HS graduation rate (%)					
	mean	35.35	35.245	36.35	36.553
	Sd	6.743	6.434	7.002	6.613
	min	10.9	15.1	9.4	8.2
	max	52.5	53.2	54.6	54.4
Bachelors degree rate (%)					
	mean	10.948	10.066	12.641	11.545
	sd	5.186	4.328	5.567	4.7
	min	3.1	2.5	3.1	1.9
	max	40	36.6	42.2	36.1
USDA amenities score					
	mean	-0.336	-0.006	-0.336	-0.006
	sd	2.131	1.777	2.131	1.777
	min	-5.4	-3.98	-5.4	-3.98
	max	8.52	6.45	8.52	6.45
USDA RUCC score					
	mean	5.089	5.399	5.089	5.399
	sd	2.802	2.616	2.802	2.616
	min	1	1	1	1
	max	9	9	9	9
Observations:		1,027	1,114	1,027	1,114

Table 3.6: Summary Statistics - county-level characteristics by boom-county status

Year		2000		2010	
County type		Non-boom	Boom	Non-boom	Boom
House expenditure share (proportion)					
	mean	0.314	0.318	0.336	0.34
	sd	0.012	0.013	0.01	0.01
	min	0.305	0.305	0.326	0.326
	max	0.347	0.347	0.36	0.36
Population					
	mean	65,291.20	72,880.93	69,817.30	78,655.98
	sd	180,470.05	227,089.44	201,107.58	243,510.08
	min	356	767	286	695
	max	3,400,578.00	2,218,899.00	4,092,459.00	2,368,139.00
Poverty rate (%)					
	mean	13.85	14.399	14.437	13.957
	sd	6.064	5.22	5.656	4.782
	min	2.9	4.7	0	1.9
	max	45.7	33.1	41.6	29.6
HS graduation rate (%)					
	mean	35.38	34.664	36.669	36.059
	sd	6.443	6.377	6.631	6.529
	min	15.1	15.1	8.2	14.4
	max	53	53.2	54.4	52
Bachelors degree rate (%)					
	mean	9.976	10.448	11.471	11.859
	sd	4.327	4.321	4.701	4.693
	min	2.5	3.3	1.9	4.3
	max	31.7	36.6	34.1	36.1
Observations:		891	223	891	223

Table 3.7: Effect of the shale boom on wage, house value and employment growth

	Dependent variable:					
	$\Delta\ln(wage)$		$\Delta\ln(house\ value)$		$\Delta\ln(employment)$	
	OLS	IV	OLS	IV	OLS	IV
Boom county	0.028***	0.228***	0.008	0.184**	0.050***	0.395***
	(0.010)	(0.079)	(0.009)	(0.075)	(0.014)	(0.124)
Δ HS grad %	-0.003*	-0.003	0.0004	0.001	-0.001	-0.001
	(0.002)	(0.002)	(0.002)	(0.002)	(0.003)	(0.003)
HS grad %, 2000	-0.003*	-0.003*	-0.00001	-0.0005	-0.005**	-0.006**
	(0.001)	(0.002)	(0.001)	(0.001)	(0.002)	(0.002)
Δ Bachelors degree %	-0.001	0.002	0.010***	0.012***	-0.001	0.003
	(0.003)	(0.004)	(0.003)	(0.003)	(0.005)	(0.005)
Bachelors degree %, 2000	-0.004**	-0.003*	0.002	0.002	0.001	0.001
	(0.002)	(0.002)	(0.002)	(0.002)	(0.003)	(0.003)
Δ Poverty rate	-0.002	-0.0002	-0.005**	-0.003	-0.004	-0.001
	(0.002)	(0.002)	(0.002)	(0.002)	(0.003)	(0.004)
Poverty rate, 2000 (%)	0.002*	0.002	0.002	0.001	-0.001	-0.002
	(0.001)	(0.001)	(0.001)	(0.001)	(0.002)	(0.002)
Δ ln(population)	0.032	-0.024	0.255***	0.205***	0.855***	0.758***
	(0.058)	(0.064)	(0.052)	(0.063)	(0.072)	(0.086)
ln(population), 2000	-0.022**	-0.024***	-0.007*	-0.009*	-0.022***	-0.025***
	(0.005)	(0.006)	(0.005)	(0.005)	(0.007)	(0.008)
Constant	0.632***	0.653***	0.429***	0.448***	0.241*	0.278*
	(0.103)	(0.120)	(0.100)	(0.106)	(0.141)	(0.169)
Weak instruments statistic		25.01		25.01		25.01
Wu-Hausman statistic		10.35		7.64		12.5
Fixed effects:	State	State	State	State	State	State
Observations	1,114	1,114	1,114	1,114	1,114	1,114
R^2	0.375	0.103	0.516	0.313	0.382	0.019

Note: *** p <0.001, ** p < 0.01, * p < 0.05.

Table 3.8: Shale boom impacts, producing counties only - panel estimation

	Dependent variable:					
	ln(wage)		ln(house value)		ln(employment)	
	IV	OLS	IV	OLS	IV	OLS
2010 dummy	0.287***	0.300***	0.367***	0.378***	-0.181*	-0.164*
	(0.063)	(0.061)	(0.033)	(0.031)	(0.104)	(0.086)
Boom county	0.162*	0.024*	-0.122	-0.037***	-0.567**	-0.007
	(0.093)	(0.014)	(0.095)	(0.014)	(0.225)	(0.025)
year=2010× boom county	0.172	0.022	0.132	0.008	0.257	0.04
	(0.144)	(0.021)	(0.143)	(0.021)	(0.302)	(0.038)
HS grad rate (%)	-0.004**	-0.004***	-0.0003	-0.0004	-0.015***	-0.015***
	(0.002)	(0.001)	(0.001)	(0.001)	(0.003)	(0.003)
Bachelors degree %	0.002	0.002	0.028***	0.028***	0.008**	0.009***
	(0.002)	(0.002)	(0.002)	(0.002)	(0.003)	(0.003)
Poverty rate (%)	-0.013***	-0.013***	-0.021***	-0.021***	-0.016***	-0.016***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.002)	(0.002)
ln(population)	0.048***	0.051***	0.096***	0.095***	1.118***	1.113***
	(0.005)	(0.004)	(0.005)	(0.004)	(0.009)	(0.008)
Constant	9.939***	9.936***	10.170***	10.173***	-1.911***	-1.893***
	(0.109)	(0.100)	(0.089)	(0.088)	(0.207)	(0.198)
Weak instruments statistic:	22.490		22.490		22.490	
Wu-Hausman statistic:	5.33		0.489		5.873	
State-by-year FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	2,228	2,228	2,228	2,228	2,228	2,228
R^2	0.523	0.614	0.834	0.838	0.945	0.956

Note: *** p <0.001, ** p < 0.01, * p < 0.05

Table 3.9: OLS estimates of shale boom impacts, all counties

	Dependent variable:								
	ln(wage)			ln(house value)			ln(employment)		
2010 dummy	0.286*** (0.032)	0.286*** (0.032)	0.318*** (0.008)	0.394*** (0.022)	0.395*** (0.021)	0.422*** (0.009)	-0.185*** (0.051)	-0.184*** (0.051)	-0.079*** (0.014)
Producing county	0.023*** (0.009)	-0.038** (0.015)	-0.111 (0.144)	-0.076*** (0.010)	-0.011 (0.015)	0.498*** (0.178)	0.004 (0.020)	-0.03 (0.034)	-0.257 (0.184)
ln(BTU)		0.005*** (0.001)	-0.002 (0.001)		-0.005*** (0.001)	-0.001 (0.001)		0.003 (0.002)	-0.001 (0.002)
year=2010 × producing county	0.037*** (0.013)	-0.043* (0.023)	-0.071*** (0.017)	-0.015 (0.015)	-0.021 (0.026)	-0.087*** (0.018)	0.041 (0.028)	-0.033 (0.050)	-0.066** (0.027)
year=2010 × ln(BTU)		0.006*** (0.002)	0.008*** (0.001)		0.001 (0.002)	0.004*** (0.001)		0.006* (0.003)	0.008*** (0.002)
HS grad %	-0.003*** (0.001)	-0.002** (0.001)	-0.001 (0.002)	-0.002** (0.001)	-0.002** (0.001)	0.004** (0.002)	-0.010*** (0.002)	-0.009*** (0.002)	-0.003 (0.003)
Bachelors degree %	0.004*** (0.001)	0.005*** (0.001)	-0.0004 (0.003)	0.029*** (0.001)	0.029*** (0.001)	0.011*** (0.003)	0.012*** (0.002)	0.012*** (0.002)	0.003 (0.005)
Poverty rate (%)	-0.010*** (0.001)	-0.010*** (0.001)	-0.010*** (0.002)	-0.021*** (0.001)	-0.021*** (0.001)	-0.017*** (0.002)	-0.014*** (0.002)	-0.013*** (0.002)	-0.013*** (0.004)
ln(popluation)	0.062*** (0.003)	0.061*** (0.003)	-0.089** (0.040)	0.087*** (0.004)	0.087*** (0.004)	0.339*** (0.045)	1.123*** (0.007)	1.123*** (0.007)	0.755*** (0.060)
Constant	9.676*** (0.071)	9.665*** (0.070)	11.155*** (0.442)	10.348*** (0.073)	10.352*** (0.072)	7.574*** (0.494)	-2.267*** (0.149)	-2.275*** (0.149)	1.128* (0.679)
Fixed effects:	State · year	State · year	County	State · year	State · year	County	State · year	State · year	County
Observations	4,282	4,282	4,282	4,282	4,282	4,282	4,282	4,282	4,282
R^2	0.632	0.64	0.955	0.842	0.843	0.98	0.953	0.953	0.996

Note: *** p <0.001, ** p < 0.01, * p < 0.05

Table 3.10: OLS estimates of shale boom impacts on quality-of-life

	Dependent variable: $\kappa \cdot \Delta \ln(rent) - \Delta \ln(wage)$			
	(1)	(2)	(3)	(4)
Producing county		-0.030***	0.01	0.027**
		(0.006)	(0.010)	(0.011)
ln(BTU)			-0.003***	-0.005***
			(0.001)	(0.001)
Δ ln(BTU)				-0.004***
				(0.001)
ln(population)	0.023***	0.023***	0.022***	0.021***
	(0.008)	(0.008)	(0.008)	(0.008)
Δ ln(population)	0.272***	0.261***	0.258***	0.260***
	(0.027)	(0.027)	(0.027)	(0.027)
HS grad %	0.002**	0.002**	0.002**	0.002**
	(0.001)	(0.001)	(0.001)	(0.001)
Δ HS grad %	0.004***	0.004***	0.004***	0.004***
	(0.001)	(0.001)	(0.001)	(0.001)
Bachelors degree (%)	0.005***	0.005***	0.004***	0.004***
	(0.001)	(0.001)	(0.001)	(0.001)
Δ Bachelors degree (%)	0.007***	0.007***	0.007***	0.007***
	(0.001)	(0.001)	(0.001)	(0.001)
Δ Poverty rate (%)	-0.001	-0.001	-0.002*	-0.002*
	(0.001)	(0.001)	(0.001)	(0.001)
Poverty rate (%)	-0.001**	-0.001**	-0.001*	-0.001*
	(0.001)	(0.001)	(0.001)	(0.001)
ln(employment)	-0.011	-0.01	-0.008	-0.008
	(0.007)	(0.007)	(0.007)	(0.007)
Δ ln(employment)	-0.269***	-0.262***	-0.256***	-0.254***
	(0.013)	(0.013)	(0.013)	(0.013)
Constant	-0.464***	-0.458***	-0.454***	-0.458***
	(0.056)	(0.056)	(0.055)	(0.055)
Fixed effects:	State	State	State	State
Observations	2,141	2,141	2,141	2,141
R^2	0.366	0.374	0.382	0.385

Note: *** p <0.001, ** p < 0.01, * p < 0.05

Table 3.11: Average Treatment Effects, equation-by-equation

	Average Treatment on Treated		Joint effect of treatment variables	
Effect type:	Discrete	Continuous	Discrete	Continuous
log wage	0.037	0.039	0.06	0.071
	(0.013)	(0.026)	(0.009)	(0.048)
log house value	-0.015	-0.01	-0.092	-0.097
	(0.014)	(0.004)	(0.010)	(0.020)
log employment	0.041	0.044	0.045	0.053
	(0.027)	(0.024)	(0.019)	(0.037)

Note: Effects and standard errors obtained from predicted values.

Table 3.12: Marginal Willingness-to-pay estimates

Measure	Equation-by-equation		SUR estimation		Difference series
Panel A (income proportion)					
MWTP 2000	-0.007	0.002	-0.007	0.001	-
			(0.0012)	(0.0011)	
MWTP 2010	-0.013	-0.005	-0.013	-0.005	-
			(0.0013)	(0.0013)	
Δ MWTP	-0.006	-0.007	-0.006	-0.006	-0.003
			-	-	(0.0011)
Panel B (monetized values)					
MWTP 2000	-163.693	36	-167.974	23.996	-
MWTP 2010	-425.907	-157.692	-439.049	-168.865	-
Δ MWTP	-262.214	-193.692	-271.075	-192.861	-106.122
Fixed effects:	State · year	County	State · year	County	State
Num. Obs	N/A	N/A	1,114	1,114	1,114

Note: Standard errors appear in parenthesis, where applicable.

APPENDIX B: CHAPTER 3 ADDITIONAL FIGURES AND TABLES

Examining the subset of wages in six of the major shale energy regions of the U.S., it becomes apparent that regional wages were roughly parallel in boom and non-boom counties prior to the start of the shale boom. In Figures B.1 – B.8, I have denoted the year 2006 with a vertical line. In Figure B.1, wage trends diverge approximately following the shale boom start years in each region, although the deviations from pre-trend are not always clear. Similar results are visible in Figure B.2, which decomposes average wages across boom and non-boom counties by industry. Agriculture, mining, transportation and wholesale trade occupations experience wage growth in boom counties that roughly follows shale boom years. Construction occupation wages follow similar trends during the boom years, but both types of counties experience construction wage growth above non-producing county trends.

