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Economics in Transition: Issues Applicable to Climate Change

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To the Graduate Council:

I am submitting herewith a dissertation written by Odysseus Bostick entitled "Economics in Transition: Issues Applicable to Climate Change." I have examined the final electronic copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Economics.

Don Bruce and Charles Sims, Major Professor

We have read this dissertation and recommend its acceptance:

Don Bruce, Charles Sims, Scott Holladay, Daniel Bergstresser,

Accepted for the Council:

Dixie L. Thompson

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

Economies in Transition: Issues Applicable to Climate Change

A Dissertation Presented for the

Doctor of Philosophy

Degree

The University of Tennessee, Knoxville

Odysseus Bostick

December 2023

“Those who have a why to live can bear with almost any how.” - Viktor Frankl

To My Wife Catherine:

Every day, in every way, you make the world a more lovely place.

And in your path, the light shall pass upon all of us in your trace.

For your grace and beauty, shines through all.

No matter what challenge shall amass.

Oh, what derelictions of time, kept me from knowing you?

My solace for that is today’s heart chime.

Acknowledgments

I want to thank every person who was patient enough to help me get here. The list is long and esteemed. In this University community, I found myself fortunate enough to learn from some amazing people. Matt Harris actually made econometrics exciting. Scott Gilpatric can immediately and spontaneously speak cogently about microeconomic theory in a way that seems effortless. I talked more deeply about garbage with Georg than anyone else in my life. I laughed the most with Mohsin.

To these people and those on my committee, I thank you. Thank you Charles, Don, Scott, and Dan. Each one of you has challenged me to grow and I am a better person because of it.

My wife is my north star and merits more than a simple thank you in this document - something I will begin rectifying immediately. And I want to thank my grandfather who made me the man I am today. I miss you.

Abstract

This dissertation presents three essays on topics that characterize the challenges of the energy transition. The first two focus on mitigating the worst impacts of climate change while the final hones in on adapting to climate change.

The first essay estimates willingness-to-pay (WTP) of electricity customers for rooftop solar within the Tennessee Valley Authority. Applying a conditional logit model, the probability of adoption rises with utility rates and emissions-reductions and declines with costs. Evidence of social contagion exists with adoption probabilities increasing $55 - 57\%$ when respondents know someone with panels. WTP also rises. Comparing aggregated to regional WTPs confirms the impact of social contagion. As residential rooftop solar adoption accelerates the energy transition while minimizing transmission investments, utility asset planners may want to incorporate this feedback loop on social contagion.

The second essay analyzes the negative impacts of carbon policy. While a carbon tax would reduce our reliance on fossil fuels, it may introduce a systemic risk to the economy by shortening the economic life of carbon assets. This essay investigates whether past policies promoting exploration increases the magnitude of stranded assets when policy changes. We find carbon taxes cause firms to leave more reserves undeveloped, but firms suffer 20% fewer stranded assets under inconsistent policy than BAU due to lower marginal production costs from larger stock effects though this yields minimal differences in profits. Policymakers hesitant to deploy carbon taxes may need to reconsider whether our current treatment of stranded assets is confusing them with sunk costs.

The third essay pivots towards the effort to adapt to climate change. We study growth and convergence across California cities after Proposition 13 normalized property tax rates and initiated a redistribution of wealth. I find strong evidence of convergence across cities as measured by per capita property values and little evidence that the transfer dampened the growth of household wealth in transfer cities. I find significant variation in line-item expenditure productivity. Investments boosting city functionality induce growth while spending on services better achieved by regional coordination reduces growth. Increasing revenues spur growth when they do not inhibit the public's marginal propensity to consume.

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Chapter 1

Behavioral Effects on the Demand for Solar Energy

Abstract

We[1] assess residents of the TVA region's willingness to pay for rooftop solar panels. Our representative sample of 2,307 respondents each participate in six choice experiments offering solar arrays that randomly vary in cost, electricity savings, and carbon emission reductions. Consistent with the low penetration of solar regionally, just 1.3% of respondents report owning panels with 19.3% stating they know someone else who does. Applying a conditional logit model, we find adoption probability of installing solar rises with utility rates and emissions-reductions and declines with system costs. Evidence of social contagion exists with adoption probabilities increasing $55-57\%$ when respondents know someone with panels and willingness to pay (WTP) estimates rising with higher rates of penetration. Comparing aggregated WTPs to regional WTPs confirms the impact of social contagion. In some areas where penetration is low, peer effects appear to reduce WTP. Utility asset planning may be more efficient if it incorporates this feedback loop.

Keywords: solar energy, solar contagion, stated-preference

JEL Codes:

1.1 Introduction

Massive expansion of renewable energy is critical to reducing pollution emissions and avoiding the catastrophic impacts of climate change [122]. Reducing costs for distributed energy sources like rooftop solar is a key driver of adoption at the household level [60]. Falling prices have led to large increases in adoption of solar. From 2015-2020, the total footprint of behind-the-meter rooftop solar in the U.S. rose from 7.4 GW in 2016 to 11 GW. The pace of adoption is accelerating while cost is declining, but the widespread adoption necessary to achieve climate goals may be limited by socioeconomic and demographic factors [97].

In this paper we estimate willingness-to-pay (WTP) for rooftop solar in the Tennessee Valley Authority (TVA) region. We use a stated-preference survey to identify how WTP

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[1] This chapter was co-authored by Odysseus Bostick, Chien-fei Chen, Islam El-adaway, J. Scott Holladay, & Charles Sims

varies with the characteristics of solar panels. Our approach allows us to estimate the WTP for solar panels based on private economic benefits and WTP inclusive of peer effects from community adoption. The results suggest that knowing someone with solar panels is associated with higher WTP. Increased solar penetration in a community is also associated with higher WTP, although the effect is much smaller.

We also identify heterogeneity in preferences for rooftop solar across regions [55] of the TVA area. Our large sample size of our survey allows us to estimate WTP separately across electrical busses in the TVA region. Our results indicate significant variation in WTP, cost sensitivity, and environmental motives across respondents in neighboring busses with some regions much more cost sensitive and other much more influenced by the adoption decisions of their neighbors.

We estimate willingness-to-pay (WTP) in a region where rooftop solar is extremely rare. Much of the literature on the determinants of WTP for rooftop solar has focused on regions where rooftop arrays are plentiful and expanding quickly ([68], [21], [71], and [90]). We conducted a stated-preference survey using a representative sample of residents of the Tennessee Valley Authority (TVA) service area, a federal corporation with regional authority over electricity generation, economic development, and environmental stewardship in 163 counties across the Tennessee Valley [67]. The survey included six choice experiments offering respondents solar arrays that vary randomly in their cost, electricity savings, and carbon emissions reductions. We also solicited household preferences for rooftop solar and their experiences with the technology. Just 1.26% of our respondents report owning solar panels and 19% report knowing someone else who has panels.

We provide two version of WTP using a conditional logit model [79], one strictly driven by the economic costs and benefits of investing in solar and one socially-influenced choice. To construct the social WTP, we included a question in the survey asking respondents if they would acquire solar panels once a randomly assigned threshold of their neighbors had them.

The overall average WTP for a typical solar array is a net present value of \$259.45 – \$342.55 when the decision is strictly based on the economics. Overall estimates decline to $46.76 − $310.07 (NPV) when social influences are included. These low overall averages obscure significant heterogeneity within the TVA footprint, however. When we dis-aggregate the data to consider city-level and regional estimates, we find that socially-influenced WTPs range from as low as $ − 112.04 to as high as $2,404.11. Economically-influenced WTPs are similarly broad in range, spanning −$883.95 up to $2,470.32.

As a final contribution, we identify evidence of social contagion in the region with economic and social WTPs varying with solar penetration. Identifying vast differences in the relative sizes of economic versus social WTP is our last contribution. We assess the possibility of solar ”contagion” across the TVA region. Understanding the regional spread of solar is important for utility planners thinking about future transmission and generation upgrades as adoption rates are highly influenced by the clustering of households with panels. There are a number of papers that examine behavioral economic motives for adoption and the crucial role that network effects play in the diffusion of solar ([49], [34], [20] and [70]). This literature has found that seeing the installation of rooftop solar in a community can cause residents to become more interested in solar and the clustering of adoptions is integral in facilitating a contagion effect. Much of this work has been done empirically using regions with relatively high solar penetration levels. Our results indicate that in TVA, respondents become slightly less price-sensitive when solar adoptions increase around them with a few regional exceptions. In these cities and regions, the social WTP is larger than the economic one. Correspondingly, areas that are more price sensitive have far larger private WTPs.

1.2 Literature Review

Demand for solar panels is frequently dampened by high upfront costs in nascent and mature solar markets ([7], [59], [88]). Correspondingly, the range of WTP estimates is generally fairly low. [22] estimates WTP for solar ranges from $6.10 − $31.16 per month while [26] presents estimates of just $1.41 − $2.69 per month. In a meta-analysis of WTP in response to the initiation of renewable energy standards, [114] found a wide range of estimates from as low as −$0.37 to as high as $53.06 per month. These overall low WTP estimates underscore the critical factor of income [5] and the negative impact of upfront capital costs on adoption rates. Earlier research finds WTP covering just $16-26.6\%$ of the upfront capital costs ([107], [33]).

Household perceptions over the economic value of solar panels often drive the formation of WTP with consumers splitting into two broad types, value and premium solar consumers. Value-driven adopters are strictly driven by minimizing the costs of installations whereas premium-driven adopters are willing to pay more for panels with a higher perceived aesthetic attractiveness. Both are more willing to adopt when their peers have already purchased panels [91]. As markets mature, research shows the magnitude of adoption is larger when imitators respond to early adopters' savings [83].

Peer effects are powerful in swaying household perceptions of affordability. These attribute perceptions are the result of social norms and the relative value of adoption [120]. This may be a function of limiting information costs ([95] and [87]) as interpersonal word of mouth relationships often drive adoption [83].

[34] identifies two types of social norms that underpin the spillover effects leading to adoption. Descriptive norms refer to the observed actions of peers while injuctive norms represent peers' social expectations of others with the two norms interacting. Seeing installations of solar panels go up establishes a descriptive norm which induces a perceived injunctive norm as more installations are completed which creates a social pressure for additional adoptions.

[89] confirms that the visual presence of solar panel systems are significantly influential in the diffusion of solar technology. Of course, the passive effect of observing panels can vary in influence based on how active early adopters are socially and how vigorously they promote the value of adoption. Ex post enthusiasm for systems has often turned early adopters into hyper-aware prosumers (producers of solar who also consume their output) who become adoption evangelists [64]. The receptiveness to these evangelists is also strongly affected by the local cultural identity that has developed with respect to self and community. [9] finds that individualistic identities result in higher probabilities of adoption in Spain as solar panels are interpreted as a symbol of autonomy while lower Swedish adoption rates are

a function of a collectivist/conformist mentality that places a higher value on centralized decision-making. The value of solar as a form of autarky is supported elsewhere [68].

Estimates vary on the range of peer effects. Social media has been found to accelerate imitation up to the city-level [23]. Strongest effects are likely more localized. [21] estimates that the probability of adoption increases by 0.78% when an installation occurs within the same zip code and 15% with each additional installation on the same street.

In both cases, these peer effects also result in larger installations. ([48] finds the range of peer effects only lasting up to one mile with the number of installations increasing by 0.44 for every new one within a half mile. Strong evidence points to more granular network effects, however, with clustering more likely at the block-level and peer effects dampened by increased population density as well as the proportion of renters and multi-family units [49].

Unsurprisingly, home ownership greatly influences an individual's willingness to pay for residential solar. The lack of institutional support for renters to install solar can dampen adoption rates despite residential willingness to invest [104]. [35] confirms renter obstacles in adoption, but also hones in on the critical element of housing and household characteristics. They find that the probability of adoption increases with household size and square footage while decreasing with domicile age. [106] shows population age also matters. An increase in one standard deviation of zip code population counts of people aged $25-34$ and $55-64$ decreased installation shares by 13.8% and 21.1% respectively. The sweet spot appears to be in proportion of people aged $45-54$ where the increased intensity of this demographic raises the solar footprint by 12%.

1.3 History of the Tennessee Valley Authority

Established under President Franklin Delano Roosevelt in 1933, this federal corporation was granted regional authority over the provision of electricity for 163 counties within the Tennessee Valley. This includes nearly all of the state of Tennessee along with adjacent portions of Alabama, Georgia, Kentucky, Mississippi, North Carolina, and Virginia. Endowed with a three-pronged mandate over regional electricity generation, economic development, and environmental stewardship, the TVA transferred \$14.6 billion (in 2000 dollars) from the federal government throughout the region via large scale infrastructure investments between $1940-1958$ before the U.S. Congress required it to be self-financing. It is estimated that direct impact of the TVA's activities in the region over this period increased national productivity by 0.3% [67].

These transfer payments facilitated the modernization of the valley's economy through the construction of dams that simultaneously harness the regions waterways to generate electricity while providing critical flood control. In this effort, the TVA built a 650 mile system of canals, an extensive network of roads, and electrified the region [67]. Today, the TVA supplies electricity to 10 million people over the second largest transmission network of high voltage lines in the nation. With the third largest fleet of nuclear power plants and its vast network of hydroelectric power, electricity provided by the TVA is 57% renewable or carbon-free [116].

Several confounding factors and decisions by the TVA may be driving lower overall WTP and adoption rates. The TVA has pursued various utility-scale solar investments on its own and in collaboration with corporate partners [116]. While programs to incentivize rooftop solar adoption exist, financial disincentives recently introduced may work to stymie future adoption. This includes the Customer Generator Resale Rate Classification system that provides local service providers the ability to assess special fees to owners of solar panel systems [117].

Other implicit disincentives to adopt rooftop solar are the utility's rates and the pollution-intensity of its generating fleet. TVA reports its regional electricity rates are 70% lower for residential customers and 90% lower for industrial ones compared to the largest 100 U.S. utilities while 57% of TVA's generation is green [116]. These lower utility rates and higher use of green energy in front of the meter may be skewing our respondents' perception over the marginal benefit of solar relative to potential utility bill savings and marginal cost of installing rooftop solar.

1.4 Experimental Design

We conducted a survey of $2,307$ households in the TVA region. The survey consisted of around 40 questions and took respondents about fifteen minutes to complete. The survey included a stated-preference experiment, which presented six choice experiments each comparing three hypothetical solar arrays that vary in three dimensions: cost, electricity savings, and carbon emissions-reductions. After the stated preference experiment, respondents were presented a battery of questions about their opinions and experience with roof top solar panels. Finally, respondents answered a handful of socio-demographic questions.

Our sample frame is the TVA region, incorporating all of Tennessee and parts of six neighboring states. Respondents were collected through the Qualtrics panel which provides a channel to distribute surveys. We asked Qualtrics to sample at the zip code level, so that the number of respondents in each zip code roughly matches the distribution of households across the TVA region. Qualtrics markets the survey to its standing panel of respondents and pays a small fee for each completed survey. In areas where initial response is below the proportion needed they conduct additional marketing and sometimes increase the fee they pay to respondents.

The stated preference experimental design was straightforward. Each respondent was presented with some general information about solar panel arrays and the solar panel characteristics used in the experiment. Then they were given a set of six consecutive hypothetical choices, each consisting of three potential solar arrays and asked which one they were most likely to purchase. After making their choice, respondents were asked how likely they were to actually purchase their most preferred array along with follow up questions about when they would purchase it and how uptake in their community would affect their decision to purchase. Afterwards, they were presented with the next set of three arrays.

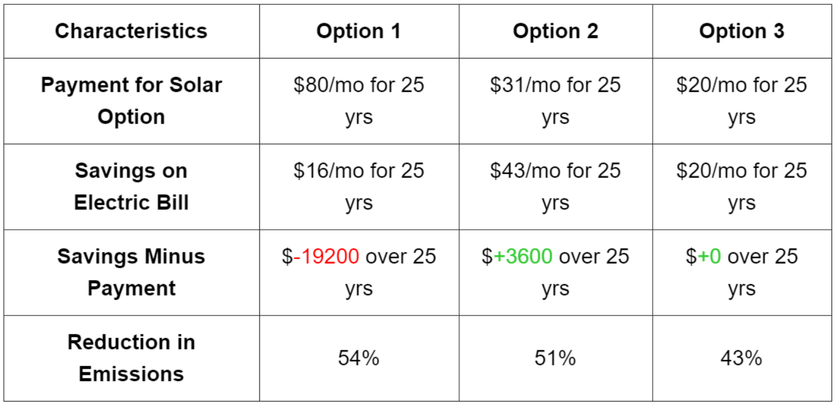
The solar arrays were characterized by three attributes. The price of the installed solar array was the amortized monthly cost over twenty-five years. The electricity savings, measured in dollars, represented the monthly savings from utility rates avoided after solar adoption over the next twenty five years. The savings minus payment was also presented separately with colored font, red if the cost exceeds the savings and green if the savings were greater than the cost. Respondents also saw a randomly generated reduction in emissions, reported in percentages. An example choice experiment graphic is presented in Figure 1.1.