Changes in house value trends are less obvious. Among the alternative measures described in Figures B.3 – B.8, only mobile home values appear to respond to the shale boom. Data points are sparse in the Bakken region, but house values, rents and mobile home values rise faster in boom counties than non-boom counties in the region. However, mobile home value growth in the Marcellus and Utica regions declines after rising during the initial boom period, while house values and gross rents follow similar trends across producing counties in these regions.

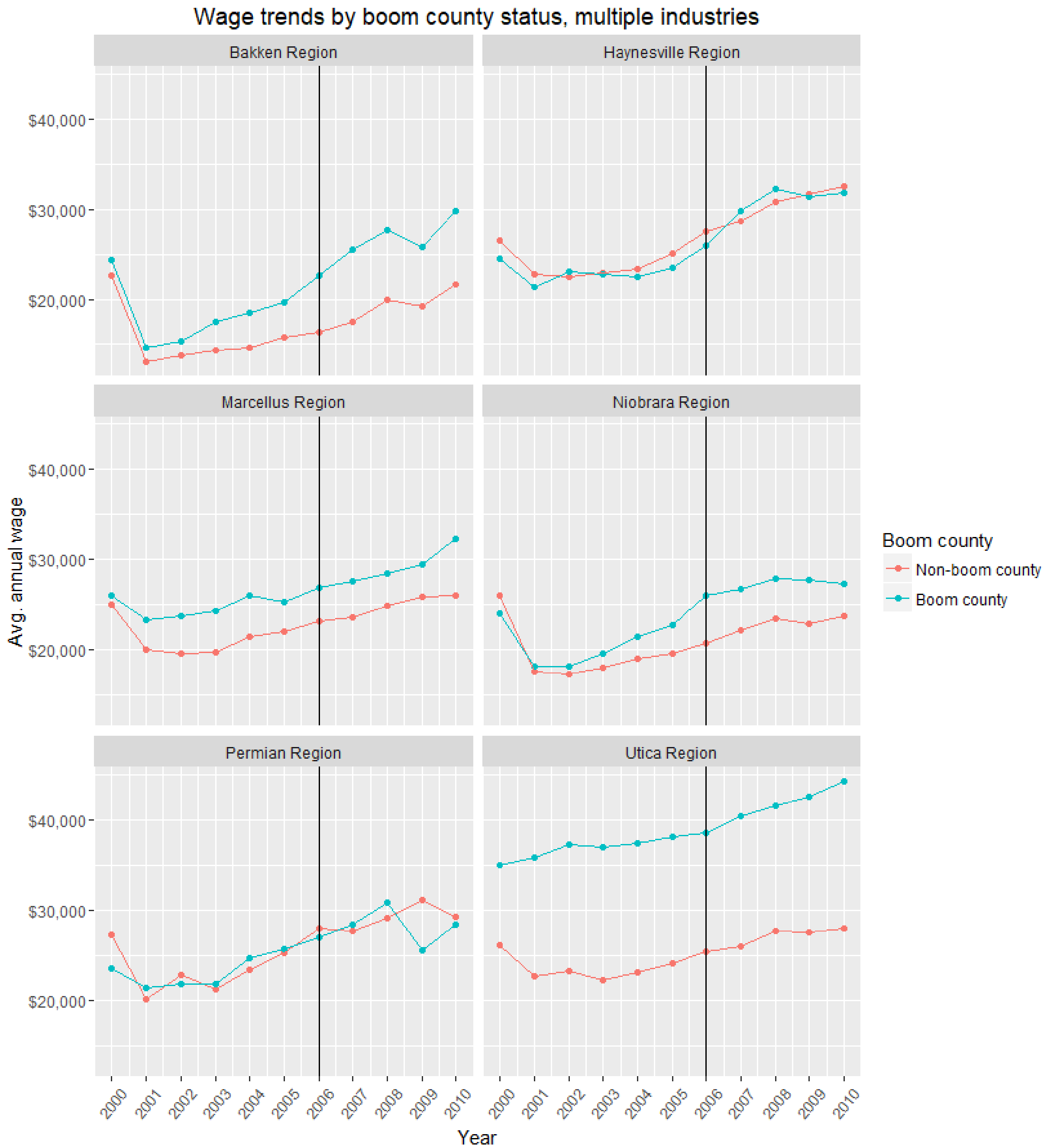


Figure B.1: Regional wage trends for boom and non-boom counties (producers only)

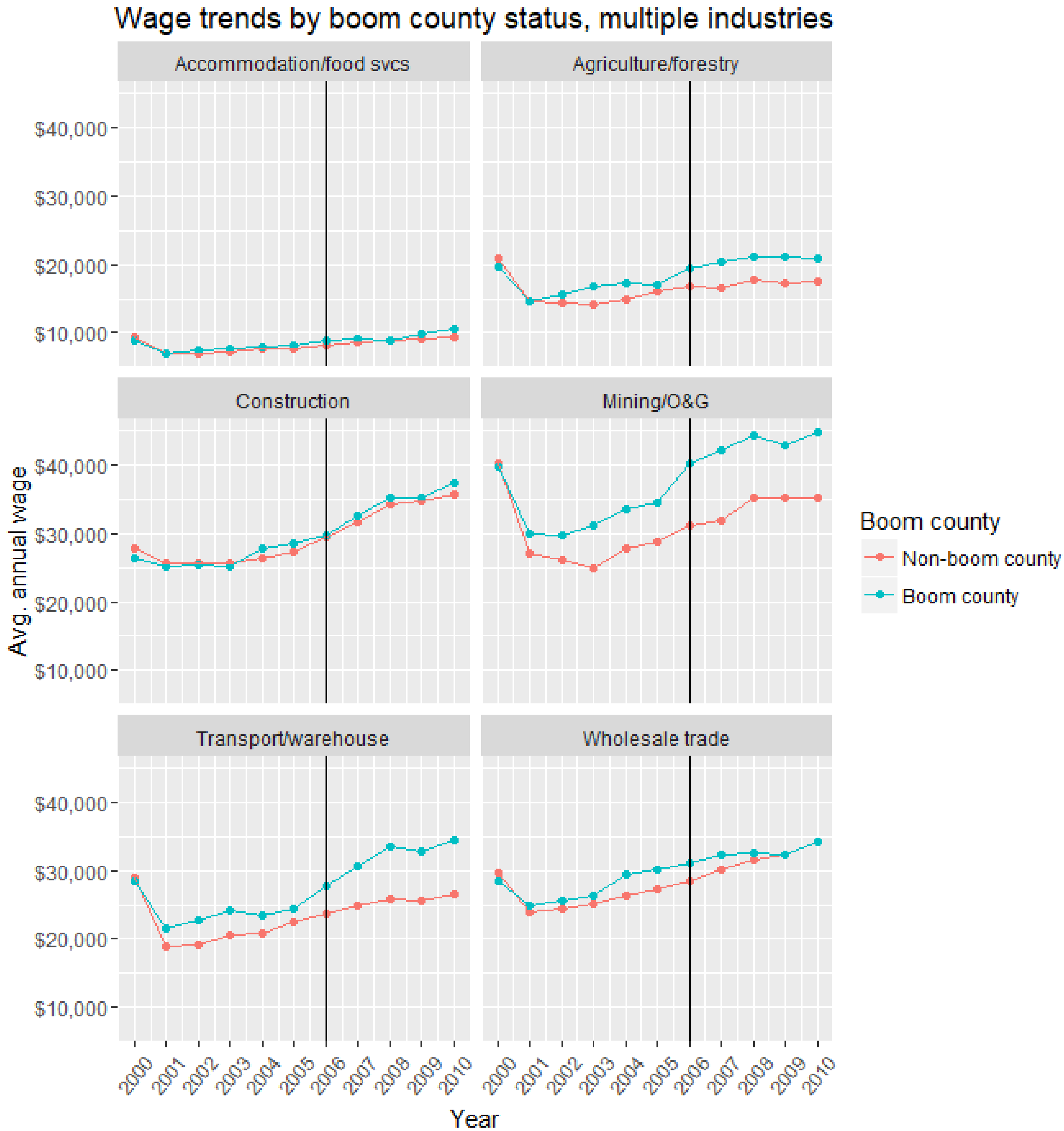


Figure B.2: Industry-specific wage trends, selected industries

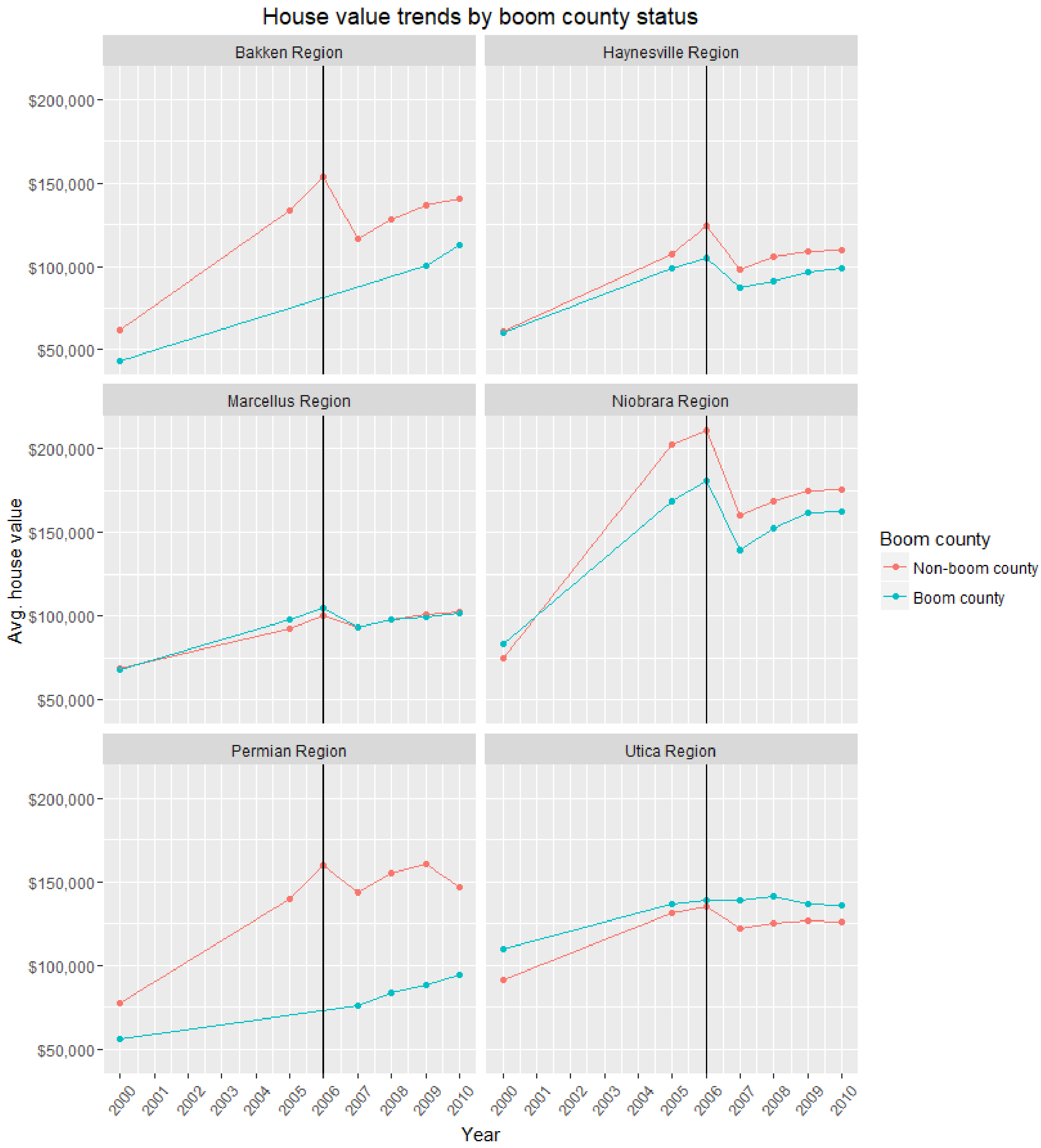


Figure B.3: Regional house value trends for boom and non-boom counties (producers only)