Each of the three solar array characteristics was randomly drawn from an independent uniform distribution. Monthly system cost varied between \$10 and \$90, monthly electricity savings varied between \$0 and \$150, and emissions-reductions varied between $0 - 100\%$. Those ranges are somewhat beyond the typical cost and electricity savings produced by solar panels installed in the region, but we wanted to ensure that we had reasonable data coverage across the entire state space. Similarly, we chose to use independent draws from the three distributions meaning that some systems appeared with very high cost and low savings or high emissions-reductions and low electricity cost savings. These particular scenarios are unlikely and in some cases clearly dominated by other choices. We decided those odd solar arrays were a worthwhile sacrifice to ensure we had independent variation in all three dimensions. This variation provides the ability to separately identify the way that cost, savings and emissions-reductions affect the decision to purchase solar. The attributes and their domains are summarized in Table 1.1.

We use the results of the stated preference experiment to assess how sensitive respondents are to the price, cost savings, and emissions-reductions of their systems. We use respondents' opinions on solar power and socio-demographic characteristics to estimate a demand function for solar panels for households in the TVA footprint.

1.5 Analytic Approach

We use McFadden's conditional logit (CL) model [79] to estimate odds-ratios for alternative-specific variables. The CL estimate is built upon a Random Utility Model (RUM) that estimates odds-ratios based on consumer good attributes. Concerned that classical demand theory assumptions of homogeneity and infinite divisibility were limiting economic inferences into consumer behavior, [79] introduced the conditional logit model to analyze results from

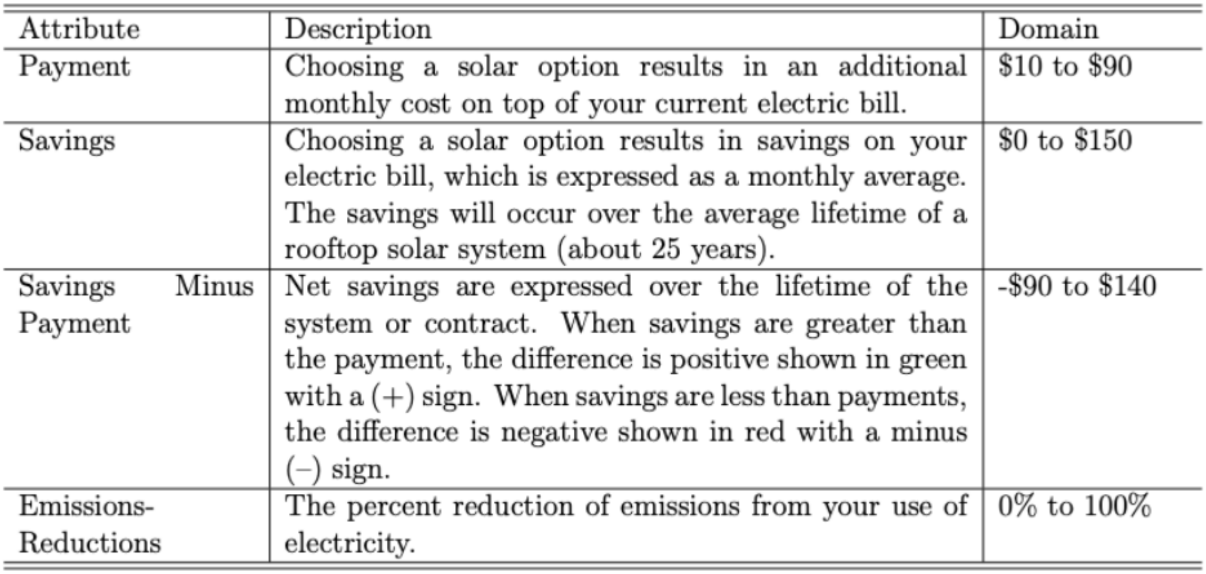


Characteristics	Option 1	Option 2	Option 3
Payment for Solar Option	$80/mo for 25 yrs	$31/mo for 25 yrs	$20/mo for 25 yrs
Savings on Electric Bill	$16/mo for 25 yrs	$43/mo for 25 yrs	$20/mo for 25 yrs
Savings Minus Payment	$-19200 over 25 yrs	$+3600 over 25 yrs	$+0 over 25 yrs
Reduction in Emissions	54%	51%	43%

Figure 1.1: Example Choice Experiment Solar Array Characteristics

Note: Respondents were presented with six different choice experiments. The solar array characteristics were presented in this way each time. The values of each of the payments, savings and emissions-reductions were randomly generated. Savings minus payment was calculated from those two numbers and color coded where green indicated net savings and red indicated net payments. All random numbers were drawn from independent uniform distributions. See the main text for details.

Table 1.1: Solar Panel Attribute Characteristics



Attribute	Description	Domain
Payment	Choosing a solar option results in an additional monthly cost on top of your current electric bill.	\$10 to \$90
Savings	Choosing a solar option results in savings on your electric bill, which is expressed as a monthly average. The savings will occur over the average lifetime of a rooftop solar system (about 25 years).	\$0 to \$150
Savings Minus Payment	Net savings are expressed over the lifetime of the system or contract. When savings are greater than the payment, the difference is positive shown in green with a (+) sign. When savings are less than payments, the difference is negative shown in red with a minus (−) sign.	-\$90 to \$140
Emissions-Reductions	The percent reduction of emissions from your use of electricity.	0% to 100%

discrete choice experiments. By loosening key behavioral restrictions and limiting the computational complexity, McFadden's model presented a tractable framework by which finite alternatives (goods) are compared based on their unique attributes.

Prior to McFadden, economists aggregated consumer decisions under the assumption that individuals possessed one distribution of utility functions and chose a unique function at random when making decisions over which goods to consume. Any variation in choice was a result of the individual's random selection of utility functions over time. McFadden posited that observed variations were not due to the random selection of a utility function as that would negate variations in preferences that drive the maximization of utility. Instead, researchers randomly observe a cross section of utility functions across individuals. Variations in consumption were the result of the heterogeneity of good attributes and individual preferences across the population.

McFadden further argued that predicting behavior was possible if the researcher knew the attributes of the available goods and the functional form of the individual's utility function. Mapping qualitative differences across attribute j as vector x_j and each individual t as vector s_t, individuals' utility functions assume the general form:

$$u_t(j) = u(x_j, s_t)$$

Two issues remained. Information asymmetries between the researcher and the individual make it impossible to identify the attributes of every possible good within the decision-maker's purview. Mapping the attributes of options presented to the decision-maker at any given time also requires assuming some functional form for utility. McFadden assumed each individual's utility was linear in parameters, no longer requiring the form of the overall utility function to be specified. A person's indirect utility assumes the form:

$$u(x_j, s_t) = v(x_{j0}, s_{t0})\beta + \epsilon_{tj}$$

Now we have the coefficient for the observed function β with ϵ_{tj} capturing the impact of the unobserved attributes. This allows McFadden's CL to use a maximum likelihood estimator to derive choice probabilities that are conditional on observations relative to the most likely choice. The computational burden of estimating the universe of odds-ratios for an individual's parameters this way is quite high, however. Here, McFadden assumes that the distribution of unobserved variables are a Type 1 extreme-value which allows the conditional logit to present as a special case of the multinomial logit [76]:

$$P(i|s_0, x_0| = \frac{exp[v(x_{io}, s0)\beta]}{\sum_{j \subset C} exp[v(x_{io}, s_0)]}$$

This is the model we take to the data.

1.6 Empirical Analysis

We report summary statistics for survey participants in Table ??. All our socio-demographic and solar experience questions were categorical, so we present the median response. The median age of respondents was $42 - 45$ with median incomes in the range of $\$35 - 50,000$. Less than 20% of respondents knew anyone with panels on their home and only 1% had panels installed, consistent with the low penetration of solar power in the TVA region. More than two-thirds of respondents were female. Female respondents were more likely to report responsibility for paying the electric bill and making decisions about utility programs or offers.

We estimate a series of choice models to capture the baseline relationship between panel attributes and the panel purchase decision. We estimate the probabilities in two different scenarios: Private or economic choice based on panel attributes only and social choice based on panel attributes and the fraction of neighbors who have installed solar. We construct the private choice estimate using a specific question posed to separate respondents' stated preferences from their actual intentions. Recall, respondents are provided options detailing solar costs and estimated savings in utility bills and emissions. After expressing their preference among the options provided, they are explicitly asked "Would you actually choose the option selected above or not install solar panels?". This forms the basis of the private choice.

The social choice is constructed similarly using the question: "Would you actually choose this option if $X\%$ of your neighborhood have solar" with X varying randomly between 25% and 100%. We construct three different sets of controls from survey questions and estimate each choice model across the different sets of control variables to assess the robustness of our estimates.

To understand the geographic distribution of WTP for solar panels, we match respondent zip codes to the electric bus within the TVA transmission system to map economic and social estimates geographically. This provides insight into regional solar adoption trends and potential differences in regional solar uptake which has important implication for regional transmission planning for grid reliability.

We report estimation results for the private choice and for social choice in separate tables. In both cases, there are four iterations of the same model. In each iteration, the conditional logit model estimates coefficients for three key variables of interest: the monthly cost for acquiring a rooftop solar system, the estimated average monthly savings on electric bills that households pocket because of the system, and the household's estimated percent reduction in pollution emissions from adopting a rooftop system. Coefficients are scaled so the odds-ratios are in response to an increase of \$100 cost, \$100 in savings, and 0.01% reduction in emissions.

The four models include different sets of controls. The first model only includes the panel attributes. Models $2-4$ add demographic variables reported by respondents. In the second model, we include gender, age, income categories, and education levels as controls. The third model focuses on controls related to housing which include ownership/renter indicators, square footage, their expected housing tenure, and respondents' experience with solar panels.[2]

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[2] The majority of respondents are home owners (55.24%) with the rest renters (42.16%) or unknown (2.62%). Square footage of housing is a categorical variable broken down into varying ranges of home size. Respondents' personal history with solar panel systems is reported in three variables: those who know

Table 1.2: Summary Statistics

Variable	Median
Age	42-45
Female	71%
Income	$35,000 to $49,999
Own Home	55%
Square Footage	1,000-1,999
Know Someone with Panels	19%
Have (or Had) panels	1%

Note: Summary statistics from 2,307 respondents in the TVA region. All socio-demographic questions were categorical. We report the median response for each category.

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someone with solar panels (19.3%), those who have ever owned panels themselves (5%), and those who currently own panels (1.3%).

The fourth model includes both socio-demographics and housing characteristics controls.

1.6.1 Private Choice

The results of the private choice specifications are reported in Table 1.3. The topmost portion reports the marginal impacts of changes in cost, electricity savings, and emission-reductions on the probability of rooftop adoption. The coefficients indicate that decreases in cost, increases in savings, and increases in emissions-reductions lead to a higher probability of purchasing solar panels. Estimates are reported as odds-ratios relative to the dominant survey response. In all cases, the dominant response to the explicit question regarding actual intentions to purchase was ”no” and so estimates are reported as marginal changes in the probability of saying ”yes” to the purchase question.

Interpreting the coefficients is straightforward. The cost estimate in model 1 is -53, which is statistically significant at the one-percent level. That implies that a $100 increase in the monthly cost of solar reduces the odds a respondent would say they want to purchase the panels by 53%. Looking at Chi-squared and Akaike Information Criteria (AIC) does not definitively reveal which model is the best fit. The AIC indicates that model 1 is the better fit where we remove most control variables while chi-squared results indicate model 4 as the better fit where we include income and education variables. Note that the range between best and worst fit of our models is not large in either statistic.

The coefficients for cost, emissions, and savings in the private choice estimates are all significant at the 1% level regardless of the sets of controls used. The results are consistent with economic theory. Higher savings make respondents more likely to purchase while cost increases reduce the likelihood of purchase. The probability of adoption declines by $53-67\%$ for every $100 increase in the cost of panels depending on the model. The probability of adoption increases by $45-49\%$ for every additional $100 in savings. This implies that respondents are more sensitive to costs than savings across all specification. This is consistent with research that finds costs are a key, salient barrier to wider solar adoption ([7], [90], and [106]). Decreasing emissions by 0.01% increases the probability of adoption by $30-37\%$.

Table 1.3: Private Choice Estimates

	(1) Model 1	(2) Model 2	(3) Model 3	(4) Model 4
Cost of Solar	-0.53***	-0.61***	-0.64***	-0.67***
Savings	0.45***	0.47***	0.49***	0.49***
Emissions Reduced	0.30***	0.35***	0.34***	0.37***
Age		-0.07***		-0.06***
Female		0.07		0.07
RESPONDENT INCOME				
Under 35, 000		0.00		0.00
35, 000−74,999		0.08		0.11
75, 000−149,999		0.02		0.09
150, 000+		0.35*		0.43**
I don't know		-0.81***		-0.69***
RESPONDENT EDUCATIONAL ATTAINMENT				
High School or Less		0.00		0.00
Associates Degree		0.19*		0.18
Bachelors Degree		0.02		0.02
Graduate Degree		-0.19		-0.23*
DO YOU KNOW ANYONE WHO OWNS SOLAR PANELS?				
Yes			0.57***	0.56***
No			0.00	0.00
Not sure			0.19	0.17
DO YOU OWN SOLAR PANELS?				
Yes (Current Home)			0.53*	0.41
Yes (Previous Home)			0.23	0.14
No			0.00	0.00
RESPONDENT HOUSING TENURE				
Own			-0.43***	-0.37***
Rent			0.00	0.00
Other			-0.20	-0.20
HOUSING SQUARE FOOTAGE				
Less than 1,000			0.00	0.00
1,000-2,999			0.10	0.07
Over 3,000			0.01	-0.06
I don't know			-0.24	-0.22
EXPECTED HOUSING TENURE				
2 Years or Less			0.13	0.02
3 to 5 Years			0.23**	0.14
5+ Years			0.00	0.00
Constant	0.85***	1.26***	0.85***	1.17***
Chi^2	83	155	175	224
AIC	14255	13999	13997	13836
N	26,368	26,368	26,368	26,368

Table reports marginal effects from a conditional logit estimation. Cost and savings are reported in \$100s and emissions reduction in 0.01%. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

In line with [18], increasing the age of respondents by one year decreases the likelihood of adoption by $6-7\%$. Note the magnitude of impact is small, but significant at the 1% level. Income is significant at the $5-10\%$ level once respondents report making $\$150,000$ or more, when the probability of adoption increases by $35-43\%$. Thinking of income variables as household flows and savings as stocks, the lack of significance for most income variables as compared to the highly significant estimates for installation costs makes sense. Up front costs are a key barrier to adoption. The income coefficient for the "I don't know" response is significant at the 1% level with a large magnitude of impact which implies that income uncertainty lowers the probability of adoption. Holding an associates degree (masters or higher) is associated with a 19% increase in the probability of adoption in model 2 and is statistically significant at the 10% level. No other education estimates are statistically significant. Many findings in the literature find that increased levels of educational attainment increase the probability of adoption ([32] and [75]) though not all [25].

Knowing someone with solar panels increases the probability of adopting a system by $56-57\%$. This is a potential channel for the social contagion of solar panels found in [20] and [49] among others. The estimate implies that knowing someone with panels is greater than the impact of saving and reductions in installation costs. Currently owning solar panels increases the probability of reporting a willingness to purchase panels by 53% and statistically significant at the 10% level. The small number of respondents who report owning panels limits the statistical power of this variable. Also note that while it is obvious that owning panels would increase the probability of adoption to 100%, but these results for our purposes likely indicate satisfaction with owning panels.

Interestingly, homeowners are $37-43\%$ less likely to adopt solar panels. Note that the distribution of homeowners and renters may be somewhat skewed by the concentration of respondent geographies. Just under 70% of our respondents live in 5 cities (Chattanooga, Knoxville, Memphis, Murfreesboro, and Nashville) with 69% of our homeowners living there. That said, there is no clear trend in the proportion of renters versus homeowners in these cities. Memphis and Chattanooga are in the upper quartile of the percentage of respondents who are renters, Nashville and Murfreesboro at the median, and Knoxville in the lowest quartile of renter concentration in our survey responses. Results based on home-ownership are thought to be plagued by underlying policy barriers where the lack of institutional support for renter acquisition of solar systems is likely dampening the overall true WTP [104].

While none of the housing size characteristics are statistically significant, the largest magnitude of impact is respondents' uncertainty over the size of their residence with adoption decreasing by $22 - 24\%$. Finally, the duration of expected housing tenure shows that households expecting to live in their current place of residence $3-5$ years are 23% more likely to adopt panels with $p < 0.05$. This may be an implicit reflection of the age of respondents with younger households expecting to remain more mobile *or* that households that report 5+ years of expected tenure have already been in place long enough that their preferences for limiting new large capital investments dominates the decision-making process.