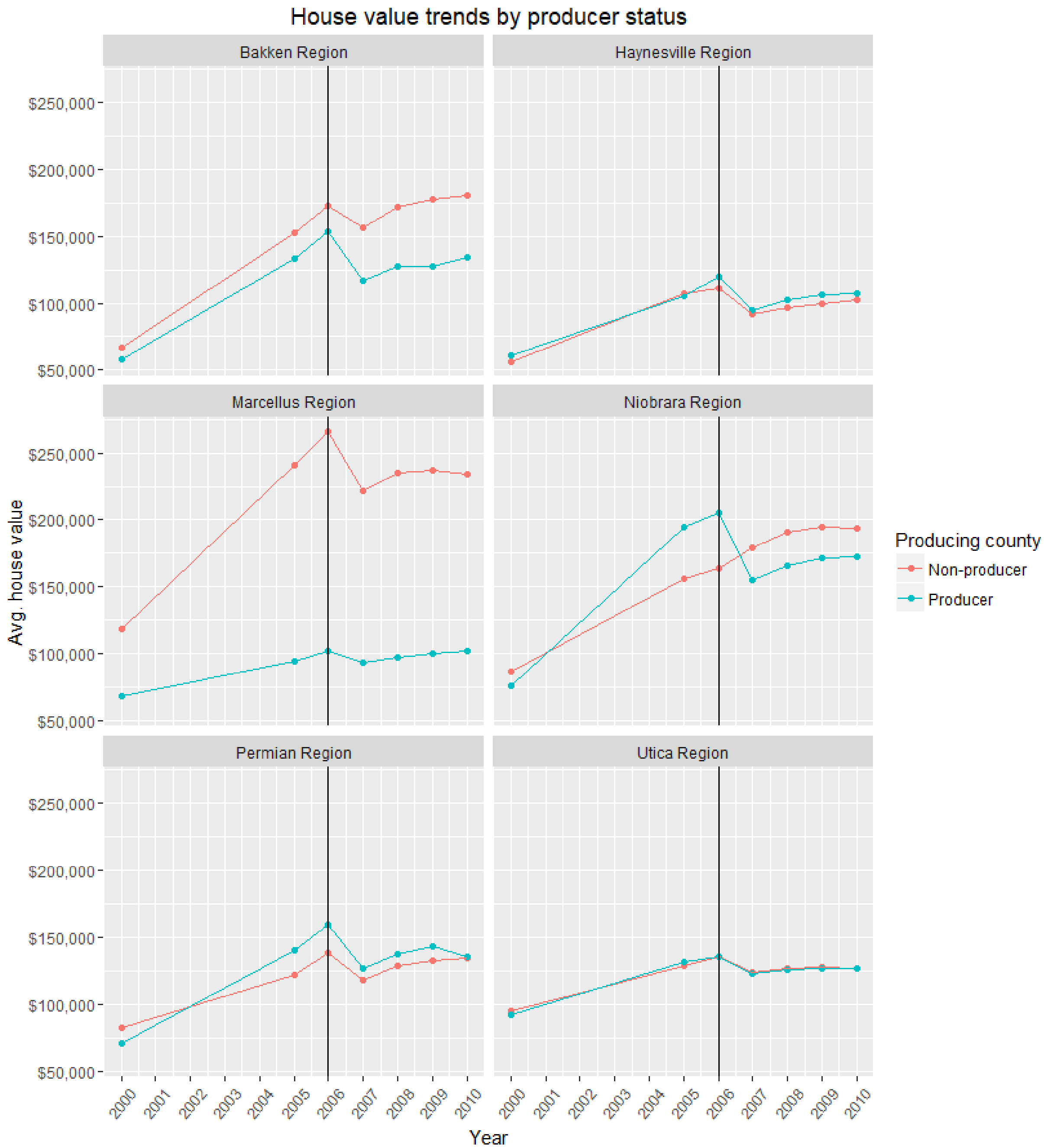


Figure B.4: Regional house value trends, producing vs. non-producing counties

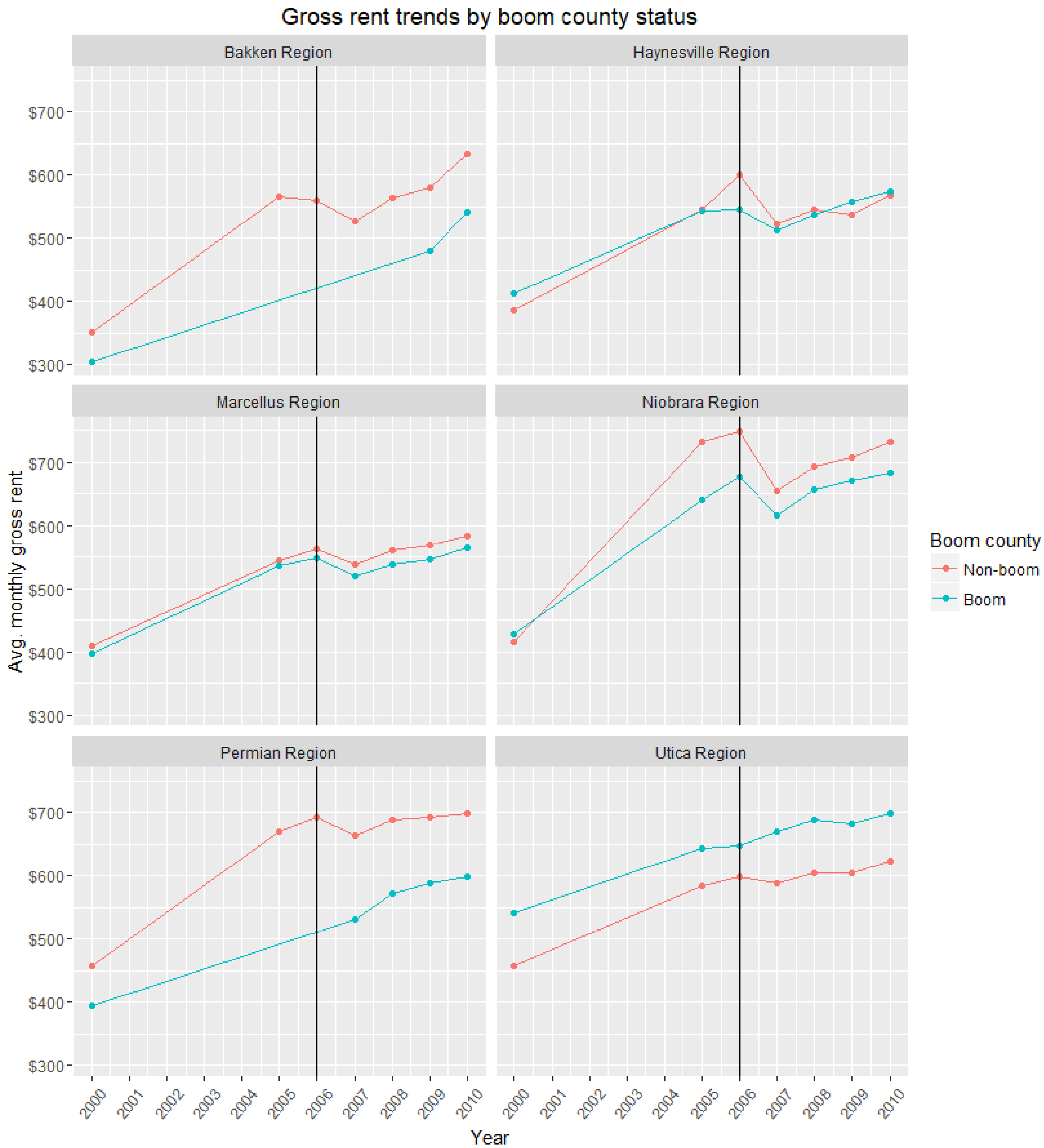


Figure B.5: Regional gross rents for boom and non-boom counties (producers only)

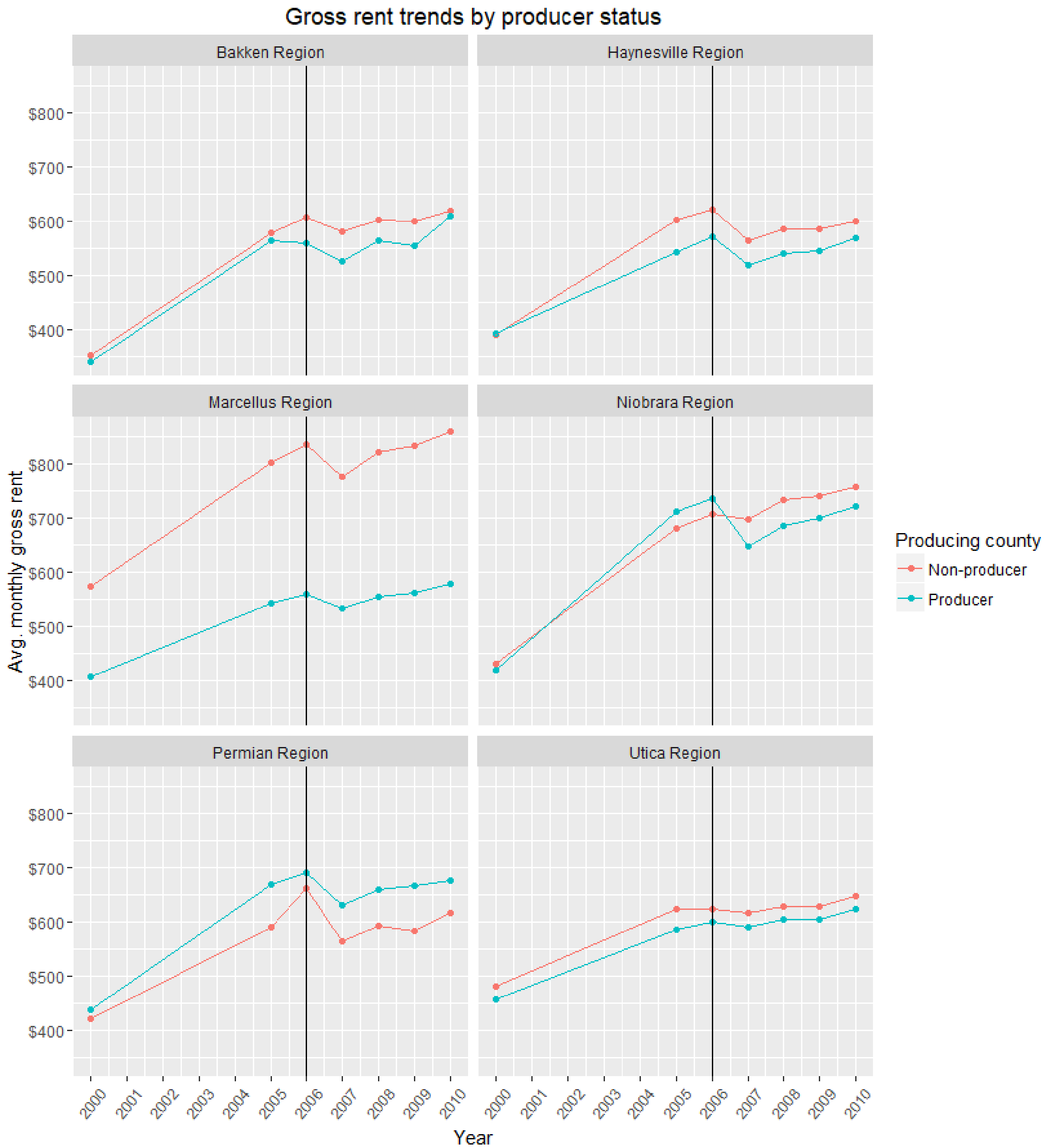


Figure B.6: Regional gross rents for producing and non-producing counties

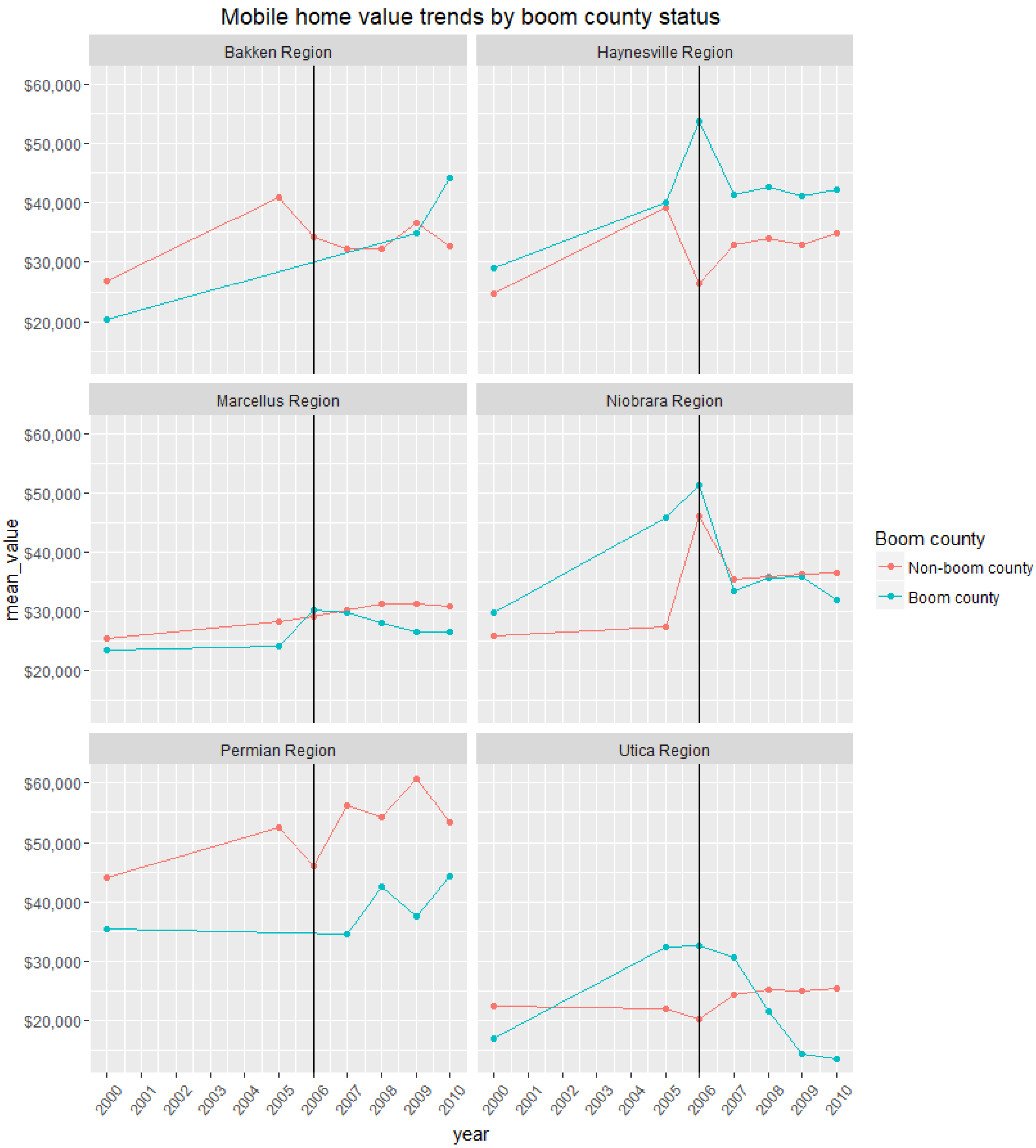


Figure B.7: Regional mobile home values for boom and non-boom counties (producers only)

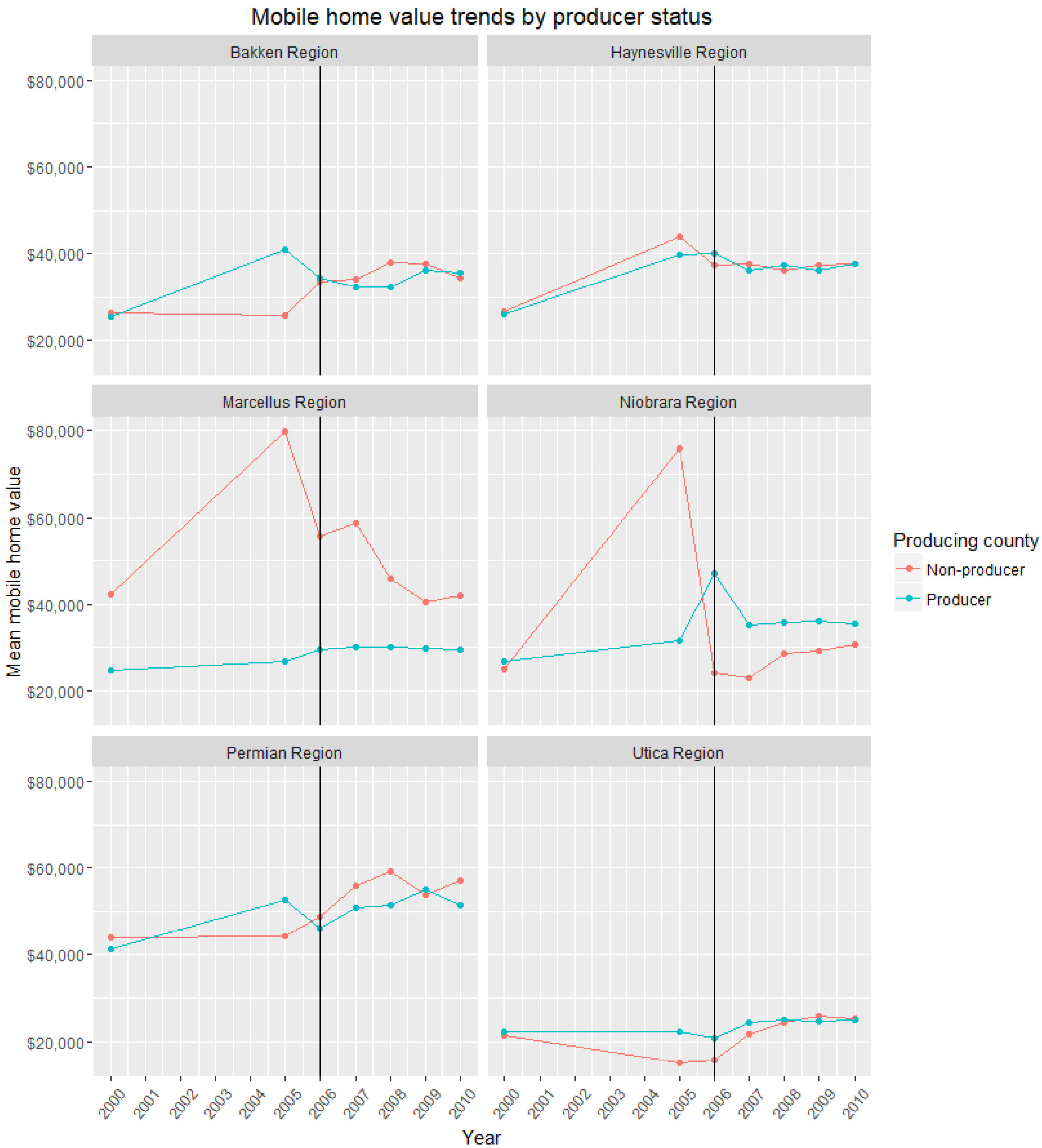


Figure B.8: Regional mobile home value for producing and non-producing counties

Table B.1: OLS specifications of marginal wage impacts

	Dependent variable: ln(wage)						
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
2010 dummy	0.299***	0.284***	0.286***	0.314***	0.269***	0.300***	0.286***
	(0.030)	(0.030)	(0.030)	(0.031)	(0.029)	(0.032)	(0.032)
Producing county		-0.003	-0.057***	-0.046**	-0.037**	-0.034**	-0.038**
		(0.011)	(0.019)	(0.019)	(0.018)	(0.017)	(0.015)
ln(BTU)			0.004***	0.004***	0.005***	0.005***	0.005***
			(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
year=2010 × producing county		0.039**	-0.045	-0.050*	-0.051*	-0.043*	-0.043*
		(0.015)	(0.028)	(0.028)	(0.027)	(0.026)	(0.023)
year=2010 × ln(BTU)			0.006***	0.007***	0.007***	0.006***	0.006***
			(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
HS grad %				-0.012***	-0.002**	-0.008***	-0.002**
				(0.001)	(0.001)	(0.001)	(0.001)
Bachelors degree %					0.017***	0.007***	0.005***
					(0.001)	(0.001)	(0.001)
Poverty rate (%)						-0.012***	-0.010***
						(0.001)	(0.001)
ln(population)							0.061***
							(0.003)
Constant	10.110***	10.111***	10.112***	10.492***	10.019***	10.510***	9.665***
	(0.022)	(0.022)	(0.022)	(0.031)	(0.041)	(0.048)	(0.070)
State-by-year FE?	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	4,282	4,282	4,282	4,282	4,282	4,282	4,282
R^2	0.463	0.464	0.472	0.523	0.559	0.593	0.64

Note: *p<0.1; **p<0.05;***p<0.01

Table B.2: OLS specifications of marginal house value impacts

	Dependent variable: ln(house value)						
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
2010 dummy	0.418***	0.423***	0.423***	0.492***	0.352***	0.413***	0.395***
	(0.044)	(0.047)	(0.048)	(0.041)	(0.030)	(0.023)	(0.021)
Producing county		-0.154***	-0.065**	-0.039	-0.012	-0.006	-0.011
		(0.018)	(0.027)	(0.026)	(0.020)	(0.016)	(0.015)
ln(BTU)			-0.007***	-0.008***	-0.006***	-0.005***	-0.005***
			(0.002)	(0.002)	(0.001)	(0.001)	(0.001)
year=2010× producing county		-0.013	-0.023	-0.034	-0.038	-0.022	-0.021
		(0.027)	(0.044)	(0.042)	(0.034)	(0.028)	(0.026)
year=2010× ln(BTU)			0.001	0.003	0.003	0.001	0.001
			(0.003)	(0.003)	(0.002)	(0.002)	(0.002)
HS grad %				-0.028***	0.002	-0.010***	-0.002**
				(0.001)	(0.001)	(0.001)	(0.001)
Bachelors degree %					0.052***	0.032***	0.029***
					(0.001)	(0.001)	(0.001)
Poverty rate (%)						-0.024***	-0.021***
						(0.001)	(0.001)
ln(population)							0.087***
							(0.004)
Constant	11.045***	11.103***	11.102***	12.027***	10.568***	11.545***	10.352***
	(0.030)	(0.032)	(0.032)	(0.043)	(0.051)	(0.056)	(0.072)
State-by-year FE?	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	4,282	4,282	4,282	4,282	4,282	4,282	4,282
R^2	0.517	0.536	0.538	0.645	0.764	0.81	0.843

Note: *p<0.1; **p<0.05;***p<0.01

Table B.3: OLS specifications of marginal employment impacts

	Dependent variable: ln(employment)						
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
2010 dummy	-0.152	-0.157	-0.156	0.189	-0.066	0.057	-0.184***
	(0.210)	(0.214)	(0.214)	(0.169)	(0.152)	(0.142)	(0.051)
Producing county		-0.111	-0.158	-0.023	0.025	0.037	-0.03
		(0.077)	(0.120)	(0.112)	(0.106)	(0.102)	(0.034)
ln(BTU)			0.004	0.001	0.005	0.006	0.003
			(0.008)	(0.008)	(0.008)	(0.007)	(0.002)
year=2010× producing county		0.014	-0.007	-0.06	-0.068	-0.034	-0.033
		(0.110)	(0.191)	(0.172)	(0.161)	(0.158)	(0.050)
year=2010× ln(BTU)			0.001	0.009	0.01	0.005	0.006*
			(0.013)	(0.012)	(0.012)	(0.011)	(0.003)
HS grad %				-0.142***	-0.087***	-0.112***	-0.009***
				(0.004)	(0.006)	(0.007)	(0.002)
Bachelors degree %					0.096***	0.056***	0.012***
					(0.008)	(0.009)	(0.002)
Poverty rate (%)						-0.049***	-0.013***
						(0.005)	(0.002)
ln(population)							1.123***
							(0.007)
Constant	9.188***	9.230***	9.230***	13.867***	11.195***	13.176***	-2.275***
	(0.142)	(0.146)	(0.145)	(0.188)	(0.269)	(0.354)	(0.149)
State-by-year FE?	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	4,282	4,282	4,282	4,282	4,282	4,282	4,282
R^2	0.236	0.237	0.237	0.454	0.487	0.502	0.953

Note: *p<0.1; **p<0.05;***p<0.01

Table B.4: Marginal house-value and wage impacts, system estimation

	SUR.1		SUR.2		SUR.3		SUR.4	
	ln(house value)	*ln(wage)*	*ln(house value)*	*ln(wage)*	*ln(house value)*	*ln(wage)*	*ln(house value)*	*ln(wage)*
2010 dummy	0.387 ***	0.306 ***	0.394 ***	0.318 ***	0.388 ***	0.303 ***	0.394 ***	0.317 ***
	(0.009)	(0.008)	(0.006)	(0.005)	(0.009)	(0.008)	(0.006)	(0.005)
Producing county	-0.077 ***	0.027 **	0.005	-0.027	0.041	-0.106 ***	0.070 *	0.060 *
	(0.010)	(0.008)	(0.016)	(0.014)	(0.034)	(0.029)	(0.033)	(0.028)
ln(BTU)					-0.008 ***	0.010 ***	-0.005	-0.004
					(0.002)	(0.002)	(0.003)	(0.002)
year=2010 × producing county	-0.031 **	0.041 ***	-0.030 ***	0.038 ***	-0.071	-0.116 **	-0.102 ***	-0.163 ***
	(0.012)	(0.010)	(0.006)	(0.005)	(0.045)	(0.038)	(0.024)	(0.021)
year=2010 × ln(BTU)					0.003	0.011 ***	0.005 **	0.014 ***
					(0.003)	(0.003)	(0.002)	(0.001)
HS grad %	-0.002 **	-0.003 ***	0.002	-0.001	-0.003 **	-0.002 **	0.002	-0.001
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Bachelors degree %	0.030 ***	0.004 ***	0.013 ***	-0.001	0.030 ***	0.005 ***	0.014 ***	0
	(0.001)	(0.001)	(0.002)	(0.002)	(0.001)	(0.001)	(0.002)	(0.002)
Poverty rate (%)	-0.022 ***	-0.011 ***	-0.017 ***	-0.012 ***	-0.022 ***	-0.010 ***	-0.016 ***	-0.010 ***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
ln(population)	0.086 ***	0.061 ***	0.375 ***	-0.078 ***	0.086 ***	0.061 ***	0.369 ***	-0.098 ***
	(0.003)	(0.003)	(0.026)	(0.023)	(0.003)	(0.003)	(0.027)	(0.023)
Constant	10.348 ***	9.680 ***	7.232 ***	11.045 ***	10.359 ***	9.651 ***	7.288 ***	11.243 ***
	(0.062)	(0.054)	(0.299)	(0.262)	(0.062)	(0.054)	(0.299)	(0.257)
Fixed effects:	State year		County		State year		County	
Num. obs. (by dataset)	4,282	4,282	4,282	4,282	4,282	4,282	4,282	4,282
R^2	0.83	0.626	0.979	0.953	0.831	0.638	0.979	0.955

Note: *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$

Table B.5: Alternative measures of rental growth (OLS)

	Dependent variable:					
	ln(house value)		ln(mobile home value)		ln(gross rent)	
Parameter	(1)	(2)	(3)	(4)	(5)	(6)
2010 dummy	0.394***	0.395***	0.174***	0.174***	0.393***	0.393***
	(0.021)	(0.021)	(0.036)	(0.036)	(0.020)	(0.020)
Producing county	-0.076***	-0.011	-0.048***	-0.016	-0.030***	-0.017*
	(0.010)	(0.015)	(0.016)	(0.027)	(0.006)	(0.009)
ln(BTU)		-0.005***		-0.003		-0.001*
		(0.001)		(0.002)		(0.001)
year=2010 × Producing county	-0.015	-0.021	0.0001	-0.009	-0.002	-0.001
	(0.015)	(0.026)	(0.032)	(0.061)	(0.010)	(0.018)
year=2010 × ln(BTU)		0.001		0.001		-0.0001
		(0.002)		(0.004)		(0.001)
HS grad %	-0.002**	-0.002**	0.004**	0.004**	-0.003***	-0.003***
	(0.001)	(0.001)	(0.002)	(0.002)	(0.001)	(0.001)
Bachelors degree %	0.029***	0.029***	-0.001	-0.002	0.014***	0.014***
	(0.001)	(0.001)	(0.003)	(0.003)	(0.001)	(0.001)
Poverty rate %	-0.021***	-0.021***	-0.015***	-0.015***	-0.013***	-0.013***
	(0.001)	(0.001)	(0.002)	(0.002)	(0.001)	(0.001)
ln(population)	0.087***	0.087***	-0.032***	-0.032***	0.063***	0.063***
	(0.004)	(0.004)	(0.008)	(0.008)	(0.003)	(0.003)
Constant	10.348***	10.352***	10.700***	10.701***	5.431***	5.430***
	(0.072)	(0.072)	(0.145)	(0.145)	(0.051)	(0.051)
State-by-year FE?	Yes	Yes	Yes	Yes	Yes	Yes
Observations	4,282	4,282	3,242	3,242	3,321	3,321
R^2	0.842	0.843	0.361	0.361	0.884	0.884

Note: *p<0.1; **p<0.05;***p<0.01

Table B.6.A: Wage effects for selected industries (OLS)