1.6.2 Social Choice

Our design allows us to differentiate between two possible sources of social contagion: acquiring information from other households who have installed panels and the observability of neighbors' panels that signal the worthiness of solar panel investments to the surrounding community. Table 1.4 reports our four models as presented in the table for the private choice with an exception. Table 1.4 includes presents the impact of the "Percentage of Solar Penetration in the Community". Recall this variable was created using responses to the social adoption threshold question: "Would you actually choose this option if $X\%$ of your neighborhood have solar" with X varying randomly between 25% and 100%. Given the low rate of adoption in the TVA service area, this social choice scenario represents a large increase in neighborhood adoption relative to the private choice. This allows us to test for stated preference versions of the social contagion phenomena identified by [20] and [49] among others.

Across all specifications, higher levels of community adoption as indicated by the variable "Percentage of Solar Panel Penetration in Community" are associated with an increased probability of adoption. Increasing the penetration of solar panels by 1% raises the probability of adoption by 1% and is significant at the 1% level. The impact of knowing someone who owns panels remains large ($56-57\%$) and significant. Respondents who know someone with panels on their home are much more likely to be willing to adopt.

Cost and savings are significant at the 1% level and results are consistent with economic theory. A \$100 increase in installation costs decreases the likelihood of adoption by $51-66\%$ implying consumers are about as price sensitive when incorporating the social contagion effect as when we do not. Consumer response to increased savings are a bit attenuated compared to table 1.3 with a \$100 increase in savings increasing adoption by $39-43\%$.

While the effect of knowing someone with panels is roughly the same, the penetration of solar panel adoption within the respondent's community appears to be correlated with an increased likelihood of adoption. This is evidenced by the impact of the respondent's historical ownership. Under the social choice framework, previous ownership of solar panels is now statistically significant with $p < 0.01$ and $p < 0.05$ with the probability of adoption increasing by $36-43\%$ for those reporting previous ownership. Compare this to the table reporting the private choice earlier where previous ownership increased adoption by $14-23\%$ but was not statistically significant. This suggests that the overall social contagion effect is driven both the information provided by friends or family members who have solar panels and the effect of seeing them on neighbors roofs which may act to confirm the known benefits of ownership. These effects appear to be distinct and independent from each other.

Age is negatively correlated to purchase, with an increase of 1 year reducing the probability of adoption by $4-6\%$. This is slightly less of an impact when strictly looking at this as an private choice. The sign of estimates for the impact of income are still in line with economic theory, but none are statistically significant except for income uncertainty. Including social contagion exacerbates the impacts of income uncertainty with the probability of adoption declining by $82-96\%$ and denuding the impact of rising incomes. Introducing social pressures exacerbates the impact of education where holding an associates degree

Table 1.4: Socially-Influenced (Social) Choice Estimates

	(1) Model 1	(2) Model 2	(3) Model 3	(4) Model 4
Cost of Solar	-0.51***	-0.57***	-0.64***	-0.66***
Savings	0.39***	0.40***	0.43***	0.42***
Emissions Reduced	0.32***	0.36***	0.38***	0.39***
Age		-0.06***		-0.04***
Female		0.04		0.04
RESPONDENT INCOME				
Under $35,000$		0.00		0.00
$35,000-74{,}999$		0.10		0.13
$75,000-149{,}999$		0.09		0.15
$150,000+$		0.13		0.19
I don't know		-0.96***		-0.82***
RESPONDENT EDUCATIONAL ATTAINMENT				
High School or Less		0.00		0.00
Associates Degree		0.30***		0.29***
Bachelors Degree		0.04		0.04
Graduate Degree		-0.08		-0.13
DO YOU KNOW ANYONE WHO OWNS SOLAR PANELS?				
Yes			0.56***	0.55***
No			0.00	0.00
Not sure			0.02	0.01
Percentage of Solar Penetration in Community			0.01***	0.01***
DO YOU OWN SOLAR PANELS?				
Yes (Current Home)			0.38	0.30
Yes (Previous Home)			0.43***	0.36**
No			0.00	0.00
RESPONDENT HOUSING TENURE				
Own			-0.42***	-0.37***
Rent			0.00	0.00
Other			-0.35	-0.36
HOUSING SQUARE FOOTAGE				
Less than 1,0000			0.00	0.00
1,000-2,999			0.11	0.07
Over 3,000			0.01	-0.04
I don't know			-0.31**	-0.27*
EXPECTED HOUSING TENURE				
2 Years or Less			0.14	0.07
3 to 5 Years			0.23**	0.16
5+ Years			0.00	0.00
Constant	0.34***	0.65***	-0.23	-0.02
Chi^2	88	163	292	347
AIC	17067	16797	16602	16438
N	26,662	26,662	26,662	26,662

1 Cost and savings reported in $100s.
2 Emissions displayed in 0.01%.
3 Conditional logit dropped 475 cases due to the lack of positive outcomes.

now increases the likelihood of adopting by $29 - 30\%$ at the 0.1% level. Also note that introducing peer effects only exacerbates the impact of uncertainty over the size of the respondents domicile which now reduces the probability of adoption by $27 - 31\%$ with statistical significance ranging $1 - 5\%$.

Relative to renting a home, respondents are $37 - 42\%$ less likely to report wanting to adopt solar panels. Recall the issue of policy barriers for renters. Results for households that expect a housing tenure of $3 - 5$ years are parallel under the pressures of social choice with the probability of adoption remaining at 22% with $p < 0.05$.

In the next section, we explore the potential for social contagion in adoption by looking more granularly at regional and city-level WTP.

1.6.3 Heterogeneity in WTP across TVA

In this section, we consider the spatial distribution of WTP for solar panel adoption within the geographic footprint of TVA. To do so, we linked respondent zip codes to the electric bus[3]. and then linked those busses to two geographic layers of increasing granularity: regions and cities.

To estimate WTP at the city and region-level, we apply the conditional logit (CL) individually to each city and region as specified in model 4 in the tables for the private and social choices to each city and region. Two exceptions are that we do not include independent variables from the categories Respondent Housing Tenure, Housing Square Footage, and Education variables. Due to limited responses in some cities and regions, this was necessary to achieve convergence. For the sake of uniformity, we excluded these variables from every city and region's CL. We also note that the lowest Chi-squared results were for models without these categories, though the Akaike Information Criteria is mixed.

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[3] A bus is a part of the electric grid that has connected loads all served by the same voltage. These are the smallest units of the grid in which supply must equal demand to maintain consistent voltage and thus the quality of electric service. We split the TVA region into 17 busses which we named for the largest population center.

To identify cities and regions, we aggregate respondent busses to zip codes and zip codes to cities and regions. Despite excluding Housing Tenure and Square Footage, some cities have low population density and thus few respondents in our representative sample. Due to a lack of significance or failure to converge, we do not report results for those cities individually, but that data is represented in the appropriate regional estimation [4]

We report estimates for the following regions (cities): East TN (Chattanooga, Cleveland, Johnson City, and Knoxville), Middle TN (Columbia, Murfreesboro, and Nashville), West TN (Jackson and Memphis), Kentucky (Bowling Green, Mayfield, and Paducah), North AL (Huntsville and Muscle Shoals), and North MS (Tupelo and Starkville).

Cost, Savings, and Emissions Estimates by Region and City

Figure 1.2 presents 4 panels. The top row and bottom left are graphs of the estimated coefficients for cost, savings, and emissions based on the distribution of the socially-influenced choice to adopt within our study area. The red marker in the center is the coefficient point estimate, the bars represent one standard error and the whiskers depict the 95% confidence interval. The bar graph on the bottom right provides data on the number of respondents who reported knowing someone with a solar panel system in each region or city.

Recall that both cost and savings coefficients are estimates of the average respondent's sensitivity to an increase in costs of \$100 per month or an increases in savings of \$100 per month. Cost estimates range -54 to -313% implying large magnitudes of cost sensitivity with significant heterogeneity within the region. The distribution of sensitivity is skewed on the right tail due to a handful of outliers with the cities falling within the range of -119 to -313% less likely to purchase panels for every \$100 increase in costs. Our three largest outliers are Starkville, MS (-323%), North MS (-255%), and Tupelo (-208%). Each of these cities reported lower than average rates of knowing someone with panels.

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[4] The conditional logit for the city of Paducah did not converge and therefore, neither a social nor a private WTP is reported. Note that the respondents within Padcuah are included in a regional estimate for Kentucky. Beyond these, if there is no entry in a graph for a particular city or region's cost coefficient, for example, then it is due to a lack of significance.

Most of the estimates for savings are clustered within the range of $32 - 63\%$ meaning most respondents are $32 - 63\%$ more likely to acquire panels in response to a \$100 increase in monthly savings. Two notable outliers where respondents are more sensitive to these long run benefits are Mayfield (KY) and Johnson City (TN) where the probability of adoption increases by about 265% and 114% for a \$100 increase in savings. Note also that Muscle Shoals presents a negative response to savings though the confidence interval is quite large. Columbia (TN), Tupelo (MS), and Starkville (MS) do not have significant estimates for savings while the state of Kentucky, Mayfield (KY), Bowling Green (KY), and Muscle Shoals (AL) do not present significant estimates in response to costs. Fewer emissions coefficients are significant and mostly fall within the range of $34 - 66\%$.

In all regions and cities, the average respondent is relatively more sensitive to costs than savings with relative cost sensitivity ranging $7 - 170\%$ higher than the average respondents' responsive to savings. Consider cost sensitivity a respondent's value over short run costs and savings their value of long run benefits. The highest relative cost sensitivity cities and regions are North MS (170%), Chattanooga (131%), and Murfreesboro (103%) and the least relatively cost sensitive areas are Johnson City (7%) and Huntsville (28%). The rest of our cities and regions are within the range of $42 - 75\%$ and more cost sensitive. These results support the overarching finding in the literature that reducing up front capital costs tends to dominate long run benefits in the decision-making process to invest in solar panels.

Comparing the percentage of people in a city or region who report knowing someone with panels to these coefficients reveals that in the cities with the highest penetration of solar panels (26% in Cleveland and 28% in Johnson City), there is evidence of a trend where cost sensitivity decreases with higher solar penetration. Johnson City is populated by people who are just 7% more cost sensitive than responsive to savings while residents in Cleveland are 42% far more cost sensitive. Just 15% of respondents in Knoxville report knowing someone with panels where residents are about 70% more cost sensitive than responsive to savings while 16% of respondents in Murfreesboro know someone with panels where we estimate residents are about 102% more cost sensitive. Comparing these to Hunstville where 19% know someone with panels are just 27% more cost sensitive.

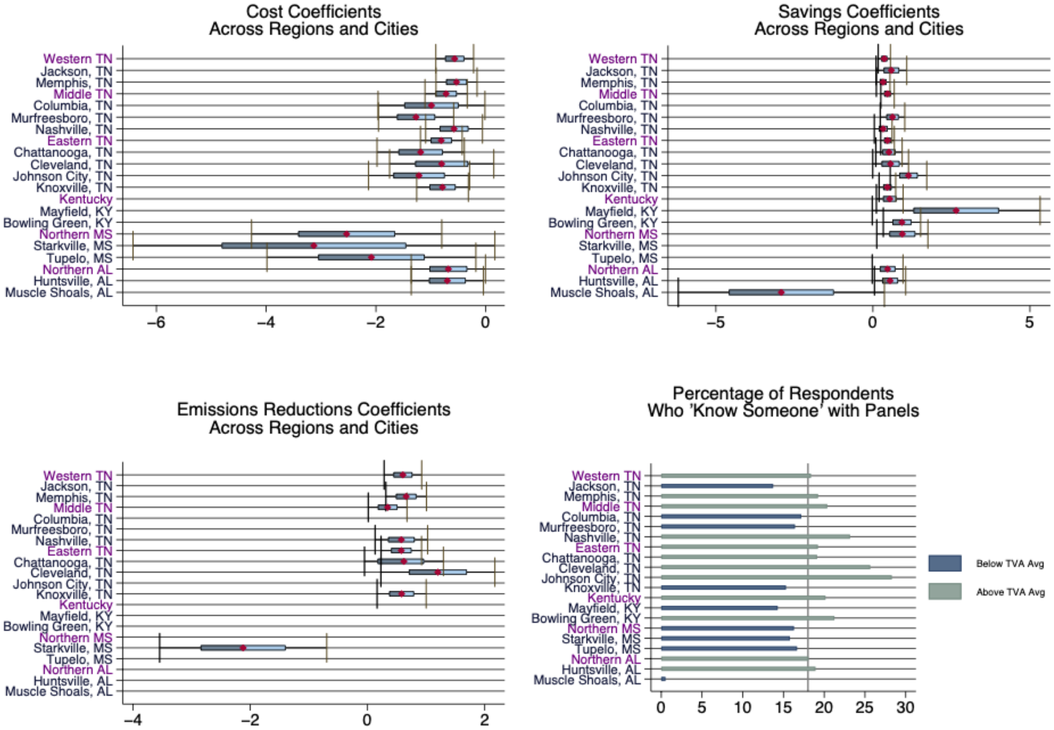

Figure 1.2: Regional Heterogeneity of Coefficients and Known Installations

1.6.4 Economic and Social WTP

We follow the technique for estimating WTP outlined in [52] to turn the coefficients in the previous figure into an estimated WTP. WTP is the ratio of the sum of coefficients α for z_j, an m-dimensional vector of household characteristics, response variables, and the attribute variable for emissions reduced, over the sum of the coefficients β for the cost of installations and savings from utility bills after switching to solar panels:

$$WTP = \frac{\sum \alpha(z_j)}{\sum(\beta(cost_j + save_j)}$$

Note that our survey did not provide respondents a place to say they did not want to share their income information. The closest options was "I don't know". This survey design choice was made following guidance in [38] that offering a "no" type of response option does not necessarily increase data quality and can actually dissuade participation within the survey by respondents. The conditional logit model produced several significant estimates for this selection. These are excluded from our estimated WTPs even when significant due to concerns that the respondents chose these answers due to privacy concerns or an unwillingness to share this information rather than actual uncertainty over their incomes. Other than this, all significant coefficients are included in our WTP estimates. If a WTP is not presented for a city or region, then it is because neither the cost nor the savings coefficient was significant.

Figure 1.3 shows two clear trends. First, there is significant variation across regions and cities and the level of aggregation influences the magnitude of both WTPs. Aggregating across cities can produce smaller estimates at the regional level with some outlier cities positively or negatively influencing the size of the regional estimate. While this trend may partially be a function of variations in sample size, varying preferences for solar clearly exist in pockets. Second, the aggregated WTP estimate for the TVA's customers ($259.45 – $342.55 for economic and $46.76 – $310.07 for social) obscures significant variation within the agency's service area. Our city-level and regional private WTP estimates fall within a range of

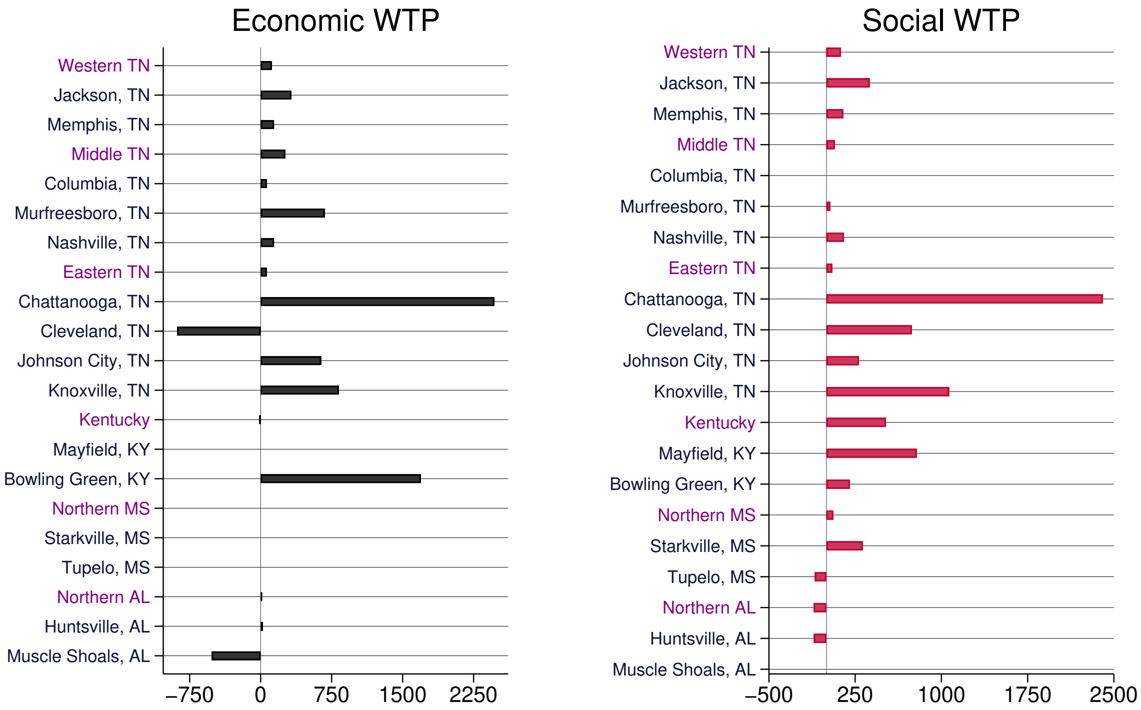

Figure 1.3: Regional Heterogeneity of WTP

$-\$883.95$ to $\$2,470.32$ with a cohort mean of \$356.23 and median of \$142.48 while our city-level and regional social WTP estimates fall within a range of $-\$112.04$ to $\$2,404.11$ with a cohort mean of \$369.52 and a median of \$152.84.

This indicates a slight boost to WTP when including the social contagion effect. Just 2 areas (Jackson, TN, and the region of Middle TN) have private WTP estimates that fall within the range of the aggregated private WTP though 8 regions fall within the range of the aggregated social WTP (Eastern TN, Middle TN, Western TN, Northern MS, Memphis, Nashville, and Johnson City).

Comparing economic and social WTP estimates for individual regions and cities reveals significant variation in preferences for rooftop solar and significant variation in the drivers of WTP with no clear directional trend immediately obvious. These variations are not wholly a function of respondent volume either.

Our respondent totals for cities and regions ranged from 168 to as many as $8,556$ with a median of $1,692$ people in any given city or region answering our survey. Five areas presented a respondent count in the top quartile (Memphis, Knoxville, Western TN, Middle TN, and Eastern TN) with respondent totals that ranged $4,236 - 8,556$. We focus on these cities to illustrate a point. Assuming that increasing the number of observations will produce more reliable estimates, this subset of cities and regions underscores the significant heterogeneity in WTP for solar. We have $7,128$ households responding in Middle TN and $7,776$ in Western TN yet the private WTP in Middle TN is more than double that in Western TN. The aggregated Eastern TN estimate of \$65.19 is far outpaced by the estimate of \$826.85 in Knoxville. Turning to areas with respondents just above the median, we find that Chattanooga with $2,196$ respondents has an private WTP of $\$2,470$ while Murfreesboro's WTP is just \$677 with $2,268$ people responding. Murfreesboro's neighbor Nashville has a private/economic WTP of \$143 with $4,092$ respondents while it's social WTP is three times that in Murfreesboro which is likely due to a much higher penetration.

There is also some evidence that higher penetrations of solar in cities results in higher social WTP estimates than the larger region around them. Ignoring areas where respondent counts were in the lowest quartile or where we couldn't estimate a social WTP, we find that Nashville's higher social WTP outpaces the regional estimate for Middle TN and has a higher estimated penetration of panels. The inverse is true for Murfreesboro. Memphis follows this trend in Western TN while Cleveland and Johnson City do the same in Eastern TN. Chattanooga has roughly the same penetration as Eastern TN with a higher social WTP while Knoxville's penetration is lower than the regional average with a higher social WTP. The higher social WTP with lower estimated penetration may be due to it being a more densely populated city than the overall region which may allow amplify the social contagion effect with fewer adoptions.

Comparing economic and social WTP within a city or region presents evidence of the bi-directionality of peer effects. North AL and Huntsville (where most AL respondents live) stands out immediately. Where both present a positive private WTP, their social WTPs are negative. Respondents who are willing to pay about \$25 a month in Huntsville and \$15 a month in Northern AL based on the economic benefits of solar also report needing a payment of about \$109 a month and \$112 a month to consider it if some threshold of their peers have panels. This is starkly evident in Bowling Green where the private WTP is $\$1,694$ and the social WTP is just \$205. From the other perspective, Cleveland, TN has a social WTP estimated to be \$743 while the economic value of the panels without social contagion is $-\$884$. Note that the penetration in Cleveland 25.6% while Bowling Green is 21.3%.

Eight areas present social WTPs that are lower than their private WTPs. They include the cities of Bowling Green, Johnson City, Huntsville, Chattanooga, and Murfreesboro, in addition to North AL, Middle TN, and Eastern TN. The mean social WTP for these areas is about \$394 less than the median private WTP. Seeing panels go up around respondents in these areas apparently discounts their value. Seven areas present social WTPs that are higher than their private WTPs (Jackson, Cleveland, Nashville, Knoxville, and Memphis as well as the regions of Kentucky and Western TN) with a mean premium of \$111.

Comparing the percentage of respondents who report knowing someone with panels to our WTP estimates, we see that the four cities without one of our WTP estimates are among the lowest reporting peer effects ($14.3 - 17.1\%$) with the fewest reported nominally ($1,000$

and less). The lone exception is Cleveland. The cities with the highest percentage of people reporting knowledge of someone with panels are Johnson City (28.3%), Cleveland (25.6%), and Nashville (23.2%) while the three lowest are Jackson (13.7%), Knoxville (15.3%), and Murfreesboro (16.4%). Most of these cities have higher social WTP where adoption rates are higher with the exception of Jackson and Knoxville where the trend flips.

Four of the five cities with a higher than average rate of solar adoption are in Tennessee (Murfreesboro, Chattanooga, Memphis, and Johnson City) with Bowling Green. KY the fifth. Significant variation relative to the median exists for WTPs. Each of these reports higher social and private WTPs than the median by an average of \$876 and \$489 respectively. Note the exception is in Nashville and Memphis where the private and social WTPs are basically the same as the overall study medians. Memphis results may be skewed by our inability to precisely identify survey results for bus 12 as within the city of Memphis and thus inside TVA's service area or the city of West Memphis and outside of it.

The overall takeaway is that the effects of social contagion are present, but bi-directional. Low levels of penetration appear to be correlated with higher private WTPs and lower social WTPs. Higher levels of penetration appear correlated with high social WTPs and slightly lower private WTPs.

1.7 Discussion and Conclusion

The results of our stated preference survey show that in the aggregate, respondents are $53-67\%$ less likely to invest in a rooftop system as the cost of that system increases by \$100, $45-49\%$ more likely as their utility bill savings increase by \$100 after adoption, and $30-37\%$ more likely if that choice decreased emissions by 0.01%. If we include social influence, estimates are roughly the same but slightly depressed. Aggregate WTPs in the TVA area are estimated to be $\$259.45-\$342.55$ when the decision is strictly based on the economics of ownership and just $\$46.76-\$310.07$ when social influenced is considered. However, when we dis-aggregate the data to consider city-level and regional estimates, WTPs jump as high as $\$2,470.32$ and for private/economic choice and $\$2,404.11$ with when social influences are factored in.

A couple issues may be dampening the cost coefficient from our survey. There exists significant regional heterogeneity across utilities in customer rates and relative size of each utility's renewable asset portfolio varies widely across utilities. This heterogeneity may present underlying distortions that dampen the impact of marginal savings from solar systems in different regions. Relative to the largest 100 utilities in the United States, TVA reports its regional electricity rates are 70% lower for residential customers and 90% lower for industrial ones while 57% of TVAs generation is green [116]. These lower initial costs to customers in rates and higher use of green energy in front of the meter may be skewing our respondents' perception over the marginal benefit of solar relative to potential utility bill savings and marginal cost of installing rooftop solar.

Second, the majority of our sample were homeowners 42.16% reporting as renters. To the extent that existing legal constraints precluding renters' ability to actually adopt solar systems are salient to these respondents, our estimates may be under-reporting interest in adoption.

The nascent state of behind-the-meter solar panel adoption in the Tennessee Valley presents specific challenges to potential policies that promote adoption. Beyond estimated responses to system costs, utility rate savings, and emissions reductions, we find significant impacts of income on adoption probabilities. Households reporting incomes of $\$150 - \$199,000$ are $35 - 43\%$ more likely. When incorporating their neighbors' acquisition of solar panels, income increases in significance. In both cases, income uncertainty makes it highly unlikely that a household would invest. Older households are less likely to adopt solar panels, though this too is muted when including peer effects.

Income clearly plays a key role in the decision to purchase solar panels. Previous research also shows that households have high discount rates for renewable energy investments. This implies that policies lowering upfront capital costs would likely induce higher adoption rates. As income effects increase when including peer effects, campaigns designed such that they target areas with existing solar arrays to maximize network effects may be more successful.

Targeting areas with existing solar for mass media campaigns may help decrease barriers to information and induce faster, broader adoption while increasing the impact of each public dollar spent to lower upfront capital costs.

In the case of the TVA, adoption rates are low, but our analysis has identified 5 areas where the potential for peer effects are strongest - all in Tennessee. They are Jackson, Cleveland, Memphis, Nashville, and Knoxville. Finally, policy designed to engage with potential local service providers to explicitly build capacity to respond to demand would foster the environment necessary for markets to develop in synchronicity.

Demographics we've collected can hone the targeted message within buses by zip code. Previous research has found that willingness to pay for solar increases with income but peaks at about $\$150,000$ and a population density of $1,000$ persons per square mile [124] where the spatial correlation of income and education may drive adoption in clusters [32]. Targeting the inner core of Nashville, for example, may prove less successful than reaching out to residents around the inner core where population densities decrease.

It also may be the case that these lower rates present conditions more supportive of 'front of the meter' increases in solar than 'back of the meter' ones. Respondents are estimated to be 1% more likely to adopt solar panels for every 1% decrease in emissions and $51-57\%$ more likely to adopt for every $100 increase in utility rates. To the extent that emissions-reductions through utility-scale solar investments are salient to ratepayers, customer response to rate increases may be cancelled out by their response to emissions reductions. Prior research has found utility customers are willing to pay premiums if it explicitly cleans up the grid ([125], [55], [11], and [10]).

Chapter 2

Policy Inconsistency and the Rise of Stranded Assets in the Oil Industry

Abstract

A carbon tax would reduce our reliance on fossil fuels but introduce a systemic risk to the economy by shortening the economic life of carbon assets. This paper investigates whether past policies designed to promote U.S. energy independence will increase the magnitude of these stranded assets. Using a dynamic programming model of nonrenewable resource exploration and production, we measure the magnitude of stranded assets by comparing the amount of undeveloped fossil fuel reserves with and without a carbon tax. We then consider an inconsistent policy scenario where government simultaneously taxes carbon *and* incentivizes the exploration for new domestic fossil fuel reserves. Our results show that a carbon tax does cause firms to leave more reserves undeveloped. But firms suffer 20% fewer stranded assets under inconsistent policy. This is due to lower marginal production costs from larger stock effects though this only yields 0.6% more lifetime profits. As actual policy already incentivizes exploration, the introduction of a carbon tax would occur under an inconsistent policy framework which implies the economic risk of carbon taxes is lower than anticipated.

2.1 Introduction

When government policies are introduced to entice firms to invest in long-term projects with high upfront capital costs, it is typically done because policymakers are targeting what they believe to be high-value, under-invested areas of the economy that are welfare-enhancing. Changing course on those policy priorities later on can cause firms to suffer losses that may differ from sunk costs when the new policy directly contradicts the old policy [62]. These firm losses were identified as stranded assets after electricity market deregulation introduced competition to what had been a monopolistic market [113, 63]. Conceptually, any policy regime change can strand assets if the market framework is fundamentally changed by the new policy. The reason policymakers care about this issue is that preserving capital liquidity is key for the new policy to be successful.

Recent research has honed in on the risk of stranded assets under a carbon tax. Within this context, stranded assets are loosely identified as investments whose value is reduced before the asset's expected economic life such that recoverability is limited because of the introduction of policy to mitigate climate change impacts [27, 58, 17, 105]. Carbon taxes are considered the most efficient strategy to pivot away from fossil fuels [6, 47, 85], but concerns over capital liquidity constraints due to stranded assets has stymied the implementation of carbon taxes. [119] recently broached this topic by exploring how uncertainty over the timing and seriousness of a carbon tax might affect the magnitude of stranded assets, but not within the context of historical policy as [62] did. The objective of this paper is to determine how historical inconsistencies in U.S. oil and natural gas policy influence the size of stranded assets created by a carbon tax.

The US government has a long history of incentivizing oil and gas exploration in pursuit of domestic energy independence goals [80], but current geopolitical conditions show this policy inconsistency is not just a historical problem. After decades of pursuing decarbonization agendas, European Union (EU) leaders are now scrambling to encourage investments to achieve energy independence from Russia and limit Russian war funding. Scaling up alternatives quickly re-prioritizes fossil fuels in the short term. The U.S. is making a similar pivot back towards fossil fuels to tame the short run problem of energy inflation even while it simultaneously introduces legislation to push for the use of renewables over fossil fuels. In both cases, short run policy goals are in contradiction to the intended outcomes of long run policy.

Approaches to estimate the magnitude of stranded assets under a carbon tax focus on a variety of timescales, from short run fluctuations in stock market value [50, Sen and von Schickfus] to longer term increases in reserves left in the ground at the terminal period of production [57] which is the approach taken in this paper. However, using this approach raises two issues that must be considered. First, not all reserves left in the ground after the firm's terminal period of production can be considered stranded. Under a competitive market with marginal production costs that depend on the size of the reserves, some reserves will never be economically recoverable [93]. Second, it's critical to differentiate between stranded assets and sunk costs because some reserves were acquired in response to pro-fossil fuel policies meant to dampen rising energy prices or achieve domestic energy independence. These reserves acquired in response to pro-fossil fuel policies should also not be considered assets stranded by a carbon tax. This motivates this paper's primary research questions. What is the size of these stranded assets that arise from consistent versus inconsistent policy?

To answer this question, we introduce government policy into [93]'s dynamic optimization model on the investment trade-offs between nonrenewable resource exploration and production. Fossil fuel production eventually ends under market forces due to competition with a renewable backstop technology and the model allows us to determine when that transition to renewables occurs and how many fossil fuel reserves are left in the ground. By comparing the number of reserves left in the ground in the terminal period with and without a carbon tax, we can estimate the size of stranded assets in the oil and gas sector attributable to a carbon tax. Key to the use of this model is Pindyck's finding that there is an optimal amount of reserves that a firm would leave in the ground at the terminal period of production without any intervention by policymakers. This result is rooted in the unique engineering dynamics of oil and gas production related to reserve size and the firm's ability to minimize costs via the stock effects on nonrenewable resource production.

In short, the marginal cost of production declines as the reserves increase. This feature of the model allows us to differentiate stranded assets from the reserves left in the ground without a carbon tax. We then identify stranded assets under a second ”inconsistent policy” scenario where the government simultaneously taxes carbon and provides exploration incentives to encourage the firm's accrual of more reserves and promote a domestic energy independence policy goal. We parameterize our model using historical data on the exploration and production activity of the U.S. oil industry in $1980 - 2007$. This picks up where [93] left off in his parameterization and stops with the fracking boom.

Our simulation shows that changing the policy framework has a significant impact on the size of stranded assets. A carbon tax roughly equivalent to the social cost of carbon *increases* the number of stranded assets by +3.2% with roughly 43% fewer profits. This is consistent with the purpose of the carbon tax. Taxing production reduces the rents collected by the firm which also reduces its competitiveness with alternate forms of energy.

When exploration incentives are introduced, the size of stranded assets *decreases* by 24%. This is due to the stock effects of nonrenewable resource production. The benefit of stock effects is captured in lower marginal production costs. The firm can choose between developing separate reserve deposits based on their costs. Larger individual reserve deposits imply higher concentrations of reserves can be produced before the boundary of the deposit decreases reserve purity and increase marginal production costs. However, we find that this only results in 0.6% more lifetime profits than BAU. Stock effects can increase competitiveness, but this only helps price-taking firms absorb more of the carbon tax.

The limitations of stock effects are underscored by the outcomes of our Inconsistent Policy framework. When the firm faces Exploration Incentives alongside a Carbon Tax, it ends up with 20% *fewer* stranded assets than BAU but 43% *fewer* lifetime profits than BAU. This is roughly the same result in lifetime profits as we found under our Consistent Policy framework with the carbon tax. In the end, the price-taking firm facing a carbon tax can lower its marginal production costs through acquiring more reserves, but this simply increases overall production by limiting lost rents from the tax. Rents are still muted by the tax.

Preserving competitiveness is key. Oil and gas firms face backstop technologies like solar whose marginal cost acts as a choke price at which oil and gas is no longer competitive. The intention of a carbon tax is to lessen the time it takes for oil and gas prices to breach that choke point. Ultimately, the efficacy of these policies is constrained by the finite supply of nonrenewable resources. Inconsistent policy can alter the timing of firm investments into fossil fuel assets, but it cannot increase aggregate investments unless it changes aggregate supply. Aggregate investments are determined by the scarcity effects of finite supply as represented in the marginal discovery costs of oil exploration.

This paper makes two primary contributions to the literature on stranded assets in the fossil fuel industry. First, by introducing the concept of inconsistent policy into [93]'s model, this paper bridges the literature on stranded assets under a carbon tax with those in utility industry under market deregulation [62, 113] to extend the model in [119]. Second, these results indicate that the literature on stranded assets is overestimating the impact of a carbon tax if it ignores historical policy designed to achieve energy independence, i.e. the impact of inconsistent policy.

The rest of the paper proceeds as follows. Section 4 outlines the inconsistent policy framework. Section 5 introduces the Pindyck model with a government that provides Exploration Incentives and then with Carbon Taxes the primary findings discussed. Section 6 provides our results. Section 7 provides our conclusion. Additional math can be found in the appendix.