Parameter	*Dependent variable: ln(wage)*							
	Ag/forestry/ fishing+hunting		Mining/quarrying/ oil+gas extraction		Utilities		Construction	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
2010 dummy	0.277***	0.276***	0.252***	0.245***	0.359***	0.358***	0.327***	0.326***
	(0.017)	(0.017)	(0.036)	(0.035)	(0.023)	(0.023)	(0.010)	(0.010)
Producing county	-0.02	-0.049	0.069*	-0.172**	-0.012	-0.05	-0.002	-0.004
	(0.019)	(0.053)	(0.036)	(0.082)	(0.025)	(0.058)	(0.011)	(0.024)
ln(BTU)		0.002		0.018***		0.003		0.0005
		(0.003)		(0.005)		(0.004)		(0.002)
year=2010 × Producing county	0.039*	-0.001	0.144***	-0.231**	0.02	0.018	0.035***	-0.139***
	(0.022)	(0.069)	(0.040)	(0.107)	(0.028)	(0.076)	(0.013)	(0.037)
year=2010 × ln(BTU)		0.003		0.024***		0.0001		0.012***
		(0.004)		(0.007)		(0.005)		(0.002)
HS grad %	0.004***	0.004***	-0.011***	-0.008***	-0.003	-0.003	-0.0002	0.00003
	(0.002)	(0.002)	(0.003)	(0.003)	(0.002)	(0.002)	(0.001)	(0.001)
Bachelors degree %	0.009***	0.009***	-0.001	0.002	0.001	0.001	0.005***	0.006***
	(0.002)	(0.002)	(0.003)	(0.003)	(0.003)	(0.003)	(0.001)	(0.001)
Poverty rate (%)	-0.004***	-0.004***	-0.007***	-0.006**	-0.007***	-0.007***	-0.008***	-0.008***
	(0.001)	(0.001)	(0.002)	(0.002)	(0.002)	(0.002)	(0.001)	(0.001)
ln(population)	0.006	0.006	0.073***	0.079***	0.079***	0.079***	0.082***	0.081***
	(0.005)	(0.005)	(0.008)	(0.008)	(0.008)	(0.008)	(0.004)	(0.004)
Constant	9.845***	9.836***	10.114***	9.903***	10.010***	10.004***	9.363***	9.353***
	(0.108)	(0.108)	(0.188)	(0.184)	(0.159)	(0.159)	(0.075)	(0.075)
State FE?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	1,907	1,907	1,369	1,369	1,296	1,296	3,483	3,483
R^2	0.379	0.38	0.379	0.416	0.567	0.567	0.583	0.588

Note: *p<0.1; **p<0.05; ***p<0.01

Table B.6.B: Wage effects for selected industries, continued (OLS)

Parameter	*Dependent variable: ln(wage)*							
	Manufacturing		Wholesale trade		Transportation/ warehousing		Accommodation/ food services	
	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
2010 dummy	0.284***	0.283***	0.357***	0.356***	0.291***	0.288***	0.265***	0.265***
	(0.012)	(0.011)	(0.012)	(0.012)	(0.015)	(0.015)	(0.009)	(0.009)
Producing county	0.003	-0.051*	0.01	-0.081**	0.035**	-0.085**	-0.046***	0.013
	(0.012)	(0.027)	(0.014)	(0.031)	(0.016)	(0.035)	(0.010)	(0.023)
ln(BTU)		0.004**		0.007***		0.010***		-0.004***
		(0.002)		(0.002)		(0.002)		(0.002)
year=2010 × Producing county	0.019	-0.017	0.018	-0.025	0.037*	-0.224***	0.040***	-0.075**
	(0.015)	(0.043)	(0.017)	(0.047)	(0.019)	(0.051)	(0.012)	(0.034)
year=2010 × ln(BTU)		0.002		0.003		0.018***		0.008***
		(0.003)		(0.003)		(0.003)		(0.002)
HS grad %	0.007***	0.007***	-0.004***	-0.003**	-0.005***	-0.004***	-0.005***	-0.005***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.002)	(0.002)	(0.001)	(0.001)
Bachelors degree %	0.009***	0.010***	0.011***	0.012***	-0.005***	-0.004**	0.007***	0.007***
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.001)	(0.001)
Poverty rate (%)	-0.011***	-0.011***	-0.012***	-0.012***	-0.011***	-0.011***	-0.002**	-0.001*
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
ln(population)	0.124***	0.123***	0.077***	0.077***	0.041***	0.041***	0.055***	0.055***
	(0.005)	(0.005)	(0.005)	(0.005)	(0.005)	(0.005)	(0.003)	(0.003)
Constant	8.880***	8.870***	9.624***	9.604***	10.157***	10.106***	8.690***	8.684***
	(0.091)	(0.091)	(0.094)	(0.093)	(0.110)	(0.107)	(0.070)	(0.069)
State FE?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	3,507	3,507	3,043	3,043	2,302	2,302	2,715	2,715
R^2	0.542	0.544	0.57	0.574	0.37	0.402	0.62	0.622

Note: *p<0.1; **p<0.05; ***p<0.01

Table B.7.A: Employment effects for selected industries (OLS)

Parameter	Ag/forestry/ fishing+hunting		Mining/quarrying/ oil+gas extraction		Utilities		Construction	
	Dependent variable: ln(employment)							
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
2010 dummy	-0.150**	-0.146**	-0.431***	-0.472***	-0.260***	-0.265***	-0.250***	-0.253***
	(0.073)	(0.073)	(0.141)	(0.130)	(0.076)	(0.076)	(0.025)	(0.025)
Producing county	-0.13	-0.061	0.695***	-0.665**	0.181**	0.276	0.049*	-0.049
	(0.079)	(0.220)	(0.141)	(0.307)	(0.083)	(0.197)	(0.028)	(0.062)
ln(BTU)		-0.005		0.102***		-0.006		0.008**
		(0.014)		(0.019)		(0.013)		(0.004)
year=2010×Producing county	-0.092	0.052	0.551***	-1.809***	0.035	-0.402	0.090***	-0.225**
	(0.091)	(0.288)	(0.156)	(0.399)	(0.095)	(0.255)	(0.034)	(0.095)
year=2010×ln(BTU)		-0.01		0.153***		0.030*		0.022***
		(0.018)		(0.024)		(0.016)		(0.006)
HS grad %	-0.034***	-0.035***	-0.036***	-0.023**	-0.011	-0.01	0.003	0.003
	(0.007)	(0.007)	(0.010)	(0.010)	(0.008)	(0.008)	(0.003)	(0.003)
Bachelors degree %	-0.026***	-0.027***	-0.069***	-0.049***	-0.018**	-0.017*	0.031***	0.032***
	(0.008)	(0.008)	(0.012)	(0.011)	(0.009)	(0.009)	(0.003)	(0.003)
Poverty rate (%)	-0.002	-0.003	-0.017**	-0.007	-0.009*	-0.008	-0.031***	-0.031***
	(0.006)	(0.006)	(0.009)	(0.008)	(0.006)	(0.006)	(0.002)	(0.002)
ln(population)	0.313***	0.314***	0.444***	0.476***	0.804***	0.805***	1.123***	1.122***
	(0.021)	(0.021)	(0.033)	(0.031)	(0.026)	(0.026)	(0.010)	(0.010)
Constant	3.362***	3.390***	1.698**	0.444	-3.180***	-3.232***	-5.543***	-5.569***
	(0.453)	(0.453)	(0.730)	(0.683)	(0.538)	(0.538)	(0.195)	(0.194)
State FE?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	1,907	1,907	1,369	1,369	1,296	1,296	3,483	3,483
R^2	0.344	0.345	0.352	0.444	0.645	0.646	0.9	0.901

Note: *p<0.1; **p<0.05; ***p<0.01

Table B.7.B: Employment effects for selected industries, continued (OLS)

Parameter	Dependent variable: ln(employment)							
	Manufacturing		Wholesale trade		Transportation/ warehousing		Accommodation/ food services	
	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
2010 dummy	-0.506***	-0.502***	-0.079**	-0.081**	-0.034	-0.039	-0.118***	-0.118***
	(0.040)	(0.040)	(0.035)	(0.035)	(0.050)	(0.050)	(0.027)	(0.027)
Producing county	-0.111***	0.084	0.04	-0.061	0.088	-0.13	0.036	0.103
	(0.043)	(0.094)	(0.039)	(0.091)	(0.055)	(0.120)	(0.031)	(0.069)
ln(BTU)		-0.016**		0.008		0.018**		-0.005
		(0.007)		(0.006)		(0.008)		(0.005)
year=2010×Producing county	0.022	0.257*	0.034	-0.01	0.011	-0.389**	0.012	-0.112
	(0.053)	(0.147)	(0.047)	(0.137)	(0.065)	(0.176)	(0.037)	(0.101)
year=2010×ln(BTU)		-0.016		0.003		0.027**		0.009
		(0.010)		(0.009)		(0.012)		(0.007)
HS grad %	0.021***	0.020***	-0.020***	-0.020***	-0.014***	-0.012**	-0.005*	-0.005*
	(0.004)	(0.004)	(0.004)	(0.004)	(0.005)	(0.005)	(0.003)	(0.003)
Bachelors degree %	-0.021***	-0.023***	0.006	0.007	-0.017***	-0.015**	0.040***	0.040***
	(0.005)	(0.005)	(0.005)	(0.005)	(0.006)	(0.006)	(0.003)	(0.003)
Poverty rate (%)	-0.024***	-0.024***	-0.023***	-0.022***	-0.020***	-0.019***	0.006**	0.006**
	(0.004)	(0.004)	(0.003)	(0.003)	(0.004)	(0.004)	(0.002)	(0.002)
ln(population)	1.255***	1.256***	1.062***	1.062***	1.133***	1.133***	1.078***	1.079***
	(0.016)	(0.016)	(0.013)	(0.013)	(0.018)	(0.018)	(0.010)	(0.010)
Constant	-5.307***	-5.263***	-4.505***	-4.526***	-5.374***	-5.458***	-4.941***	-4.946***
	(0.316)	(0.315)	(0.268)	(0.269)	(0.368)	(0.366)	(0.208)	(0.208)
State FE?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	3,507	3,507	3,043	3,043	2,302	2,302	2,715	2,715
R^2	0.796	0.798	0.834	0.834	0.787	0.79	0.911	0.911

Note: *p<0.1; **p<0.05; ***p<0.01

CHAPTER 4. THE IMPACT OF THE U.S. SHALE BOOM ON AGRICULTURE: EVIDENCE FROM NORTH DAKOTA

A modified version of this essay to be submitted for publication in peer-reviewed journals

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4.1 – Introduction, Background and Literature

The potential for health risk and environmental damage from oil and gas activity has been well-documented (see, for example, Allred et al (2015), Barbot et al (2013), Hill (2013), Vengosh et al (2014), Vidic et al (2013)). Indeed, shale region residents are wary of possible hazards: Gopalakrishnan and Klaiber (2012) and Muehlenbachs et al (2015) document house value declines of 24% for houses in Pennsylvania located within 2km of a shale gas well, and Wrenn et al (2016) find a significant spike in bottled water sales in response to increased shale energy development in Pennsylvania and Ohio. A complicating factor, however, is that mineral royalties generate wealth gains that may partially offset these negatives, making the net effect more difficult to estimate. Highlighting this difference, Boslett et al (2016) estimate the capitalized environmental damage from shale oil and gas development in regions of Colorado in which mineral rights are permanently severed from surface estates, finding significant negative capitalization when value gains from mineral ownership are not present.

It remains unclear if the underlying preferences causing consumers to bid down house prices is due to subjective risk assessment, a distaste for noise or visual reminders of oil activity (e.g. wellheads and pumpjacks), or to objective information regarding changes to environmental variables with long-term negative consequences. I address this problem in the present study by examining agricultural land rents in North Dakota's Bakken region. Using lease data from the North Dakota Department of Trust Lands, I estimate the impact of the presence of oil and gas wells on parcel rental rates. I find that rents to do not respond significantly to the presence of oil and gas infrastructure, although locational attributes correlated with shale geography are associated with lower rents. This finding suggests that the negative valuations of shale energy infrastructure stem from aesthetic rather than environmental concerns.

Prior studies have found that visibility of energy infrastructure is often capitalized into house values (e.g. Dröes and Koster (2015), Gibbons (2015), Muhelenbachs et al (2015)). However, agricultural land will not capitalize the value of the viewshed.[34] On the other hand, if environmental damage is widespread and attributable to the drilling and operation of oil wells, theory predicts that land values should capitalize production differences that derive from these environmental changes. Additionally, areas affected by increased oil and gas activity also experience gains in wages and employment (Brown (2014), Komarek (2015)). In an agricultural context, higher labor prices can also affect rents; however, these conditions will affect all parcels in shale boom areas, while only parcels located near the source of environmental damage will be additionally affected.

I test for this capitalization of environmental damage using the hedonic rents framework of Palmquist (1989), in which land is treated as a differentiated factor of production. My analysis takes advantage of the geographic distribution of North Dakota's shale geology and the timing of the shale energy boom between 2006 and 2012. The state of North Dakota is of interest due to its high output of shale oil and to the large proportion of the state surface acreage devoted to agriculture. Approximately 80% of North Dakota's total land area is devoted to agriculture (see Table 4.1), while shale energy resources lie below just under half of the state's surface area (see Figure 4.1). Furthermore, there is evidence that agricultural rents have behaved differently in areas affected by the shale boom than in areas that did not experience increased energy-industry activity. County-level cash crop rents in shale and non-shale counties followed parallel trends prior to 2006, the year after which North Dakota's oil production increased, and subsequently diverged. Figure 4.2 shows this result visually—crop rents in counties located outside the bounds of the Bakken shale play increased at a greater rate than Bakken county rents in the years from 2006 to 2012.

[34] I do not consider costs of transition to non-agricultural uses or questions of irreversibility. North Dakota state trust lands are legally under the control of the State Land Board and cannot be sold without the board's express action.

This study is one of the few to directly examine spillovers between shale drilling and agriculture. In a review of the literature, Mason et al (2015) point out that stable petroleum prices should translate to savings on fertilizer expenses. However, they also highlight that competition over labor and transportation inputs as well as water quality degradation may harm agricultural output. Hitaj (2014) reports substantial variation in the number of farm businesses receiving royalty income, while Brown et al (2016) find that royalty payments are concentrated among a relatively small number of rural landowners. Hitaj et al (2014) examine case studies of agricultural interaction with shale development, finding anecdotal examples of uncompensated damages and speculating about the extent of potential impacts.

The complicated circumstances of oil and gas leasing present additional challenges. Under North Dakota law, surface rights holders are entitled to compensation for damages (North Dakota Century Code, Chapter 38-11.1), including compensation for lost agricultural production, and provides legal recourse for surface owners who otherwise would be left uncompensated. Thus, if damages do occur, it is unclear as to whether this compensation scheme would fully mitigate expectations of damages when surface estates are sold. Another complicating factor is that oil and gas rights are often pooled into spacing units that can be leased in blocks, making the total compensation paid to non-absentee mineral owners difficult to attribute to specific surface real estate.[35]

By using public lease data, I control for ownership of the surface and mineral estates, effectively circumventing the problem of unobserved aspects of private land transactions. My data come from records of 16,629 leases for parcels of public agricultural land in North Dakota from 2000 to 2016. I use a hedonic land rents regression to examine changes in land value associated with variation in geology that enables shale energy activity. I find that parcel location characteristics largely drive rents, and that the presence of oil industry activity (in the form of existing oil wells on or near a given parcel) has little to no effect on the land rental rate.

[35] See North Dakota Department of Mineral Resources, "Notice to Surface Owners Concerning the Right of Compensation for Damages Caused by Oil and Gas Operations," available at https://www.dmr.nd.gov/oilgas/surfaceowner.pdf

The next section describes the theory underlying my analysis; Section 3 discusses empirical methods and econometric specifications; Section 4 presents the data; Section 5 discusses the results and Section 6 concludes.

4.2 – Theory

I motivate my analysis with a static profit-maximization framework. Consider a vector of agricultural inputs x, which includes land, with an input cost vector given by c. For simplicity, land ownership is assumed to be traded via markets, i.e. the rights to the use of any particular unit of land can be leased by any participant in the market. Accordingly, its price per unit is contained in c. Let P be the price of an agricultural output. Assuming that farm operators use identical technology and face the production function $f(x)$, operators choose inputs x to maximize

$$P \cdot f(x) - c \cdot x$$

which yields the system of first-order conditions

$$P \cdot \nabla_x f(x) - c = 0 \qquad (4.1)$$

Assuming that the gradient $\nabla_x f(x) \leq 0$ and that f has a negative semi-definite Hessian, this system can be solved for the vector of optimal input quantities $x^*(P,c)$, which are functions of the output price, the input price vector and any parameters of the production function. Substituting this into the expression for profit yields the indirect profit function $\pi(P,c)$, i.e. profit as a function of parameters exogenous to the farm operator's decision.

To add oil and gas resource activity to the framework, let g be a continuous measure of resource extraction activity. In the presence of spillovers in production, g may enter the function f as a parameter, implying the indirect profit function

$$\pi(P,c,g) = P \cdot f(x^*(P,c,g),g) - c \cdot x^*(P,c,g) \qquad (4.2)$$

The treatment of g as a parameter rather than a choice variable captures the fact that surface-rights owners have little to no control over the placement of oil and gas infrastructure on surface land, as pointed out in Hitaj et al (2014). In the context of Roback (1982) and Rosen (1979), Equation (4.2) builds on the production-function dual to the cost-function approach. In particular, indirect profit should equalize for all values of P, c and g when a spatial equilibrium holds.

Applying the Envelope Theorem, I differentiate $\pi(P,c,g)$ with respect to g to obtain

$$\begin{aligned}\frac{\partial \pi(P,c,g)}{\partial g} &= P \cdot \nabla_x f(x^*(P,c,g),g) \cdot \nabla_g x^*(P,c,g) \\ &\quad + P \cdot \frac{\partial f}{\partial g}(x^*(P,c,g),g) - c \cdot \nabla_g x^*(P,c,g)\end{aligned} \tag{4.3}$$

where $\frac{\partial f}{\partial g}$ refers to the derivative of f with respect to its second argument. The right-hand side simplifies to the expression

$$\frac{\partial \pi(P,c,g)}{\partial g} = \left(P \cdot \nabla_x f(x^*(P,c,g),g) - c\right) \cdot \nabla_g x^*(P,c,g) + P \cdot \frac{\partial f}{\partial g}(x^*(P,c,g),g) \tag{4.4}$$

The first parenthetical of Equation (4.4) is zero by the system of first-order conditions in Equation (4.1), and thus can be reduced to the expression for the value of the differential production associated with a change in the shale drilling activity measure g. Simplifying yields:

$$\frac{\partial \pi(P,c,g)}{\partial g} = P \cdot \frac{\partial f}{\partial g}(x^*(P,c,g),g) \tag{4.5}$$

The sign of this change is *a priori* ambiguous; it depends on the nature of the interaction of the shale industry's practices as measured by g with extant agricultural production technology.

If negative spillovers exist—that is, if increased oil and gas activity decreases agricultural output relative to the baseline of no drilling—then $P \cdot \frac{\partial f}{\partial g}(x^*(P,c,g),g) < 0$. The assumption implicit in the exposition above is that shale activity g shifts the production function monotonically for all optimal levels of inputs. By construction, the indirect profit function accounts for substitution among inputs as parameters change such that profit is maximized. That is, farm operators will still do the best they can conditional on the level of oil activity that affects them.

The effect characterized in Equation (4.5) can result from both direct and indirect consequences of shale energy extraction. Effects on production due to spills, chemical contamination or lost scale economies from overlapping land uses can cause reduced yields, directly lowering the marginal productivity of land. However, indirect effects include increases in the prices of factors of production—such as labor or transportation capacity—used both as inputs to agricultural production and as inputs to marketing agricultural product (Brown (2014), Hitaj et al (2014), Mason (2016), Weber (2014)). The mobility of factors of production suggests that all agricultural parcels within the greater region of an active shale play will experience similar indirect effects of energy production, such as increased factor prices. In the presence of direct environmental effects, intensive shale energy activity in close proximity with agricultural operations will have an additional effect.

Changes to agricultural productivity due to spillovers from oil and gas activity has implications for land rents. Consider a parcel of land i in the input vector x, above, with corresponding rent r_i. A producer deciding whether to lease the parcel will only do so if $P\frac{\partial f}{\partial x_i}(x;g) \geq r_i$, i.e. if the value of parcel i's marginal product is greater than or equal to the rental rate. The exposition above predicts that a negative spillover should decrease the parcel's marginal product; if marginal product decreases sufficiently, the return on land may fall below the landowner's reservation price and the parcel will not be leased.

This suggests an empirical analysis that treats rents as a measure of agricultural profitability. Below, I specify an empirical model that captures this behavior and apply it to agricultural rental leases of state-owned land. The institutional characteristics of North Dakota's State Trust Lands include a public reservation price that is not contemporaneously related to shale oil and gas development, allowing me to check for selection as well as estimate the rental effects of shale energy activity.

4.3 – Empirical Methods

I estimate a reduced-form econometric specification that approximates Equation (4.5). Following the hedonic rents model of Palmquist (1989), which treats land as a differentiated factor of production, I regress parcel-level rent on parcel size, the number of oil wells within 2 kilometers of the parcel and an indicator of mineral location associated with the parcel. Parcel data come from the North Dakota State Department of Trust Lands. I observe the rental values of 17,874 lease transactions for state-owned agricultural parcels, which I merge with geospatial data on North Dakota's shale geology and measures of energy industry activity to create a dataset that relates variation in lease prices to variation in g as required by theory. The presence of oil and gas infrastructure on public lands is exogenous to bidders' decision processes—North Dakota's surface leases and mineral leases are transacted separately, and surface lease renters do not have authority to exploit any state-owned minerals from within the bounds of the surface parcel.

North Dakota allocates public land contracts via a bidding process. Prospective operators submit auction-style bids for a parcel-level contract of pre-determined length, subject to a minimum price. Necessarily, this implies that bids are subject to censoring at the minimum price. Published guidelines set the minimum bid, which is meant to reflect private valuations of similar land within the state, and thus represent the opportunity cost of the land to the State Department of Trust Lands.[36] In addition, not all parcels are leased when auctioned. If no bids at or above the minimum price are received, the state will

[36] North Dakota's minimum required bid for a parcel is defined as 90% of the 5-year moving average of minimum county-level average rent within the parcel's home region, defined as a pre-specified cluster of contiguous counties. The 10% markdown is meant as an allowance for costs of transition between leaseholders, such as installation of new fencing or other infrastructure. See https://land.nd.gov/Docs/Surface/minimum%20bid%20calculation.pdf for documentation of the state's minimum bid calculation.

leave the land idle and offer the lease again in a subsequent auction. Parcel leases are generally 5 years in length, meaning that I observe a number of parcels in multiple years.

Unleased parcels can be thought of as having an observed price of zero; this motivates a convenient cutoff for a censored regression. Let lease transactions be indexed by i. I denote the rental bid for transaction i at time t by b_{it}. I specify a Tobit regression of the form

$$b_{it} = \begin{cases} \alpha + \rho \cdot \ln(Acres_i) + \theta \cdot NCCPI_{C(i)} + \delta_t & \\ \quad + \beta \cdot Shale_i + \psi \cdot Wells_{it} \cdot Shale_i + \nu_{it} & \text{if } b_{it} \geq b_{it}^{min} \\ 0 & otherwise \end{cases} \tag{4.6}$$

where δ_t is a year effect and ν_{it} is the error term. I measure g with $Shale_i$, an indicator variable equal to 1 if transaction i deals with a parcel that is located within the bounds of a shale play that was active during the boom, and $Wells_{it}$, an integer denoting the number of oil wells in operation on the parcel leased in transaction i at time t. During the shale boom, no new oil and gas wells were constructed outside the boundary of the Bakken shale; henceforth I denote the interacted well term as $Wells_{it}$. $Wells_{it}$ is a measure of the intensity with which the land is used in oil and gas production; a negative and significant estimate of ψ is evidence of negative externalities from well operation. In addition, parcels range in size from approximately 5 acres to 640 acres; since the rental bids apply to the entire parcel, I also control for parcel size, denoted $Acres_i$. A positive and significant coefficient for the log of $Acres_i$ may plausibly reflect returns to scale due to the increased flexibility in use for larger parcels; in general, however, ρ captures the marginal willingness to pay for an additional acre conditional on lot size. I also control for land quality using the county-average NCCPI measure for the county in which parcel i is located, denoted $C(i)$ in the specification above. The minimum bid can also serve as a measure of land quality; however, I do not use it in estimating Equation (4.6) due to its close correlation with received rent (correlation coefficient: 81% off-shale, 73% in the Williston basin and 75% for on-shale parcels). I estimate Equation (4.6) by maximum likelihood.

The coefficients of greatest relevance to the theoretical model are β and ψ. If the presence of oil wells is correlated with plot-level spillovers, the willingness to pay for the parcel's lease should change accordingly—therefore, a negative and significant estimate of ψ is evidence of negative spillovers from shale energy activity. The interpretation of a significant estimate of β is less straightforward: although the underlying geology of North Dakota's shale zones is exogenous to both surface lease operators and oil and gas firms, there may be correlation between the subsurface geology and surface land quality, which may result in a significant parameter estimate despite the lack of a causal relationship. I address this issue by further subdividing the set of parcels within the bounds of the greater Bakken shale play into parcels located within the unconventional oil fields and parcels within the Williston basin but outside of the area of unconventional oil recovery.

In the results below, I estimate Equation (4.6) for the subset of transactions related to parcels located within the Williston basin and the Bakken/Three Forks oil play as well as for the full set of observations. In the full-sample estimations, I include an $In\ basin_i$ dummy variable equal to 1 if parcel i is located within the Williston basin, which includes Bakken parcels. This allows Bakken and non-Bakken parcels to have a different intercept but assumes that the effect of parcel size and minimum rent behave similarly across regions. Restricted-sample specifications compare Bakken parcel transactions directly to non-Bakken parcel transactions and do not require the Williston basin dummy.

4.4 – Data

My dataset is drawn from several sources. Fiscal records of surface lease transactions come from the North Dakota Department of State Trust Lands. State public lands are leased to private operators, and the proceeds are used to fund public educational institutions throughout North Dakota. The data cover the years from 2000 to 2016. The full dataset has records for 17,784 transactions, each coded to a specific land parcel. Historically, surface parcels held in the public trust were granted to the state of North Dakota by the federal government in 1889; later updates to the legislation clarified the availability of mineral land for state ownership (*An Act to provide for the division of Dakota into two states*, United States Statutes at Large 25 (1889): p. 676). The original distribution of surface land, however, was imposed prior to the discovery of oil in North Dakota, effectively un-linking the land from the geographic distribution of mineral resources.

Geospatial data were obtained from the Oil & Gas Division of the North Dakota Department of Mineral Resources (ND DMR).[37] The data contain geocoded location information for all state-owned surface parcels. In addition, the data include the geocoded locations of all operating and capped oil wells within state borders, as well as the location and direction of the horizontal wellbores used in unconventional oil recovery. I combine the ND DMR data with geocoded shale play boundaries obtained from the Energy Information Administration website[38] to construct the $Shale_i$ and $Wells_{it}$ variables.

Table 4.2 reports the summary statistics. In nominal dollars, rental bids in the sample average $1277.13, while per-acre bids average $9.87. Mean parcel size is 146 acres with a median just under 160 acres; the majority of parcels fall within a range of 100 to 200 acres. Approximately one-third of leases transacted were for parcels within the unconventional portion of the Bakken shale play, while roughly 80% of all transacted leases occurred within the Williston basin.[39] Well counts across all transactions are relatively low at 0.256 wells per parcels.

Minimum bids average $1,189.42, with the middle 50% of observations ranging from $746 to $1,442. However, the average minimum bid varies significantly with location. Parcels located within the Bakken shale, i.e. within the area of greatest horizontal drilling and fracking activity, have average an average minimum bid of $860, while parcels outside the greater Williston basin have average minimum

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[37] https://www.dmr.nd.gov/oilgas/

[38] https://www.eia.gov/maps/maps.htm#shaleplay

[39] The Bakken shale is entirely located within the boundary of the Williston basin; the 80% includes on-shale parcels.

bids of $1,549. Average minimum rent for parcels located within the Williston basin but outside the boundary of the Bakken play is approximately $1,266. Soil survey data supports the conclusion that this is due to poor soil quality throughout the Bakken region's surface land. Table 4.3 lists region-averaged acre-weighted National Commodity Crop Productivity Index[40] (NCCPI) values by shale geology. The NCCPI is an index that grows monotonically with soil quality, accounting for a range of soil characteristics. Off-shale soil quality is generally higher than in either Bakken shale or Williston basin areas. Of the transactions observed, approximately 32% concern on-shale parcels, while approximately 82.6% of trades concern parcels within the Williston basin. This includes on-shale transactions—that is, parcels located within the Williston basin but outside of the Bakken play comprise around 50.6% of total transactions.