2.2 Literature Review

The current approach in the literature on stranded assets is to focus acutely on the introduction of a new policy without regard for how that policy differs to the original policy. This framework leads to estimates that may be confusing sunk costs with stranded costs while failing to account for the unique benefits of stock effects that reduce marginal production costs. The size of stranded assets estimated under prevailing approach is nudging policymakers away from first best solutions to embrace less efficient mechanisms [105] under the theory of second best.

[93] presents a dynamic optimization problem where the firm chooses to allocate capital to produce existing reserves or invest in additional exploratory effort to acquire more reserves for future production under a present value profit maximizing environment. His model leverages the stock effects of nonrenewable extractive resource production to show how the firm benefits from holding larger, more plentiful reserves in order to minimize the cost of future production. The stock of nonrenewable resources is fixed meaning that as the firm produces more in time t, the cost of production in time $t+1$ rises.

The depletion of stock increases the scarcity of remaining stock which increases future production costs as remaining reserves would tend to be less pure and more mechanically challenging to extract. These are the stock effects of nonrenewable resource production.

By engaging in exploration alongside production, the firm can increase its access to the remaining stock and thus, decrease production costs in the future.

Under this precept, the firm will acquire more reserves until it is no longer economically viable to do so. That is, exploration does not increase the total supply of stock. Assuming exploration and production costs decrease with resource proximity to the surface, there is a point of resource exploitation where the return to acquiring and producing scarcer reserves is negative unless technology changes. The terminal period of production is then determined by competition with a backstop technology. Due to the stock effects, the marginal cost of production eventually exceeds the price of the backstop technology as reserves go to zero. As such, there is a nonzero number of reserves the firm will acquire and leave in the ground at the terminal period of production under optimal conditions [93].

[119] recently updated [93] to outline four sources of risks of stranded assets under one broad framework. The first is the size of reserves that remain in the ground at the terminal period of production due to carbon taxes. The second is the lost value of equipment due to carbon policy that induces early obsolescence. The magnitude of this risk is compounded by the extent to which capital investments are irreversible. Third is the decline in firm market valuation and scarcity rents due to sudden changes in policy that restrict the use of fossil fuels.

Finally, if there is uncertainty in the implementation or seriousness of the carbon tax policy, then this can induce a boom in exploration investment that compounds the first three sources. Under this framework, [119] finds that the timing of policy implementation matters with respect to the size of stranded assets under a carbon tax, that uncertainty compounds the magnitude of their size due to investor behavior, that firms shift production across time to limit the effect of the tax, and adjustment costs limit capital liquidity.

The shift from a partial equilibrium (PE) focus in [93] to a general equilibrium (GE) solution in [119] introduces a nuanced change in the math that abstracts away from the impact stock effects have on costs in Pindyck's original model. Specifically, the updated model deviates from Pindyck's functional form and first derivative assumptions for production costs. Where Pindyck made production costs a function of reserves directly with $C_1'(R_t) < 0$, the updated model's production costs are abstracted into a function of the demand for capital such that $D'(K_t) > 0$. This adjustment is a simple, elegant abstraction away from reserves under the assumption that as production volume increases, then the capital intensity to acquire more more reserves increases due to the finite nature of nonrenewable resources.

This presents two lingering questions, though. How do we differentiate stranded assets from sunk costs under a carbon tax and does this framework account for the innate risk of investments? If it is true that an optimal level of reserves will remain in the ground at the terminal period of production [93] and if markets remained efficient during times of policy uncertainty [39], then how do you differentiate sunk costs from stranded assets under a carbon tax?

[62] presents a clear framework to do this for the utility industry after electricity market deregulation stranded power sector assets. Prior to deregulation, utilities operated under policy that granted them monopoly status in exchange for the mandated provision of electricity supply to customers. This distorted firm perception on the efficiency of capital investments into electricity assets, but this didn't harm firms as long as they retained their monopoly status. When policy changed to suddenly introduce a competitive market, the inconsistency over policy goals regarding competition before-versus-after deregulation resulted in stranded costs - i.e. the representation of asset holdings in terms of the utility's accounting.

While the dynamics of production in the utility industry do not parallel the complex tradeoff of exploration and production in oil and gas, the prevalence of policies that contradict over time within Joskow's framework provides guidance for how stranded assets could be treated under a carbon tax. It was inconsistent and contradictory policy that stranded utility industry assets [113, 63]. Earlier policy to encourage monopoly status had distorted capital markets such that utilities acquired assets in direct response to the market as designed by regulators. Assets acquired under this policy distortion were not purchased according to what [39] considered efficient markets and the policy distortions created the latent potential for stranded assets.

Key to this conceptual framework is that the capital market distortions would not have been realized as firm losses without the change in policy that restructured the market (deregulation). Once the policy changed to encourage competition in the utility industry, those historical inefficiencies in power sector assets acquired under monopoly status were revealed and thus, stranded.

US policy has long targeted the petroleum industry through taxes on property valuations, production volume, and incomes at the corporate level. Increasing oil production severance taxes in Alaska shows that while it does redirect a portion of scarcity rents to the government, it has only modest impacts on firm decision-making over exploration and production [99] which is supported by [8].

The caveat is that marginal fields will shut down [73]. [36] found that when adding production and property tax policies to [93], it does shift the firm's decision-making such that the timeline for reserve production is shortened.

2.3 Inconsistent Government Policy

Similar to deregulation in the utility industry, our modeling framework establishes a mechanism whereby inconsistent policy can generate stranded assets. Policy over oil and gas exploration and production falls into two regimes depicted in Figure 1.

To start, some policy is chosen to govern oil and gas exploration and production. That could be business as usual (BAU) policy with no government intervention or a policy to encourage exploration through incentives and subsidies. In reality, these types of policies have been common in the U.S. since the early days of the oil and gas industry (1920s). The ability to expense intangible costs on firm tax bills [51], basing production taxes on percentage depletion [61], and prorationing at the state level [118] are all real-world examples.

Taken together, these policies stimulated the flow of capital to oil exploration, incited an increase in overall exploration effort, an increase in oil reserves, a decline in oil prices, a forward shift in production, and a greater dependence on oil throughout the economy [80].

At some unknown point in time t, a carbon tax τ is suddenly introduced by the government under Policy B[1]. The tax is designed to penalize the firm for producing its reserves, R, under the goal of mitigating the magnitude of climate change. The tax may generate stranded assets measured as $S(\tau) = R_T(\tau) - R_T(0)$ where T is the time the firm chooses to cease operations.[2]

Because of the different policy environments that our model allows to have been in place under Policy A, the size of stranded assets under a carbon tax would vary according to the Policy A regime. We assume an efficient market exists for the firm in all aspects except for the case when Exploration Incentives exist. Efficient markets are ones where the expected returns of investment in acquiring reserves are rooted in oil prices that fully reflect the information available at the time of purchase [39].

If the firm benefited from Exploration Incentives in Policy A, then the its decision-making over asset investments was affected by government policy to incentivize exploration. Furthermore, the introduction of carbon taxes ends the BAU environment, but the firm may be grandfathered in to continue receiving exploration incentives while facing carbon taxes.

This creates an inconsistent policy framework if the firm initially received exploration incentives under Policy A. Policy A incentives may also continue under a federalist framework where policy alignment is not achieved. The exploration incentives may coexist with the carbon tax or end when the tax is enacted. Our model chooses to consider the caarbon tax and the exploration incentives simultaneously.

Our inconsistent policy framework concept fits well within the broader themes that dominate the literature on climate change policy and the energy transition. Specifically, the issues of time inconsistency, policymakers inability to commit, and the lack of continuity between economic and political outcomes are oft-discussed issues in climate change economics [82, 53, 46, 81].

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[1] We assume that although firms may have been aware of the validity of climate change science, they have no foresight into the timing of the introduction of the carbon tax.

[2] To reduce complexity, we assume that all fossil fuel firm assets can be generalized to a measure of reserve units R.

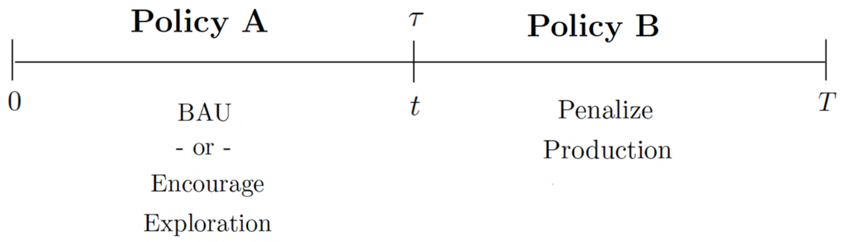

Figure 2.1: Inconsistent Policy Framework

2.4 The Model

The basis of our model is Pindyck's 1978 model of optimal exploration and production of a non-renewable resource [93]. We begin with a representative oil firm that is a price-taker in a competitive market producing a nonrenewable resource q_t at prices p_t with average production costs $C_1(R_t)$ that vary inversely with the level of identified reserves R_t, both extensively and intensively[3]. Depletion of finite reserves implies rising costs with $C_1'(R_t) < 0$ and $C_1''(R_t) < 0$.

In an effort to keep production costs lower for longer periods of time, the firm can engage in exploratory efforts w_t at costs $C_2(w_t)$. The finite nature of total supply for a nonrenewable resource implies that securing additional reserves in any given period is a function of firm efforts w_t as well as the cumulative addition of reserves x_t each period such that $\dot{x}_t = f(w_t, x_t)$ with $f_w > 0$ and $f_x < 0$. The marginal discovery cost are $\frac{C_2'(w_t)}{f_w}$ and increase with exploratory effort. This further implies that the size of reserves the firm holds in any given period, R_t is a function of the equation of motion for reserve additions less the production volume in that period q_t such that $\dot{R}_t = f(\dot{x}_t - q_t)$.

This paper now deviates from Pindyck's original model by introducing government in two iterations: carbon taxes and exploration incentives.

2.4.1 Carbon Taxes

We first consider a constant carbon tax τ applied to each unit of production to analyze its impact on the firm's decision-making between exploration and production. All assumptions and functional forms remain in the format presented in [93]. Given initial conditions for reserves R_0 and cumulative reserve additions x_0, firms maximize welfare such that:

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[3] That implies that the more reserves a firm controls and the larger the deposits remaining in each reserve, the lower production costs are. As reserves at a site are depleted, overall reserve purity lowers and requires more costly technology to bring to market. Firms holding more numerous reserve sites are better positioned to prioritize which reserves to produce based on their purity and corresponding costs to produce. This is also a matching exercise by the firm. As prices may fluctuate higher, the firm may produce more costly reserve holdings and vice versa as prices decline. In this sense, the economic recoverability of reserves changes with prices and reserve quality.

$$Max_{q,w} \quad \int_{0}^{T} [q_t p_t - C_1(R_t) q_t - C_2(w_t) - \tau q_t] e^{-\delta t} dt \tag{1}$$

$$s.t. \quad \dot{R}_t = \dot{x}_t - q_t \tag{2}$$

$$\dot{x}_t = f(w_t, x_t) \tag{3}$$

$$R_t \geq 0, q_t \geq 0, w_t \geq 0, x_t \geq 0 \tag{4}$$

The Hamiltonian for the optimization problem is:

$$H = q_t p_t e^{-\delta_t} - C_1(R_t) q_t e^{-\delta_t} - C_2(w_t) e^{-\delta_t} - \tau q_t p_t e^{-\delta_t} + \\ \lambda_1 [f(w_t, x_t) - q_t] + \lambda_2 [f(w_t, x_t)] \tag{5}$$

Since H is linear in q, each producer should produce either nothing or at some maximum capacity level. We derive our first order conditions starting with the reserves:

$$\frac{\partial H}{\partial R} \rightarrow \dot{\lambda}_1 - C_1'(R_t) q_t e^{-\delta_t}$$

Rearranging, we solve for the shadow value of additional reserves:

$$\dot{\lambda}_1 = C_1'(R_t) \tag{6}$$

We find λ_1 is the present value of future profits resulting from an additional unit of reserves (i.e., shadow value of the proved reserve base). We now take the first order condition for x_t:

$$\frac{\partial H}{\partial x} \rightarrow \dot{\lambda}_2 - \lambda_1 f_x - \lambda_2 f_x = 0$$

We simplify and solve:

$$\dot{\lambda}_2 = -(\lambda_1 + \lambda_2) f_x \tag{7}$$

We now take the first order condition with respect to production q_t:

$$\frac{\partial H}{\partial q} = p_t e^{-\delta_t} - C_1(R_t)e^{-\delta_t} - \tau e^{-\delta_t} - \lambda_1 = 0$$

And solve for the market clearing condition to find that the change in value of future profits from one additional unit of reserves is equal to the rents less the value of the tax:

$$\lambda_1 = [p_t - C_1(R_t) - \tau]e^{-\delta t} \tag{8}$$

This confirms the intuition that taxes reduce rents.

2.4.2 Deriving the Price Pathway

We take the market clearing condition (equation 8) and differentiate it with respect to time.

$$\dot{\lambda}_1 = \dot{p}e^{-\delta_t} + p_t(-\delta)e^{-\delta_t} - C_1'(R_t)\dot{R}e^{-\delta_t} - C_1(R_t)(-\delta)e^{-\delta_t} - \tau(R_t)(-\delta)e^{-\delta_t}$$

We substitute for $\dot{R}$:

$$\dot{\lambda}_1 = \dot{p}e^{-\delta_t} + p_t(-\delta)e^{-\delta_t} - C_1'(R_t)\dot{R}e^{-\delta_t} - C_1(R_t)(-\delta)e^{-\delta_t} - \tau(R_t)(-\delta)e^{-\delta_t}$$

We set this equal to equation 6:

$$\begin{aligned} C_1'(R_t)q_t e^{-\delta_t} = \dot{p}e^{-\delta_t} + p_t(-\delta)e^{-\delta_t} - C_1'(R_t)[f(w_t, x_t) - q_t]e^{-\delta_t} \\ - C_1(R_t)(-\delta)e^{-\delta_t} - \tau(R_t)(-\delta)e^{-\delta_t} \end{aligned}$$

Finally, we simplify and rearrange to solve for the price pathway with taxes:

$$\dot{p} = \delta_t[p_t - C_1(R_t) - \tau] + f(w_t, x_t)C_1'(R_t) \tag{9}$$

Equation 9 shows that the tax directly affects the price pathway in one way when taxes are τ. The tax reduces rents. Indirectly, the firm can offset the cost of the tax by reducing its marginal cost of production. Recall that the marginal cost of production is lower when the firm has more reserves, $C_1'(R_t) < 0$. This stock effect, a common feature in non-renewable resource models, slows the rise in prices. If the firm can exploit stock effects to lower production costs and offset the tax, the tax policy will not necessarily reduce production. This trade-off emphasizes the importance of policymakers' understanding the shadow value of additional reserves λ_2 and the importance of exploration.

2.4.3 Deriving the Optimal Pathway for Exploration

Finally, we differentiate the Hamiltonian with respect to w_t to derive the equation of motion that characterizes firm exploration decisions:

$$\frac{\partial H}{\partial w} \to C_2'(w_t)e^{-\delta_t} = f_w(\lambda_1 + \lambda_2)$$

Rearranging and replacing λ_1 with the price pathway, we solve for the marginal cost of discovery, $\frac{C_2'(w_t)e^{-\delta_t}}{f_w}$:

$$\frac{C_2'(w_t)e^{-\delta_t}}{f_w} = \lambda_1 + \lambda_2$$

We substitute 8 for λ_1 and rearrange:

$$\frac{C_2'(w_t)e^{-\delta_t}}{f_w} = p_t e^{-\delta_t} - C_1(R_t)e^{-\delta_t} - \tau e^{-\delta_t} + \lambda_2$$

Discounted marginal discovery costs rise with rents and the shadow value of additional reserves. Discounted taxes reduce the size of rents implying that discounted marginal discovery costs actually decrease with increasing taxes. This is reflected in the impact of the shadow value of additional reserves (λ_2) on marginal discovery costs. Solving for λ_2:

$$\lambda_2 = \frac{C_2'(w_t)e^{-\delta_t}}{f_w} - p_t e^{-\delta_t} + C_1(R_t)e^{-\delta_t} + \tau e^{-\delta_t} \tag{10}$$

Equation (10) illustrates that the underlying factor that affects the shadow value of exploration is production costs and the size of the firm's reserve holdings R_t. First, the shadow value of additional reserves λ_2 rises as the marginal discovery cost rises. This reflects the scarcity of nonrenewable resources. Note that λ_2 decreases with prices p_t while it increases with average production costs $C_1(R_t)$ and taxes τ.

When the firm depletes its reserve holdings R_t, its average production costs rise and signal to the firm through λ_2 that the value of additional exploration is increasing. Higher reserves mean lower average costs $C_1(R_t)$ which diminishes the value of additional reserves.