Finally, Table 4.4 reports summary statistics by region. Bid rates, minimum bids and the bid ratio decrease for parcels deeper in the shale territory. Similarly, acres per parcel and well counts increase, reflecting both increased presence of oil and greater availability of additional acres for agricultural use. There are more total parcels and a greater number of transactions within the greater Williston basin and Bakken shale region than in the off-shale region in the eastern portion of North Dakota.

As outlined above, there may be selection into whether or not a parcel is leased. If selection is correlated with variables that also influence rent conditional on the land being leased, coefficient estimates will be biased. Table 4.5 reports the pairwise correlations between variables, with p-values and number of non-missing observations included. Although the correlation statistic is significantly different from zero for many of them, the correlations themselves are not large. As a further check, I specify a first-stage selection equation that directly estimates the impact of possible covariates on the probability of a parcel being leased. I also specify a linear probability model (LPM), i.e. a linear regression estimating the impact of covariates on the binary outcome of whether or not a parcel was leased during a particular

[40] Values in Table D.3 reflect my calculations with data provided by the USDA's Nebraska field office. See https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/16/nrcs143_020559.pdf for detailed NCCPI documentation.

auction. The LPM results appear below, and a probit estimation of the same model appears in the Appendix.

To address the possible selection bias, I estimate auxiliary specifications that use higher-order nonlinear transformations of possible selection covariates. These serve as non-parametric "nuisance terms" that account for variation associated with the source of the bias. More generally, they comprise a higher-order approximation to the unknown rental function. I specify the nuisance terms as

$$\sum_{n=2}^{4}\left(\ln(NCCPI)^n + \ln(Acres)^n\right).$$

4.5 – Results

Table 4.6 presents the results of the first-stage regression. A majority of the coefficients is significant at the 10% level or better, indicating that the selection issue described above may bias the second-stage results. However, adding the nuisance parameters causes NCCPI and the minimum bid to lose statistical significance. As described above, the nuisance parameters are nonlinear functions of both of these variables—when included in the LPM specifications, the set of nuisance parameters is jointly significant, although not all of them are individually significant. In the second-stage estimation, I use these as non-parametric controls for selection into the group of leased parcels. Including the nuisance terms changes the sign of $\ln(Acres)$ from positive to negative, possibly due to the quadratic variation in the nuisance term. Similarly, NCCPI loses its statistical significance in specifications 6 and 9, which include the nuisance terms.

The second-stage results are presented in Table 4.7, with robustness checks presented in Tables 4.8 through 4.10. County NCCPI is significant, with a change of 0.1 associated with a $190 to $200 increase in total parcel value. Consistent with expectations, β_{basin} and β_{shale} are negative, indicating that on-shale parcels suffer a significant location penalty. The well count coefficient ψ is not statistically significant, although it is jointly significant with β_{shale}. There is some evidence of bias in Table 4.7 The effect of an increase in the logarithm of parcel acres, ρ, has an estimated coefficient of 438 in the full-sample specifications and 267 in the restricted-data specifications. By logarithmic differentiation, dividing by average acreage of 146 yields the marginal impact of an additional acre—the estimates of ρ imply an unrealistic marginal land value of less than $3 per acre.

In the robustness check presented in Table 4.8, ρ is significant only for the full sample results, and returns an implied per-acre value of $31. NCCPI is no longer significant in models 1 and 2, and has an unintuitive magnitude and sign in the Williston basin data. The estimates of β_{shale} and ψ are jointly significant, and the nuisance parameters are not jointly significant. This is reassuring, since they are jointly significant in the first-stage selection estimations. The cost of the strategy, however, is that it makes the "bias-corrected" coefficients more difficult to interpret. The coefficients of interest do not change greatly, though, indicating that oil and gas activity does not produce direct spillovers that are captured by rental bids on North Dakota State Trust Lands.

4.6 – Conclusion

While agricultural parcels within the Bakken shale region lease at lower values than off-shale land, I conclude that the presence of oil and gas industry activity is not a primary driver of this difference. Rather, the average rental bid is increasing in parcel size and the state's opportunity cost as signaled by the minimum bid. In practical terms, the presence of oil and gas wells is not significantly related to the per-parcel bid.

With this in mind, it seems unlikely that the presence of the oil and gas industry is responsible for the divergence in county-level agricultural rents growth observed in Figure 4.2. Although on-shale counties experience slower rent growth in the years coinciding with the shale boom, parcel-level oil industry activity measures are neither significant nor negatively related to bid premiums, as would be the case in the presence of negative spillovers. Given the lack of statistical significance in my results, by contrast, it appears that agricultural land does not capitalize a negative impact from shale oil activity into its rents. In light of the current literature, this implies that house value changes due to shale oil and gas proximity may not be due to any objective environmental hazard, but rather to residents' subjective beliefs about the risk of an environmental hazard.

The limitations of this study suggest two extensions that can be carried out in future research. First, while use of public lands data avoids the issue of valuing a mineral estate, the surface plots owned by the state of North Dakota are not as heavily exposed to oil wells as other parcels. While roughly a quarter of leases I observe were within two kilometers of at least one oil well, I do not observe much variation in the number of wells within the boundaries of a parcel. Anecdotal evidence suggests[41] that within-parcel well pad locations can be disruptive to agricultural operations; private agricultural land transactions may reflect this. To further distinguish the aesthetic disamenities from negative health outcomes and environmental damage, private agricultural land transactions in areas with federal or state mineral rights ownership can be considered. Once again, this would take advantage of known mineral rights distributions, un-linking the surface transactions from the mineral estate. Second, it is possible that the requirement of compensation and availability of legal recourse for surface owners mitigates value losses. This kind of "insurance" at least partially offsets losses in the presence of spills or lost production, affording a modicum of protection to surface owners who may not be able to negotiate with shale energy developers in the same manner as combined-estate owners might be able to do. While this may still fail to mitigate downstream environmental hazards (e.g. surface water contamination), it would still provide a mechanism through which surface owner welfare is preserved.

The policy implications are clear. If the negative externality capitalized into shale-region house transactions is not based on objective environmental degradation but rather on a visual or noise disamenity, areas with the lowest population density will have the lowest external cost of shale development. Especially if the institutions governing surface and mineral ownership allow welfare-

[41] Hitaj et al (2014) cite topical reporting that appeared in the *Earth Island Journal* claiming that shale energy developers perpetrated a systematic set of abuses and denials of due process to surface owners. The story's focus is not broad, however, and it does not report useful statistics that can substantiate the claims of systematic abuse.

maximizing outcomes for energy developers, mineral owners and surface operators, then agricultural land is an ideal place to frack.

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Chapter 4 Figures and Tables

Extent of the Bakken/Three Forks shale and Williston Basin in North Dakota

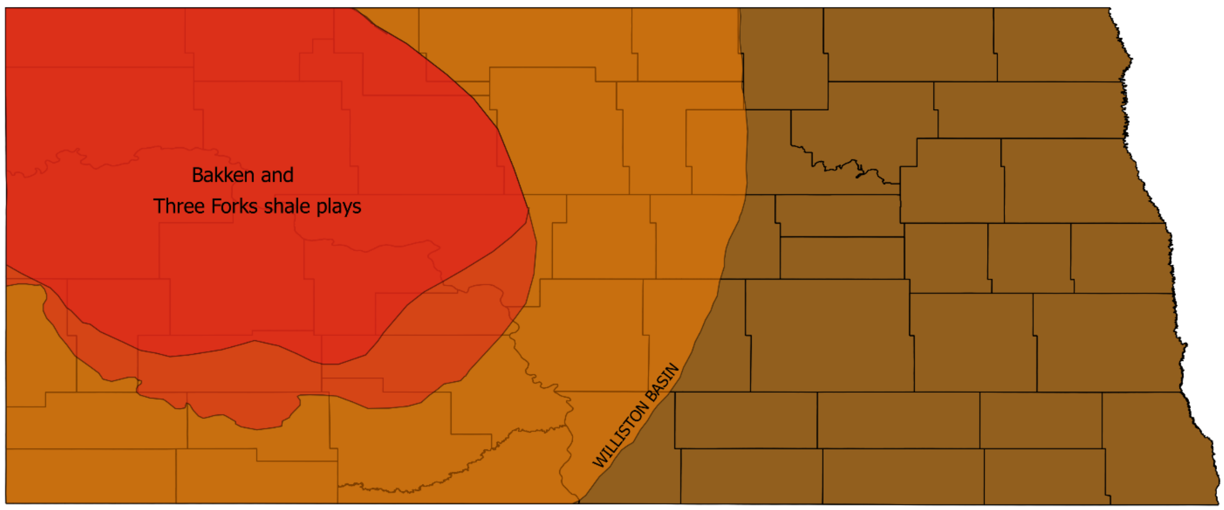

Figure 4.1: North Dakota’s oil geography

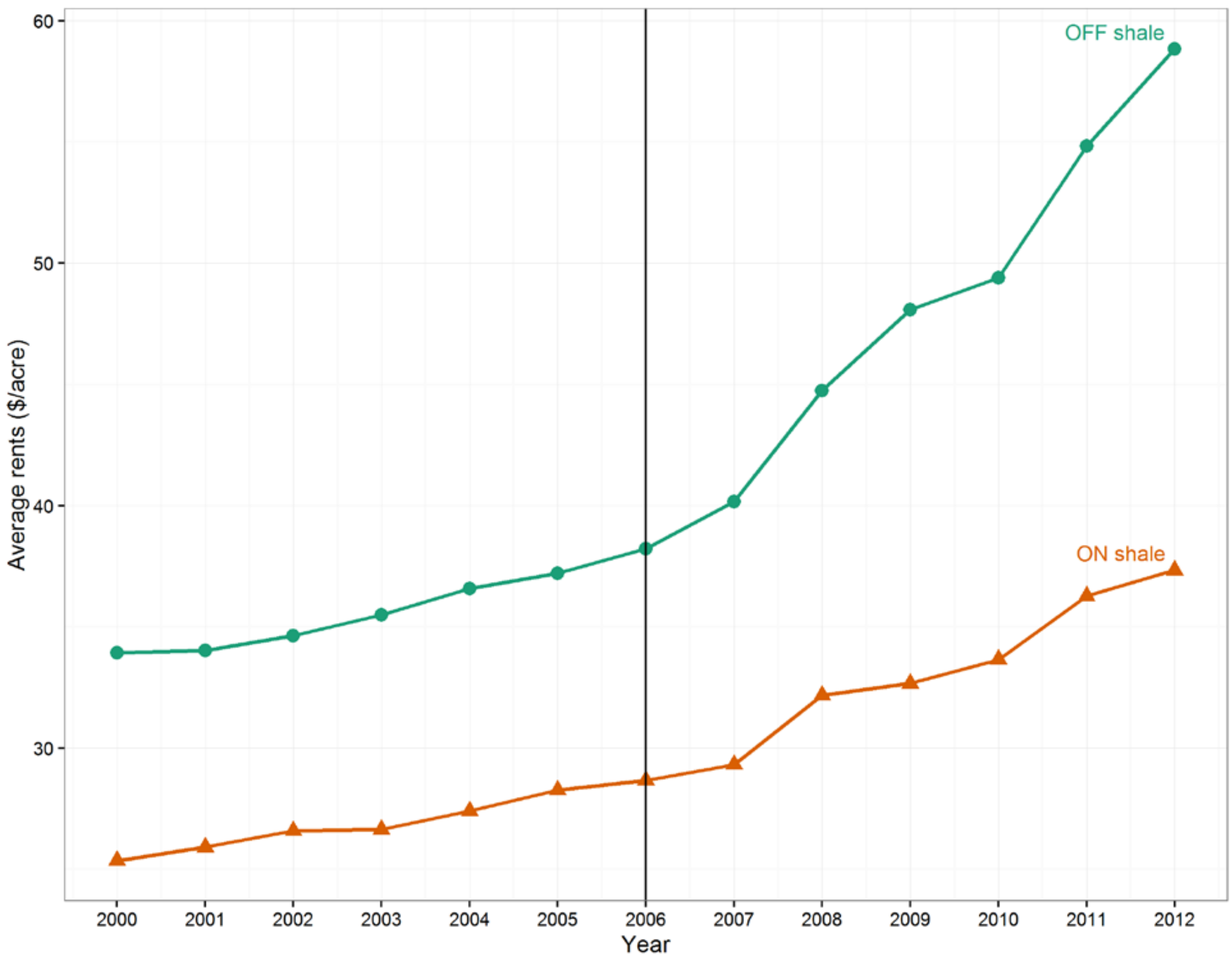

Figure D.2: North Dakota County-level Cash Rents

Data source: county-level yearly rent series, USDA Quickstats

Table 4.1: North Dakota agricultural acreage

Census Year	Acres	% state land area
2002	34,490,007	78.10%
2007	35,255,002	79.83%
2012	35,134,184	79.56%

Data source: author's calculation from USDA acreage data and U.S. Census estimates of state surface area.

Table 4.2: North Dakota State Trust Lands parcel summary statistics

Variable	Mean	St. Dev.	Min	25%	Median	75%	Max	N
Rental bid	1,277.13	1,113.07	0	700	1,077	1,584	22,900	18,320
Bid per acre	9.869	12.913	0	4.78	7.191	10.861	337.019	17,874
Minimum bid	1,189.42	773.642	14	746	1,062	1,442	15,685	18,320
Bid ratio	1.041	0.502	0	1	1	1	8.752	18,320
Parcel acres	146.082	35.184	5.038	158.147	159.488	160.539	643.344	17,874
Well count	0.256	2.433	0	0	0	0	77	18,320
On shale dummy	0.313	0.464	0	0	0	1	1	18,320
Williston basin dummy	0.822	0.382	0	1	1	1	1	18,320

Note: the number of observations (N) reports the total number of nonmissing values for each variable.