Just as we observed with the price pathway, the interplay between tax rates and production costs is key to whether the tax policy reduces firm exploration. When the firm holds a lot of reserves, its production costs are lower and more of the tax is offset. This decreases the shadow value of additional reserves via low average production costs. If reserves are low, then production costs are high and the firm would benefit from acquiring additional reserves to leverage stock effects to lower production costs. As long as the firm can benefit from stock effects, it can acquire more reserves, lower its production costs, and offset the impact of the tax.

We now solve for the equation of motion for exploration. To do so, we substitute 8 and 10 into equation 7 and simplify:

$$\dot{\lambda}_2 = -[\frac{f_x}{f_w}]C_2'(w_t)e^{-\delta_t} \tag{11}$$

Take the time derivative of equation 10:

$$\dot{\lambda}_2 = \frac{[C_2''(w_t)\dot{w}e^{-\delta_t} + C_2'(w_t)(-\delta)e^{-\delta_t}]f_w - C_2'(w_t)e^{-\delta_t}[f_{ww}\dot{w} + f_{wx}\dot{x}]}{(f_w)^2} - \dot{p}e^{-\delta_t} - p_t(-\delta)e^{-\delta_t} + C_1'(R_t)\dot{R}e^{-\delta_t} + C_1(R_t)(-\delta)e^{-\delta_t} + \tau(-\delta)e^{-\delta_t}$$

Substitute with 2, 3, and 9, reduce and group for $\dot{w}$ to find that the tax has canceled out:

$$\dot{\lambda}_2 = \dot{w}\frac{[C_2''((w_t)e^{-\delta_t}f_w + C_2''((w_t)e^{-\delta_t}f_{ww}]}{(f_w)^2} - \frac{[\delta C_2'(w_t)e^{-\delta_t}f_w e^{-\delta_t} - C_2'(w_t)e^{-\delta_t}f_{wx}[f(w_t, x_t)]e^{-\delta_t}]}{(f_w)^2} - C_1'(R_t)(q_t)e^{-\delta_t} \tag{12}$$

Set 11 = 12:

$$-[\frac{f_x}{f_w}]C_2'(w_t)e^{-\delta_t} = \dot{w}\frac{[C_2''(w_t)e^{-\delta_t}f_w + C_2''(w_t)e^{-\delta_t}f_{ww}]}{(f_w)^2} - \frac{[\delta C_2'(w_t)e^{-\delta_t}f_w e^{-\delta_t} - C_2'(w_t)e^{-\delta_t}f_{wx}[f(w_t, x_t)]e^{-\delta_t}]}{(f_w)^2} - C_1'(R_t)(q_t)e^{-\delta_t}$$

Reduce and solve for the equation of motion for exploration:

$$\dot{w} = \frac{C_2'(w_t)[\frac{f_{wx}}{f_w}[f(w_t, x_t) - q_t] + \delta - f_x] + f_w q_t[C_1'(R_t)]}{C''(w_t) - C_2'(w_t)[\frac{f_{ww}}{f_w}]} \tag{13}$$

Looking at the equation of motion for exploration holistically, we see the scarcity effects of producing a nonrenewable resource with finite supply. This effect largely shows up in the exploration cost function $C_2(w_t)$. With $C_2'(w_t) > 0$ and $C_2''(w_t) > 0$, we see that as exploratory effort w_t increases over time, the difference between the first and second derivative of the exploratory cost function grows thereby dampening the overall pathway $\dot{w}$ in the denominator. We find that taxes τ do not directly affect the equation of motion for exploration.

Looking at the terms in the denominator, there is an interplay between marginal exploration costs $C_2'(w_t)$ and the collective impact of marginal production costs $C_1'(R_t)$ with scarcity effects. This dampens the exploratory pathway. On the right-hand side of the denominator, we see that the scarcity signal of marginal production costs $C_1'(R_t)$ results in higher levels of exploration while marginal tax rates also elevate the exploration pathway when reserves are high.

2.4.4 Terminal Period of Production T

Recall that adding reserves benefits the firms in two potential ways. Every additional unit discovered has the potential to be extracted, refined, and brought to market so the firm can extract rents. Rents are determined in equation 8 as the difference between market prices p_t and firm production costs which are $C_1(R_t) + \tau$ with taxes and $C_1(R_t)$ without taxes.

Accumulating additional reserves helps the firm minimize the cost of production and keep it competitive with backstop technologies for longer. From the perspective of production costs, the firm has little downside to acquiring reserves as long as there is no cost of cumulative additions x_t in the terminal period of production. This is the basis for the finding in [93] that there is an optimal amount of reserves left in the ground at the terminal period of production un-produced, R_T. It is marginal discovery costs that determine the terminal period of effort w_T. Consider figure 2.2.

As cumulative effort w_t increases over time, cumulative reserve additions x_t increase but so do marginal discovery costs $\frac{C_2'(w_t)}{f_w}$ along the y-axis. Barring a change in technology (which this paper does not consider), the finite supply of nonrenewable resources implies that the marginal discovery costs strictly increase with effort. The increasing steepness of the cost curve is intended to represent the increasing per unit costs of discovery for an increasingly scarce resource. As aggregate effort increases over time and the firm accumulates more

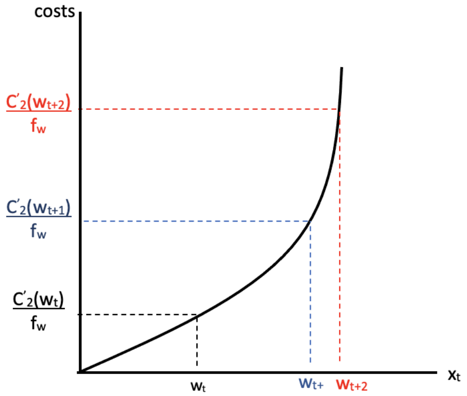

Figure 2.2: Marginal Discovery Cost Dynamics

reserves from $x_t \rightarrow x_{t+1} \rightarrow x_{t+2}$, it becomes increasingly costly to acquire more. This is the baseline condition that characterizes the upper bound constraint of reserve accumulations. The firm will engage in exploration until the increasing scarcity of un-discovered reserves becomes prohibitively costly. However, that terminal period of production T is when the price pathway crosses the choke price which is exogenously determined by the price-taking firm.

Following [93], the firm faces marginal discovery $\frac{Cs_2'(0)}{f_w} = \phi \geq 0$. If $\phi = 0$, then discovery efforts will continue up until the terminal time period of production T when $\lambda_2(T) = 0 = \lambda_1(T)$. At time T, both exploration and production simultaneously fall to zero and that terminal period of production is identified by the firm when $p_T = C_1(R_T) + \tau$ with taxes and $p_T = C_1(R_T)$ without taxes. We use these conditions to define the terminal reserves with taxes as $R_T(\tau)$ and the terminal reserves without taxes as $R_T(0)$. In either case, R_T is nonzero due to stock effects. We hypothesize $R_T(\tau)$ is larger because carbon taxes add to firm costs and reduce rents collected for a price-taking firm. We define stranded assets as:

$$S(\tau) = R_T(\tau) - R_T(0) \tag{14}$$

Since $R_T(0)$ was acquired by the firm via exploration and left in the ground by the firm at the terminal period of production under optimal conditions, we do not treat them as stranded.

Equation 14 isn't comprehensive, however. It represents the basis of how stranded assets must be measured in order to differentiate the optimal reserves left in the ground from those stranded in the ground due to an intervention in the market that might distort capital markets. This brings the concept of stranded assets in line with [39]. In equation 14, we considered how a carbon tax increased the size of reserves left in ground relative to the counterfactual when reserves are left in the ground without taxes, under optimal conditions. Additional government intervention in the market through other policy mechanisms can also affect the size of stranded assets such as exploration incentives that we consider in the next section.

Turning back to $\frac{C_2'(0)}{f_w} = \phi$, we consider how the case of $\phi > 0$ affects the decision to terminate production. Here, the firm faces a fixed cost of ϕ implying that $\lambda_2(T_1) = 0$ while $\lambda_1(T_1) > 0$. In this case, the terminal period for exploration efforts is T_1 but the firm continues production in $t > T_1$ with rents $\lambda_1 = [p_t - c_1(R_t) - \phi]e^{-\delta t} > 0$. Because the firm no longer engages in exploration, the marginal costs rise. As production continues under declining stock effects the overall average costs begin to rise at an increasing rate until $t \to T_2$ and $\lambda_1 = p_{T_2} - c_1(R_{T_2}) = \phi$. This is the final period of production.

Note that the terminal period of production T_2 is later than the terminal period of exploration T_1, but T_2 is still determined by the relationship between rents and firm costs. Nonzero fixed discovery costs just act in a similar fashion to a fixed carbon tax in that they add to firm costs and reduce rents. The firm will only stop production when $\lambda_1 = p_{T_2} - c_1(R_{T_2}) = \phi = 0$. In any period $t > T_2$, it must be that the net present value of future profits from an additional reserve is less than zero, i.e. $\lambda_1 < 0$, or the firm would continue to produce.

Recall the market clearing condition (equation 8) that characterizes the change in the discounted value of future profits, λ_1. With taxes, it is $\lambda_1 = [p_t - C_1(R) - \tau]e^{-\delta t}$. As average costs $C_1(R_t)$ increase, the discounted value of future profits decreases and average taxes τ rise, the value of λ_1 increases. Also recall equation 10 for the present discounted value of storage (i.e. future production), $\lambda_2 = \frac{C_2'(w_t)e^{-\delta_t}}{f_w} - p_t e^{-\delta_t} + C_1(R_t)e^{-\delta_t} + \tau e^{-\delta_t}$.

As figure 2.3 illustrates above, the tax increases the overall value of λ_1 and raises the overall value of λ_2 compared to the counterfactual where no tax exists. We also observe that λ_1 rises with prices and λ_2 declines with prices. As equations 8 and 10 illustrate, the value of both shadow values depends on the size of rents collected $p_t - C_1(R_t) - \tau$. While λ_2 may equal 0 and $w \to 0$ before production, all firm activity shuts down once $p_T < C_1(R_T) - \tau$.

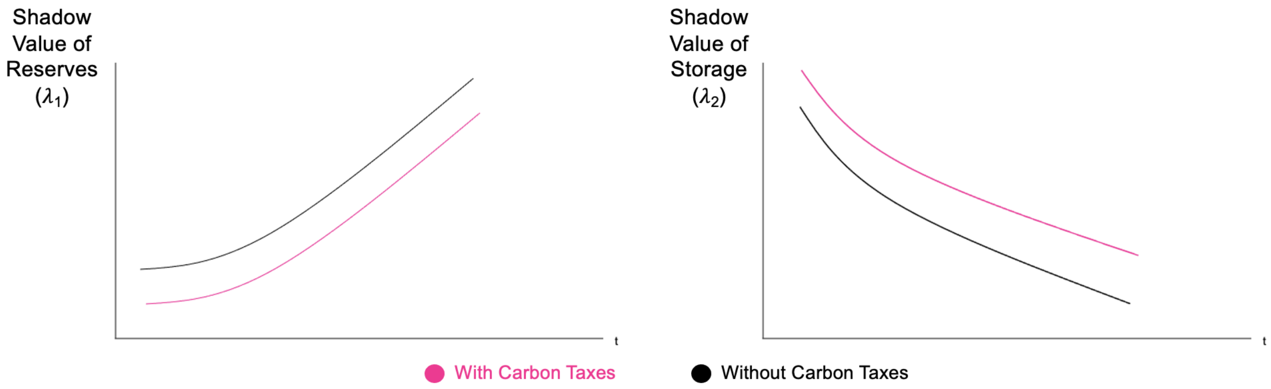

Figure 2.3: The Shadow Value of Additional Reserves and Storage: No Taxes vs. Taxes

2.4.5 Comparing the Impact of Taxes: $\tau(R_t)$ vs. τ

A carbon tax that is a function of reserves $\tau(R_t$ is solved in Appendix E. It functions similarly to τ, but directly affects more of the firm decision-making over exploration. As we compare the key equations, note that all equations denoted with an A indicate the simple tax τ while equations marked with a B indicate the tax is a function of reserves $\tau(R_t$. We start with the shadow value of production λ_1:

$$\lambda_1 = [p_t - C_1(R_t) - \tau]e^{-\delta t} \tag{L1 - A}$$

$$\lambda_1 = [p_t - C_1(R_t) - \tau(R_t)]e^{-\delta t} \tag{L1 - B}$$

Though the magnitude of the tax can affect rents collected based on R_t, the overall impact is the same. It denudes rents. Turning to the shadow value of additional reserves λ_2, we again observe similar results with the magnitude of the tax being the only difference:

$$\lambda_2 = \frac{C_2'(w_t)e^{-\delta_t}}{f_w} - p_t e^{-\delta_t} + C_1(R_t)e^{-\delta_t} + \tau e^{-\delta_t} \tag{L2 - A}$$

$$\lambda_2 = \frac{C_2'(w_t)e^{-\delta_t}}{f_w} - p_t e^{-\delta_t} + C_1(R_t)e^{-\delta_t} + \tau(R_t)e^{-\delta_t} \tag{L2 - B}$$

This pattern plays out in the price pathway (PP) equations A vs. B, however we note that the impact of the tax on the price pathway $PP - B$ with $\tau(R_t)$ is multifaceted whereas the impact of the simple tax τ on the price pathway $PP - A$ is straightforward:

$$\dot{p} = \delta_t[p_t - C_1(R_t) - \tau] + f(w_t, x_t)C_1'(R_t) \tag{PP - A}$$

$$\dot{p} = \delta_t[p_t - C_1(R_t) - \tau(R_t)] + f(w_t, x_t)[C_1'(R_t) + \tau'(R_t)] \tag{PP - B}$$

When the tax is just τ in $PP - A$, the only impact of the tax is to denude rents. Equation $PP - B$ shows that the tax reduces discounted rents and because it is an increasing function of reserves, the tax also puts upward pressure on the price pathway in a manner that characterizes the long-run impact of tax policy.

Turning to the equation for the optimal exploratory pathway ($EP - A$ and $EP - B$), we see that tax only directly impacts the decision-making over exploration when it is a function of reserves ($EP - B$):

$$\dot{w} = \frac{C_2'(w_t)[\frac{f_{wx}}{f_w}[f(w_t, x_t) - q_t] + \delta - f_x] + f_w q_t [C_1'(R_t)]}{C''(w_t) - C_2'(w_t)[\frac{f_{ww}}{f_w}]} \tag{EP - A}$$

$$\dot{w} = \frac{C_2'(w_t)[\frac{f_{wx}}{f_w}[f(w_t, x_t) - q_t] + \delta - f_x] + f_w q_t [C_1'(R_t) + \tau'(R_t)]}{C''(w_t) - C_2'(w_t)[\frac{f_{ww}}{f_w}]} \tag{EP - B}$$

Overall, the impact of the tax is roughly the same for most equations of interest despite changing the functional form of the tax though the magnitude of the tax does change based on the size of reserves R_t when the we have $\tau(R_t)$. This difference is not considered critical as the size of the tax without consideration of reserves could just as easily be larger than with $\tau(R_t)$ per policymaker discretion.

We do observe in the theory that the impact of the tax is muted in the price pathway with the common thread being that it reduces the discounted rents collected, however we see the impact of the simple tax τ has no direct impact on exploration decision-making in the the optimal pathway for exploration.

2.4.6 Policy Regime A: Exploration Incentives

The stranded assets created by the carbon tax are dependent on the size of the reserves when the carbon tax is enacted: $S(\tau; R_0)$. Thus exploration incentives in place before the carbon tax is enacted can have unintended consequences on the size of stranded assets created by the carbon tax if these exploration incentives increase R_0.

To consider how the inclusion of exploration incentives affects R_0, we assume government policy incentivizes additional exploration such that $\dot{x} = f(w_t, g_t, x_t)$ where $g_t \geq 0$ represents the amount of government intervention with $f_g > 0$. In an effort to stabilize resource supplies, government incentives increase as reserves dwindle: $\dot{g} = y(R_t)$ with $y'(R_t) < 0$ controlling how sensitive governments are to dwindling domestic reserves. The extended producer's problem is now:

$$Max_{q,w} \quad \int_0^T [q_t p_t - C_1(R_t)q_t - C_2(w_t)]e^{-\delta t}dt \tag{15}$$

$$s.t. \quad \dot{R}_t = \dot{x}_t - q_t \tag{16}$$

$$\dot{x}_t = f(w_t, g_t, x_t) \tag{17}$$

$$\dot{g}_t = y(R_t) \tag{18}$$

$$R_t \geq 0, q_t \geq 0, w_t \geq 0, x_t \geq 0, \& \ g_t \geq 0$$

Forming the Hamiltonian:

$$\begin{aligned} H = q_t p_t e^{-\delta t} - C_1(R_t)q_t e^{-\delta t} - C_2(w_t)e^{-\delta t} + \lambda_1[f(w_t, g_t, x_t) - q_t] \\ + \lambda_2[f(w_t, g_t, x_t)] + \lambda_3[y(R_t)] \end{aligned} \tag{19}$$

See Appendix B for the full derivation of this problem with government policy. For brevity, we consider the key equations of interest. The first is the market clearing condition, derived from taking the partial of the Hamiltonian with respect to reserves R_t and solve:

$$\dot{\lambda}_1 = C_1'(R_t)q_t e^{-\delta_t} - \lambda_3 y_R \tag{20}$$

We observe that exploration incentives $-\lambda_3 y_R > 0$ offset the negative impact of marginal production costs on $\dot{\lambda}_1$. Taking the first order condition with respect to reserve additions x_t, we solve for the change in the shadow value of storage:

Simplify:

$$\dot{\lambda}_2 = -(\lambda_1 + \lambda_2) f_x \tag{21}$$

Exploration incentives do not affect λ_2 as the scarcity of finite reserves dominates the value of storing reserve additions through f_x. Taking the partial with respect to production q_t, we solve for the market clearing condition:

$$\lambda_1 = [p_t - C_1(R_t)]e^{-\delta t} \tag{22}$$

This shows that the present value of future profits λ_1 (i.e. rents) is equal to the difference between market price p_t and average costs $C_1(R_t)$. Firm rents λ_1 rise with prices p_t and decrease with average costs $C_1(R_t)$. Without the tax, rents are higher given the exogenously formed price. Notably, exploration incentives have no direct impact on the size of rents.

We take the first order condition with respect to government policyg_t:

$$\frac{\partial H}{\partial g} = \dot{\lambda}_3 + \lambda_1 f_g + \lambda_2 f_g + \lambda_3 y_R = 0$$

Rearranging:

$$\dot{\lambda}_3 = -(\lambda_1 + \lambda_2) f_x - \lambda_3 y_R \tag{23}$$

We find that the shadow value of exploration incentives is increasing over time: $\dot{\lambda}_3 > 0$.[4] Taking the first order condition with respect to exploratory effort, we derive the shadow value of storage:

$$\lambda_2 = \frac{C_2'(w_t)e^{-\delta t}}{f_w} - p_t e^{-\delta t} + C_1(R_t)e^{-\delta t} \tag{24}$$

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[4] See Appendix B.3 for the signing of $\dot{\lambda}_3$

Notably, the presence of exploration incentives has no direct impact on the shadow value of storing reserve additions. It is still driven by the scarcity of nonrenewable reserves as signalled by discounted marginal discovery costs, prices, and production costs.

Optimal Price Pathway

Following the same strategy as we did in the model with carbon taxes, we derive the price pathway with exploration incentives:

$$\dot{p}_t = \delta[p_t - C_1(R_t)] + f(w_t, g_t, x_t)[C_1'(R_t)] - \frac{\lambda_3 y_R}{e^{-\delta t}} \tag{25}$$

We note that the impact of exploration incentives is two-fold. First, it raises the level of exploration effort which slows the rise in prices due to the stock effects accrued as lower production costs. Second, it increases the rate of change in prices via $\frac{-\lambda_3 y_R}{e^{-\delta t}} > 0$ which is the future value of a change in government incentives. This additional upward pressure on prices should incentivize more exploration.

Optimal Pathway of Exploration

The full derivation of the optimal pathway for exploration follows quite similarly to the process outline for carbon taxes earlier. See Appendix B for details. Skipping to the end result, we find the optimal pathway for exploratory effort to be:

$$\dot{w} = \frac{C_2'(w_t)[\frac{f_{wx}}{f_w} f(w_t, g_t, x_t) + \delta - f_x] + f_w[C_1'(R_t)q_t - \frac{\lambda_3 y_R}{e^{-\delta t}}]}{C_2''(w_t) - \frac{f_{ww}}{f_w} C_2'(w_t)} \tag{28}$$

Government policy $\frac{-\lambda_3 y_R}{e^{-\delta t}} > 0$ elevates the optimal pathway for exploration and induces the firm to explore more. However, the influence of exploration incentives is limited by the finite supply of nonrenewable resources as evidenced by the presence of exploration costs $C_2''(w_t) - \frac{f_{ww}}{f_w} C_2'(w_t)$ in the denominator. Just as we observed in the model with carbon taxes, the cost of exploring is strictly increasing such that $C_2'(w_t) > 0$ and $C_2''(w_t) > 0$ (assumptions from [93]). This means effort w_t is limited in its efficacy to continually discover more reserves over time.

Effect of Exploration Incentives on Reserve Holdings

The impact of policy that incentivizes exploration is to induce more exploratory effort. But the indirect impact is to reduce marginal production costs through the stock effects of nonrenewable resource production. This leads to lower overall average production costs and larger resource rents in equation 22. Recall equation 20:

$$\dot{\lambda}_1 = C_1'(R_t)q_t e^{-\delta t} - \lambda_3 y_R \tag{20}$$

Without exploration incentives, the change in present value of future profits is negative due to the stock effect in marginal production costs: $\dot{\lambda}_1 = C_1'(R_t)q_t e^{-\delta t} < 0$. Exploration incentives slow this decline in resource rents or, if government is sufficiently responsive to dwindling reserves (i.e., y_R is large), resource rents may rise. The firm's acquisition of additional reserves following the exploration incentives will mute negative impact of the stock effect. Since exploration incentives increase (indirectly) resource rents for all values of R, we conclude that exploration incentives increase the opportunity cost of drawing down reserves.

Exploration incentives can clearly induce the firm to hold larger reserves, but there exists a natural upper bound that limits the magnitude of the firm's response. This upper bound is rooted in the engineering and physical constraints presented by the finite supply of a nonrenewable resource. Consider the equation of motion for government policy:

$$\dot{\lambda}_3 = -\frac{f_g}{f_w} C_2'(w_t) e^{-\delta t} - \lambda_3 y_R \tag{23}$$

The persistence of government policy in equation 23 is a function of the interplay between the effective return of government policy, $-\lambda_3 y_R > 0$, and the marginal discovery costs,

$\frac{C_2'(w_t)}{f_w} > 0$. Thus exploratory effort is bounded by the scarcity of nonrenewable resources as demonstrated by the increasing marginal discovery cost considered earlier in Figure 2.

Government policy may incentivize the firm to increase its effort to find more reserves, but it doesn't change how much can be found. Marginal discovery costs present an insurmountable economic constraint on the magnitude of policy's impact. Exploration incentives can really only change the timing of when reserves are acquired. Thus, the increase in resource rents indirectly caused by exploration incentives causes the firm to shift reserve discovery earlier in time.

2.4.7 Inconsistent Policy

We now consider the impact of a scenario where the firm simultaneously inconsistent policy. Specifically, the firm faces carbon taxes and exploration incentives with each unit of production is taxed at rate $\tau(R_t)$ and $\tau'(R_t) > 0$ as well as incentives g with $\dot{g} = y(R_t)$, and $y'(R_t) < 0$. All other assumptions remain the same as in prior models.

Given initial conditions for reserves R_0 and cumulative reserve additions x_0, firms maximize welfare such that:

$$Max_{q,w} \quad \int_0^T [q_t p_t - C_1(R_t)q_t - C_2(w_t) - \tau(R_t)q_t]e^{-\delta t}dt \tag{32}$$

$$s.t. \quad \dot{R}_t = \dot{x}_t - q_t \tag{33}$$

$$\dot{x} = f(w_t, x_t, g_t) \tag{34}$$

$$\dot{g}_t = y(R_t) \tag{35}$$

$$R_t \geq 0, q_t \geq 0, w_t \geq 0, x_t \geq 0, g_t \geq 0$$

The Hamiltonian for the optimization problem is:

$$H = q_t p_t e^{-\delta_t} - C_1(R_t) q_t e^{-\delta t} - C_2(w_t) e^{-\delta t} - \tau(R_t) q_t p e^{-\delta t} + \lambda_1[f(w_t, x_t) - q_t] + \lambda_2[f(w_t, x_t)] + \lambda_3[y(R_t)] \quad (36)$$

We take the first order conditions starting with the reserves and solve for the shadow value of additional reserves $\dot{\lambda}_1$[5]:

$$\dot{\lambda}_1 = [C_1'(R_t) + \tau'(R_t)] q_t e^{-\delta t} - \lambda_3 y_R \quad (37)$$

We observe that under inconsistent policy, both taxes and exploration incentives offset the scarcity signal of increasing marginal production costs. Taking the first order condition for x_t, simplifying, and solving:

$$\dot{\lambda}_2 = -(\lambda_1 + \lambda_2) f_x \quad (38)$$

Again, there is no impact on the shadow value of additional storage. We now take the first order condition with respect to reserve additions q_t and solve for the market clearing condition. We find the same results as in the model with only taxes, i.e. taxes reduce the rents collected by the firm and act as an added cost alongside the average production cost:

$$\lambda_1 = [p_t - C_1(R) - \tau(R_t)] e^{-\delta t} \quad (39)$$

Deriving the Price Pathway

Taking the market clearing condition (equation 39), we differentiate it with respect to time. Then we substitute for $\dot{R}$, set the equation equal to 37, simplify, and solve for the equation of motion for prices:

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[5] The math for this model is abbreviated within this section as it follows the previous two models. The full derivation of our inconsistent model is available in Appendix C.

$$\dot{p} = \delta[p_t - C_1(R_t) - \tau(R_t)] + f(w_t, x_t, g_t)[C_1'(R_t) + \tau'(R_t)] - \frac{\lambda_3 y_R}{e^{-\delta_t}} \tag{40}$$

As observed in the models before it, equation 40 shows that the tax affects the price pathway in two ways. First, it slows the rise in prices by lowering rents. Second, because the tax is an increasing function of reserves, the tax also hastens the rise in prices through exploration. Exploration incentives $-\frac{\lambda_3 y_R}{e^{-\delta t}} > 0$ also raise the price pathway.

This likely is a result of the fact that we set taxes as a function of reserves. Price rise faster to account for the fact that exploration adds reserves x_t to the firm's holdings which increases a tax rate that is based on the size of firm reserves. However, prices may not necessarily rise on the aggregate because of this. If adding reserves lowers marginal production costs such that it offsets or exceeds the rise in marginal taxes. This is possible if the ratio of tax increases to reserves additions doesn't account for the reduction in marginal production costs achieved through stock effects.

Deriving the Optimal Pathway for Exploration

Finally, we differentiate the Hamiltonian with respect to w_t, rearrange, substitute 39 for λ_1, and solve for λ_2:

$$\lambda_2 = C_2'(w_t)e^{-\delta t} f_w - p_t e^{-\delta t} + C_1(R_t)e^{-\delta t} + \tau(R_t)e^{-\delta t} \tag{41}$$

Substituting equations 39 and 41 into 38 and simplifying:

$$\dot{\lambda}_2 = -[\frac{f_x}{f_w}]C_2'(w_t)e^{-\delta t} \tag{42}$$

Take the time derivative of equation 41, substitute with equations 33, 34, and 40, then reduce and group for $\dot{w}$:

$$\begin{aligned}\dot{\lambda}_2 = \dot{w}\frac{C_2''(w_t)f_w e^{-\delta t} - C_2'(w_t)f_{ww}e^{-\delta t}}{f_w^2} \\ - \frac{\delta C_2'(w_t)e^{-\delta t}}{f_w} - \frac{C_2'(w_t)f_{wx}[f(w_t, x_{t],g_t)]e^{-\delta t}}]}{f_w^2} \\ - \tau'(R_t)e^{-\delta t} + \lambda_3 y_R - C_1'(R_t)q_t e^{-\delta t} \quad (43)\end{aligned}$$

Setting 42 = 43, we reduce and solve for the equation of motion for exploration:

$$\dot{w} = \frac{C_2'(w_t)[\frac{f_{wx}}{f_w}[f(w_t, x_t, g_t) + \delta - f_x] + f_w[C_1'(R_t)q_t + \tau'(R_t)q_t - \frac{\lambda_3 y_R}{e^{-\delta_t}}]}{C_2''(w_t) - C_2'(w_t)(\frac{f_{ww}}{f_w})} \quad (44)$$

When the firm faces inconsistent policy, taxes affect the pathway for exploration in the same manner as it did when the firm only faced carbon taxes while exploration incentives affect exploration in the same manner as they did when the firm only faced exploration incentives. The interesting area to consider is how this inconsistent policy framework affects the magnitude of stranded assets.

2.4.8 Comparing the Magnitude of Stranded Assets Across Models

Recalling the scenario when the firm faced exploration incentives without carbon taxes, we observe that the decision to terminate exploration and production are governed by the same forces and this holds true when considering the inconsistent policy framework derived just before this subsection.

The introduction of exploration incentives does not change the decision to end production nor do they affect the timing of $w \to 0$ versus $q \to 0$. Exploration and production simultaneously end in the terminal period of production T unless marginal discovery present some fixed cost ϕ in which case $w \to 0$ in time T_1 while $q > 0$ until the terminal period of production T_2 when $p_T = C_1(R_T)$. The same holds for our inconsistent policy framework.

The size of stranded assets may be different, however. Recall from earlier that equation 14 $R_T(0)$ is the optimal number of reserves left in the ground under the original model presented in [93] None of these reserves are considered stranded by the carbon tax since these reserves are optimally left in the ground in the absence of a tax. We also measure stranded assets as a function of carbon taxes as $S(\tau)$. We now consider the size of stranded assets under inconsistent policy as:

$$S(g, \tau) = R_T(g, \tau) - R_T(g, 0) \tag{46}$$

If $S(g, \tau) > S(\tau)$, policies designed for U.S. energy security will exacerbate the assets stranded by a carbon tax. Estimates of stranded assets that do not account for past domestic oil and gas policy will over-estimate the size of assets stranded by a carbon tax. In the absence of analytic solutions for $S(g, \tau)$ and $S(\tau)$, we parameterize our model to historic U.S. oil data to simulate the size of stranded assets with and without policy inconsistency.

2.5 An Application to U.S. Oil Producers

The purpose of this numerical application of the model is to compare the size of assets stranded by a carbon tax with and without resource exploration incentives. To do this we need to solve for the optimal reserves left in the ground under four scenarios. First, a "Business-As-Usual" (BAU) scenario representative of Pindyck's original problem where competition against a backstop technology is the primary reason that the firm's reserves will remain in the ground, un-produced, at the terminal period of production. This scenario documents the reserves abandoned due to the stock effect and should not be considered assets stranded by a carbon tax. We then compare the size of these reserves to our second scenario ("Carbon Tax") where the firm faces a carbon tax under a punitive government policy designed to end the fossil fuel era earlier than in a BAU scenario. By comparing the optimal reserves left in the ground at the terminal period of production in the two scenarios, we can identify the assets stranded due to a carbon tax.

Our third scenario (”Exploration Incentives”) introduces a supportive government policy designed to encourage the firm to explore for additional reserves in pursuit of a domestic energy independence policy. Our fourth scenario combines a carbon tax with exploration incentives and is referenced as our ”Policy Inconsistent” scenario. By comparing the optimal reserves left in the ground at the terminal period of production in the two scenarios, we can identify the assets stranded due to policy inconsistency.

If the size of assets stranded due to policy inconsistency is different from the assets stranded due to a carbon tax along, the current approach to measuring stranded assets may be overestimating the negative impacts of a carbon tax to the oil industry.

2.5.1 Data and Parameterization

Pindyck’s application is based on reserves in the Permian Basin of Texas and New Mexico and this paper seeks to replicate that modeling effort as closely as possible. Following [93], we have three equations of interest that this paper parameterizes with updated data. All data on oil exploration, production, prices, costs, and assorted variables are aggregated from the Energy Information Administration (EIA) Annual Energy Report in years $1980 - 2007$. The study period stops in 2007 as that was the last year leading up to the fracking revolution when oil and gas exploration and production technology rapidly evolved to expand the scope of economically recoverable reserves. This discrete shift in production technology and viable reserves makes it difficult to obtain a consistent parameterization over both periods.

Pindyck used the number of exploratory and development wells drilled in a year to represent effort, but our update uses the average depth of exploratory and development wells drilled. Research on policy incentives has shown the industry tends to drill more wells than is optimal in response to state-level pro-rationing of production [118] which implies that the number of wells drilled is not a true indication of exploratory efforts.[6]

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[6] This paper did run the model with exploration characterized as the number of wells and separately ran the model using the average depth of drilling. Regressions based on the number of wells drilled were not significant and presented an $AdjR^2 = -0.03674$. Moreover, using the estimates from ’number of wells drilled’ in did not result in model convergence.

Based on the ratio of overall Permian reserves to US reserves, we estimate the initial reserves in 1980 as $7,152$ million barrels. We specify the functional form for average costs $C_1(R_t)$ as $\frac{m}{R_t}$ with m equal to the real production price of a barrel of oil in 1980 (\$1.04 a barrel) multiplied by total reserves $(7,152)$ such that $m = 7,438$.