Table 4.3: North Dakota NCCPI by region

Region	Average NCCPI
Off-shale	0.247
	(0.0609)
Williston Basin	0.157
	(0.0628)
Bakken shale	0.141
	(0.0582)

Note: standard deviations in parenthesis

Table 4.4: State Trust Lands parcel summary statistics by region

Region	Off-shale	Williston basin	Bakken play
Rental bid	1756.992	1350.352	885.865
	(1781.466)	(981.863)	(544.987)
Bid per acre	15.181	10.393	6.418
	(17.898)	(12.894)	(8.138)
Minimum bid	1549.010	1266.378	860.310
	(1227.798)	(665.493)	(381.047)
Bid ratio	1.089	1.041	1.013
	(0.627)	(0.512)	(0.393)
Parcel acres	133.298	147.227	150.474
	(46.15)	(34.646)	(27.597)
Well count	-	0.001	0.816
		(0.037)	(4.294)
Parcel count	843	2,433	1,598
Number of transactions	3,253	9,331	5,736

Note: standard deviations appear in parenthesis

Table 4.5: Pairwise correlations of variables

Panel A: Off-shale parcels

	NCCPI	Rental bid	Minimum bid	ln(acres)
NCCPI	1			
p-value				
Num. Obs.	2807			
Rental bid	-0.0013	1		
p-value	0.9433			
Num. Obs.	2807	3253		
Minimum rent	0.0028	0.8185***	1	
p-value	0.882	<0.001		
Num. Obs.	2807	3253	3253	
ln(acres)	0.0673***	0.2299***	0.2263***	1
p-value	0.0004	<0.001	<0.001	
Num. Obs.	2807	2807	2807	2807

Panel B: Williston basin parcels not located on Bakken shale

	NCCPI	Rental bid	Minimum bid	ln(acres)
NCCPI	1			
p-value				
Num. Obs.	9331			
Rental bid	0.1293***	1		
p-value	<0.001			
Num. Obs.	9331	9331		
Minimum rent	0.1149***	0.7388***	1	
p-value	<0.001	<0.001		
Num. Obs.	9331	9331	9331	
ln(acres)	-0.0454***	0.0744***	0.0377***	1
p-value	<0.001	<0.001	0.0003	
Num. Obs.	9331	9331	9331	9331

Panel C: On-shale parcels

	NCCPI	Rental bid	Minimum bid	ln(acres)
NCCPI	1			
p-value				
Num. Obs.	5736			
Rental bid	0.1616***	1		
p-value	<0.001			
Num. Obs.	5736	5736		
Minimum rent	0.1482***	0.7530***	1	
p-value	<0.001	<0.001		
Num. Obs.	5736	5736	5736	
ln(acres)	-0.1492***	0.1167***	0.0900***	1
p-value	<0.001	<0.001	<0.001	
Num. Obs.	5736	5736	5736	5736

Note: *p<0.10; **p<0.05; ***p<0.01.

Table 4.6: First-stage linear probability model results

	Dependent variable: 1 if parcel is leased, 0 otherwise							
Parameter	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
ln(minimum rent)			0.0846***	0.0847***	0.0869***	0.0846***	0.0870***	0.0847***
			(0.003)	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)
County NCCPI	-0.154***	-0.256*			-0.230***	-0.0734	-0.229***	-0.0733
	(0.031)	(0.147)			(0.030)	(0.145)	(0.030)	(0.145)
ln(acres)	0.0749***	-0.496***	0.0458***	-0.391***	0.0435***	-0.351***	0.0435***	-0.351***
	(0.005)	(0.122)	(0.005)	(0.089)	(0.005)	(0.120)	(0.005)	(0.120)
On-shale dummy	0.0166***	0.0123***	0.0503***	0.0443***	0.0458***	0.0441***	0.0470***	0.0453***
	(0.004)	(0.004)	(0.004)	(0.004)	(0.004)	(0.004)	(0.004)	(0.004)
In-basin dummy	-0.0282***	-0.0279***	-0.00404	-0.0199***	-0.0189***	-0.0200***	-0.0188***	-0.0200***
	(0.005)	(0.006)	(0.005)	(0.005)	(0.005)	(0.005)	(0.005)	(0.005)
Well count							-0.00146**	-0.00142**
							(0.001)	(0.001)
Constant	0.595***	1.811***	0.119***	0.986***	0.167***	0.952***	0.165***	0.951***
	(0.025)	(0.167)	(0.028)	(0.153)	(0.029)	(0.167)	(0.029)	(0.167)
Nuisance parameters?	No	Yes	No	Yes	No	Yes	No	Yes
Significant nuisance?	-	Yes	-	Yes	-	Yes	-	Yes
Year FE?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Num. Obs.	17,870	17,870	17,870	17,870	17,870	17,870	17,870	17,870
R^2	0.030	0.035	0.065	0.070	0.068	0.070	0.068	0.071

Note: * p<0.05; ** p<0.01 ***; p<0.001

Table 4.7: Tobit regression results

Parameter	*Dependent variable: Rental bid*			
	Full-sample		*Greater Williston basin only*	
	(1)	(2)	(3)	(4)
County NCCPI (θ)	1914.0***	1914.8***	2052.7***	2052.7***
	(135.186)	(135.191)	(116.055)	(116.061)
ln(acres) (ρ)	438.1***	438.2***	267.9***	267.9***
	(20.696)	(20.697)	(20.198)	(20.199)
In-basin dummy (β_{basin})	-374.5***	-374.4***		
	(24.073)	(24.073)		
On-shale dummy (β_{shale})	-428.8***	-427.2***	-418.4***	-418.4***
	(17.417)	(17.607)	(14.327)	(14.483)
Well count (ψ)		-1.939		0.0506
		(3.151)		(2.588)
Constant (α)	-1180.8***	-1181.8***	-653.8***	-653.8***
	(109.848)	(109.859)	(105.749)	(105.763)
Year FE?	Yes	Yes	Yes	Yes
S.E. of the regression:	1007.8***	1007.7***	828.0***	828.0***
	(5.612)	(5.612)	(5.025)	(5.025)
Num. Obs.	17,870	17,870	15,063	15,063

Note: * p<0.10; ** p<0.05; *** p<0.01.

Table 4.8: Robustness check - Tobit regression with nuisance parameters

Parameter	*Dependent variable: Rental bid*			
	Full-sample		*Williston basin only*	
	(1)	(2)	(3)	(4)
County NCCPI (θ)	-8569.9***	-8570.3***	-4724.5***	-4724.5***
	(641.716)	(641.713)	(678.252)	(678.252)
ln(acres) (ρ)	4609.1***	4608.4***	-134.6	-134.6
	(528.142)	(528.140)	(551.961)	(551.963)
In-basin dummy (β_{basin})	-359.1***	-359.1***		
	(23.812)	(23.812)		
On-shale dummy (β_{shale})	-458.6***	-457.2***	-472.6***	-472.6***
	(17.638)	(17.815)	(14.831)	(14.974)
Well count (ψ)		-1.813		-0.00758
		(3.104)		(2.565)
Constant (α)	-940.4	-940.3	3940.4***	3940.4***
	(719.355)	(719.351)	(756.840)	(756.840)
Significant nuisance?	No	No	No	No
Year FE?	Yes	Yes	Yes	Yes
S.E. of the regression:	992.6***	992.6***	820.6***	820.6***
	(5.526)	(5.526)	(4.979)	(4.979)
Num. Obs.	17,870	17,870	15,063	15,063

Note: * p<0.10; ** p<0.05; *** p<0.01.

APPENDIX C: CHAPTER 4 ADDITIONAL TABLES

Table C1: First-stage probit marginal effects

	Dependent variable: 1 if parcel is leased, 0 if not							
Parameter	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
County NCCPI	-1.191	1.59			-1.2	-0.372	-1.194	-0.361
	(0.262)**	-2.027			(0.270)**	-3.141	(0.271)**	-3.141
	[-0.024]	[0.032]			[-0.024]	[-0.007]	[-0.024]	[-0.007]
ln(min. rent)			0.534	0.529	0.535	0.53	0.536	0.53
			(0.025)**	(0.026)**	(0.026)**	(0.026)**	(0.026)**	(0.026)**
			[0.417]	[0.411]	[0.418]	[0.412]	[0.418]	[0.412]
ln(acres)	0.471	-9.915	0.26	-5.572	0.246	-5.056	0.246	-5.065
	(0.032)**	(2.799)**	(0.037)**	(1.433)**	(0.037)**	-4.583	(0.037)**	-4.583
	[0.274]	[-5.738]	[0.148]	[-3.162]	[0.140]	[-2.869]	[0.140]	[-2.873]
On-shale dummy	0.172	0.139	0.378	0.343	-0.187	-0.205	-0.188	-0.205
	(0.037)**	(0.039)**	(0.038)**	(0.041)**	(0.050)**	(0.051)**	(0.050)**	(0.051)**
	[0.005]	[0.004]	[0.011]	[0.010]	[-0.019]	[-0.020]	[-0.019]	[-0.020]
In-basin dummy	-0.217	-0.223	-0.113	-0.205	0.349	0.343	0.362	0.356
	(0.047)**	(0.048)**	(0.047)*	(0.051)**	(0.039)**	(0.042)**	(0.040)**	(0.042)**
	[-0.022]	[-0.022]	[-0.011]	[-0.020]	[0.010]	[0.010]	[0.011]	[0.010]
Well count							-0.013	-0.013
							(0.006)*	(0.006)*
							[-0.000]	[-0.000]
Constant	-0.545	18.723	-3.356	9.741	-3.029	8.986	-3.04	8.983
	(0.175)**	(4.321)**	(0.206)**	(2.631)**	(0.219)**	-6.882	(0.219)**	-6.882
Nuisance parameters?	No	Yes	No	Yes	No	Yes	No	Yes
Significant nuisance?	-	Yes	-	Yes	-	No	-	No
Year FE?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Num. Obs.	17,798	17,798	17,798	17,798	17,798	17,798	17,798	17,798

Note: *p<0.05; **p<0.01. Marginal effects listed in brackets.

CHAPTER 5. SUMMARY AND CONCLUSIONS

The three studies in this dissertation examine separate but related aspects of changes in the U.S. energy portfolio between 2000 and 2015. Energy development has the potential to affect a wide range of outcomes, including wealth creation, demand for labor, and environmental variables, and understanding the nature of how these outcomes are affected informs the greater cost-benefit analysis of future energy portfolio changes. The studies themselves consider ways to value the spillovers produced by the rollout of energy generation and recovery infrastructure. In two essays, I draw on the theory of wages and rents to assess the implicit price of resource exploitation, using as case studies the rollout of wind energy generation installations in Iowa and the increase in oil and gas production of the U.S. shale energy boom of the mid-2000s. In the third essay, I conduct a hedonic land rents analysis to examine possible production spillovers between shale oil extraction and agriculture.

Taken together, the studies support the conclusion that the local valuation of energy development is negative (or at least non-positive). This plays out in different ways. In the case of the first essay, I examine the impacts of wind energy development on incomes and house values in rural Iowa. The economic literature has documented reduced real estate values and increased incomes and employment associated with large-scale wind energy development. However, mine is the first study to examine both outcomes at once at the same geographic scale, allowing me to interpret my results without having to aggregate to the county level. I find that the implicit price of wind farm size is negligible. I find no evidence of widespread wind turbine lease income within 5 miles of a wind farm; in the context of the existing literature, this implies that personal income gains attributable to wind energy development are distributed far away from wind farms themselves.

In the case of the second essay, I measure significant benefits to the labor market associated with the U.S. shale energy boom. The large increase in oil and gas extraction in the continental U.S. has been associated with negative house-value impacts and positive labor market impacts, but existing studies are often confined to specific geographic areas. I use a nationally-representative sample of shale energy counties in the U.S. and I consider house values and incomes simultaneously—this allows me to estimate a welfare measure that values the local impacts of the shale resource. Counties experiencing greater oil and gas extraction during the boom benefitted from 3.9% wage growth and 4.4% employment gains as compared to other counties in the same states with no access to shale resources. However, a 1.5% decrease in median house prices suggests that the disamenities of shale energy development are potentially sizable, and the implicit price of additional energy production is between $160 and $425 to avoid a 1% increase in total energy produced within a county.

Capturing spillovers between shale energy development and agriculture is less straightforward. While some studies find that agricultural landowners' subjective valuations of their land increased during the boom, others find that rural real estate values capitalize large negative impacts of proximity to oil and gas wells. In the case of large swaths of agricultural land like those found in North Dakota's Bakken region, few residents will live near enough to oil wells to experience the disamenities of proximity. Agricultural land, however, should capitalize production spillovers, resource rents and the opportunity cost of the land's surface area. In the third essay, I examine bids on agricultural leases for state trust lands in North Dakota, finding that proximity with oil and gas infrastructure has no effect on agricultural lease bids. As compared to the majority of existing studies, I am better able to control for property rights ownership since state-owned agricultural lands and mineral lands are leased separately. Since surface operators do not own mineral rights on state land, their bids must reflect an expected return on land without regard to the mineral estate. My finding of "no effect" is potentially evidence that the negative value of shale energy infrastructure derives from its properties as a nuisance rather than as an environmental hazard.

The studies lay the groundwork for future research. While I find no evidence that state trust land lease bids in North Dakota are affected by the presence of oil wells, I cannot distinguish whether this is truly due to a lack of physical effect or to selection into renting state-owned land. The data are censored by a legally-mandated minimum bid; this argues for an extension that isolates privately traded agricultural land in areas with known mineral rights distribution. Similarly, my estimates of wind energy's local impacts have the benefit of high-resolution income data, but could be easily extended to use agricultural land transactions to generate more-precise rental estimates.

The long-run environmental costs of wind energy and the shale boom are also avenues for future work. Though the labor demand shock of the shale boom may be transient rather than structural, the changes to rural landscapes from wellheads, pipelines and pumpjacks may portend lost welfare as less-visible effects of the shale boom become more apparent. The analyses presented above are limited in the time horizon they consider, and can be updated as new data becomes available. Similarly, the negative impact of wind energy installations may attenuate over time as residents re-sort their locations. This premise has yet to receive attention in the literature, and it would inform the cost-benefit analysis of new wind power development as technological advances and renewable portfolio incentives drive greater renewable generation deployment.