Beyond this, we follow Pindyck's three primary equations of interest with some adjustments. Exploration costs $C_2(w_t)$ are represented in equation $A1$:

$$\frac{C_2(w)}{w_1 + w_2} = 0.02797 + \frac{0.019346^{*}}{w_1} - \frac{0.020715^{**}}{w_2}$$

$$(0.85) \qquad (2.74) \qquad (-3.279)$$

$$Adj.R^2 = 0.2448 \qquad SE = 0.002321 \qquad *p < 0.01 \qquad **p < 0.001 \tag{A1}$$

We assume $f(w_t x_t) = Aw^{\alpha}e^{-\beta x}$ for the discovery of additional reserves with $\alpha > 0$ and $\beta > 0$. This paper follows Pindyck's process for constructing reserve additions to produce $A2$:

$$\log \text{DISC}= 0.1456 + 0.09498 \log w_1 + 0.5649 \log w_2 + 0.9844x$$

$$(0.009) \qquad (0.063) \qquad (0.467) \qquad (1.433)$$

$$Adj.R^2 = 0.2055 \qquad SE = 0.3682 \tag{A2}$$

Specifically, reserve additions are comprised of discoveries, extensions of old discoveries (for example, through reserve development), and revisions. As revisions are not a direct function of exploratory or development effort, Pindyck accounts for the ex-post revision of reserve estimates by assuming they act as a random process with a mean larger than the mean of discoveries. Therefore, the estimate for $DISC$ is produced by multiplying the sum of discoveries and extensions by a ratio of the mean for reserve additions to the mean of the sum of reserve discoveries and extensions.

Finally, we adjust Pindyck's linear demand function to reflect the increased volatility of oil prices and the decreasing costs of backstop technologies. This was also necessary to achieve model convergence given an update on the data deployed for parameterization:[7]

$$q = 550 - 10p \tag{A3}$$

This paper introduces government policy as a 5% nudge affecting the parameters governing firm effort. This enters into the functional form of additional discoveries $Aw^{\alpha}e^{-\beta x}$. Specifically, we introduce it as a negative term -0.05 affecting A and α, but not β as identified in $A4$:

$$Aw^{\alpha - 0.5\alpha}e^{-\beta x} \tag{A3}$$

The rationale for this is fairly straightforward. First, this paper assumes the government term mathematically enters as a negative value based on comparing the observed results to when it is positive. Appendix E presents the results of the government term as a positive value. There, the size of reserves left in the ground at the terminal period of production with exploration incentives and taxes is less than the reserves left in the ground with exploration incentives but no tax. This is logically nonsensical as the tax reduces the rents collected for each unit of production and would result in more reserved left in the ground than when the tax is removed. Also, the intent of introducing exploration incentives is to increase the rate of

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[7] Several adjustments to the original parameterization design are planned for this paper moving forward. As the current results indicate that government policy to incentivize exploration has a nonzero effect on the size of stranded assets, the primary adjustment needed is to specify a functional form for how varying size and quality of reserves affects production costs. This would also introduce the opportunity to merge the firm adjustment costs presented in [119]'s simulation to better characterize the trade-off between exploration and production costs.

effort a firm makes for exploration which may indirectly result in technological innovations. Adjusting β changes how the firm values profits across time which is not the intent.

Second, research [118, 51, 61], shows that government policy can incentivize exploration effort, but not production, and much of that additional exploratory effort is not productive. Therefore, we do not introduce government incentivizes to the β term which functions more like an industry technology term. Direct changes in β increase the efficiency of exploratory effort in our numerical results.

Carbon taxes τ are set at \$15 per unit of production and introduced in various equations of interest following the theoretical model. The \$15 tax is roughly 33% of the initial first purchase price (adjusted for inflation). Our \$15 carbon tax also implies a social cost of carbon of \$109.95 per ton of CO_2 which is double the federal estimate of the social cost of carbon (\$51) but broadly in line with current research on the social cost of carbon [12, 100].[8]

Table 2.1 presents the exhaustive list of parameters.

2.5.2 Summary of Simulation Findings

Table 2.2 summarizes the results of our simulation. It is presented in terms compared to the BAU scenario. Specifically, it provides the results from the model under the BAU scenario where the firm faces no carbon tax and no exploration incentives and the model results for the other scenarios are reported in percentage terms relative to BAU. For example, we find the the model estimates that total profits over the entire lifetime of production are $\$199,878$ millions. In comparison, total profits under the Carbon Tax scenario are 41% *lower* than the BAU scenario. Operating under exploration incentives, total profits are 3% *higher* than BAU while they are 39% lower under the Inconsistent Policy framework.

Interestingly, total production is 3% *lower* under Carbon Taxes, but Exploration Incentives and Inconsistent Policy produce 7% and 8% *more* than BAU. The firm produces more when it engages in more exploration effort, but this does not necessarily mean that it

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[8] In terms of 'barrels of oil', it takes an average of roughly 7.33 barrels of crude oil to produce one tonne of CO_2. Based on a \$51 social cost of carbon, this would imply a price of \$6.96 carbon tax per barrel based on the worldwide average gravity of crude at the wellhead [24].

Table 2.1: Numerical Parameters and Initial Conditions

Parameters	**Numerics**
Initial Reserves	R(1) = 7,152
Initial Additions	x(1) = 0
Initial Price p_0	min = 11, max = 55
Initial Effort w_0	min = 5150, max = 10150
Tax	τ = 15
Exploration Incentives	g = 0.05
Discount Rate	delta = 0.05
Cost Parameter 1	c1 = 0.004629913
Cost Parameter 2	c2 = 0.02797019
Demand Parameter 1	A = 0.1956262
Demand Parameter 2	a = 550
Demand Parameter 3	b = 10
Demand Parameter 4	alpha = 0.6599042
Demand Parameter 5	beta = 0.0000984416

Table 2.2: Comparing Optimal Production and Reserve-Holdings to Business as Usual

Model	**Profits**	**Production**	**Per Unit Profits**	**Shutdown**	**Unproduced Reserves**
BAU	199,878	9,975	\$20	37 Years	3,145 M Barrels
Carbon Taxes	−41%	−3%	−39%	+19%	+3%
Exploration Incentives	+3%	+7%	−4%	+5%	−26%
Inconsistent Policy	−39%	+8%	−43%	+30%	−26%

makes more profits. In terms of total profits, receiving exploration incentives without facing a carbon does result in more overall profits, but the per unit profits for the firm are the highest under BAU. Long story short, we show that Stranded Assets are largest under the Carbon Tax followed by BAU, Inconsistent Policy, and Policy Incentives if all we care about are the number of reserves left in the ground un-produced.

We basically show that Policy Incentives without carbon taxes are a good result for the firm, but the ideal result is BAU. However, given the history of actual policy in the US that has favored oil firms, the most realistic result under a tax would be the Inconsistent Policy scenario where the firm is the worst off in per unit profit and just a little better in overall profit than Carbon Taxes.

The big question is, has the existence of government policy that incentivized exploration set the firm up to incur stranded assets under a hypothetical carbon tax? This is precisely what the Inconsistent Policy scenario attempts to simulate and the answer is... not really if we treat un-produced reserves as stranded assets. We estimate that the firm leaves $3,145$ million barrel of oil in the ground at the end of its production life under BAU. These un-produced reserves are considered the optimal amount of un-produced reserves under [93] and therefore, are not stranded. Under the Carbon tax scenario, the firm leaves 3% more reserves un-produced at the end of its production lifetime which is roughly 87 million barrels of oil that could be considered ”stranded” by a carbon tax policy which is roughly $4.5 billion USD based on the estimated price of oil. When we compare the introduction of a carbon tax under our Inconsistent Policy framework to the scenario where the firm only received Exploration Incentives, we estimate that the firm strands only 12.3 million barrels of oil at a value of $679 million USD. Inconsistency also generates higher profits than a carbon tax, so inconsistency is not universally bad. It does reduce per unit and total profits, but it is clearly better than a carbon tax by itself.

2.5.3 Optimal Pathways

Figure 2.4 plots the optimal price pathways for all four models (left) and the optimal exploration pathways (right) based on the parameterization discussed in the previous section. Consider the curvature of the optimal exploratory effort for the BAU profile (black line) as compared to the curvature of effort for the model with exploration incentives (green line). While the pathway under government incentives starts off with the firm engaging in lower level of efforts to explore, the firm is exploring far more under incentives by year 3 and remains so throughout the production timeline. The same pattern repeats when comparing the model under inconsistent policy (blue line) as compared to the model under just carbon taxes (pink line) albeit at a lower magnitude.

The resulting price pathways in the left hand graph show that engaging in less effort to acquire reserves results in a higher baseline price. Without a tax, the price pathways for BAU and Exploration Incentives remain lower than when the firm faces a tax (both Carbon Taxes and Inconsistent Policy) until just after year 25 of production when they cross pathway. At this point, the price pathway for BAU and Exploration Incentives have a much steeper slope than the pathways with Carbon Taxes with prices at higher levels. Recall that by years 37 and 39, the firm ceases production under our BAU and Exploration Incentives assumptions while the firm continues producing under the model profiles with Carbon Taxes. This is partly a result of the finite nature of nonrenewable resources where the firm's choice is to produce more today and leave less to produce tomorrow or restrain production today in order to scale up production in the future.

These timelines for the production of nonrenewable resources are bound by the physical limits of supply. Economic markets further limit that timeline by decreasing the competitiveness of extraction under the assumption that production costs increase with dwindling supply. Introducing a tax in our model changes the timeline of production. In our simulation, it results in a longer production timeline as a result of the decreased competitiveness of production under the tax in any given time period. Specifically, the firm has a decision to make based on prices. When prices are low, the per unit rents collected from production is smaller but the firm's product is more competitive. The firm may produce

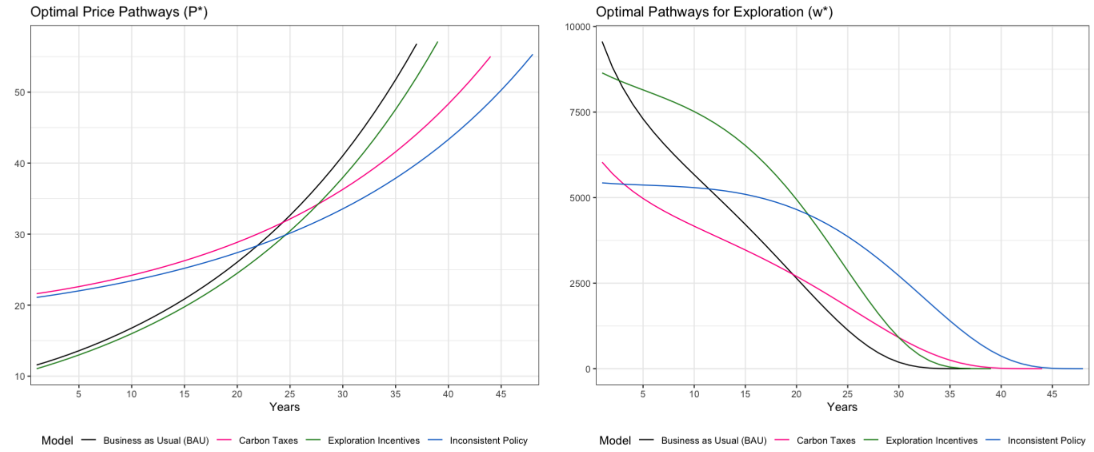


Figure 2.4: Comparing Optimal Price and Exploration Pathways

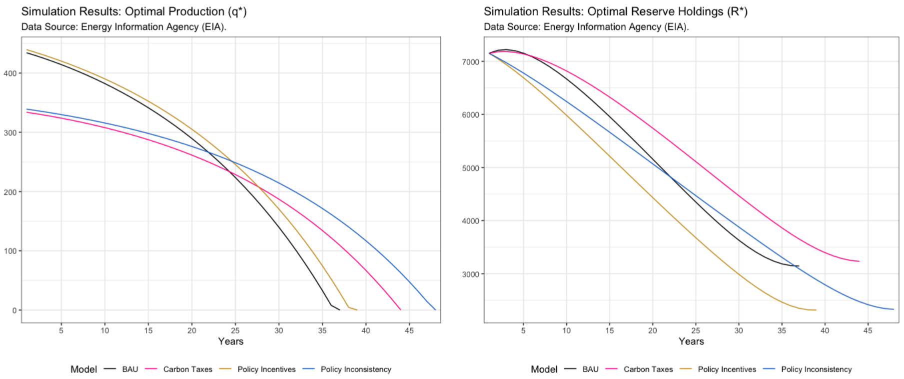
more to increase profits and meet demand, but producing more runs down total supply earlier than if prices were higher and yearly production volume is lower. When the price pathway is higher to start, the firm is less competitive and will produce less as demand is lower. In figure 2.4, this dynamic plays out to its ultimate conclusion when the price pathways cross just after year 25 when the scarcity of reserves kicks in for the model when it is producing more in earlier years (BAU and Exploration Incentives).

Figure 2.5 looks more deeply into the firm's decision-making over its production pathway (left) and the size of its reserve holdings (right). Comparing the pathways of production to reserves by scenario, we can see that exploration incentives don't manifest as an increase in reserves. Rather, they result in an increase in production. Firms receive subsidies to explore which increases reserves but they don't sit on those reserve; they immediately extract them. This also highlights a major downside in inconsistent policy. We observe that it results in more $C0^2$ emissions. The purpose of a carbon tax is to strand assets so that we don't burn them. Under Inconsistent Policy, we are stuck with a trade-off, we can strand more assets or we can produce more CO2 emissions.

Turning to figure 2.6, we compare aggregate totals over the lifetime of production for Profits, Effort, Production, Reserves, Stranded (Assets), and the years until Shutdown to compare overall outcomes. Again, our BAU profile is represented in black, Carbon Taxes in pink, Exploration Incentives in green, and Policy Inconsistency in blue.

2.5.4 Stranded Assets

Figure 2.7 compares the results of our BAU model where no government intervention occurs to the model scenario where the firm faces a carbon tax (Carbon Tax). We observe that the level of production is higher under BAU compared to Carbon Tax, but the firm produces for more years under the Carbon Tax (44 compared to 37 under BAU). In accordance with the theory (and intuition), we do see 41% lower profits and 21% larger reserves held by the firm under Carbon Tax. Because the tax decreases rents, the firm adds to its reserves to lower the marginal cost of production.



Simulation Results: Optimal Production (q*)

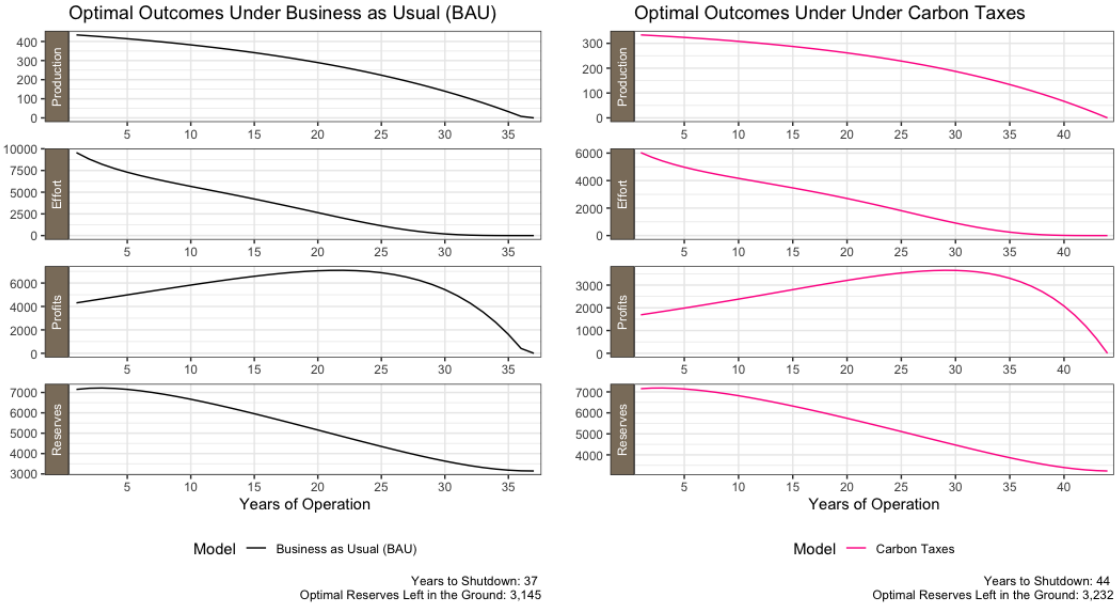
Data Source: Energy Information Agency (EIA).

Simulation Results: Optimal Reserve Holdings (R*)

Data Source: Energy Information Agency (EIA).

Figure 2.5: Comparing Optimal Production and Reserve-Holdings

Figure 2.6: Variations in Optimal Outcomes


Optimal Outcomes Under Business as Usual (BAU)

Optimal Outcomes Under Under Carbon Taxes

Years to Shutdown: 37
Optimal Reserves Left in the Ground: 3,145

Years to Shutdown: 44
Optimal Reserves Left in the Ground: 3,232

Figure 2.7: Comparing Production Dynamics: Business as Usual vs. Carbon Taxes

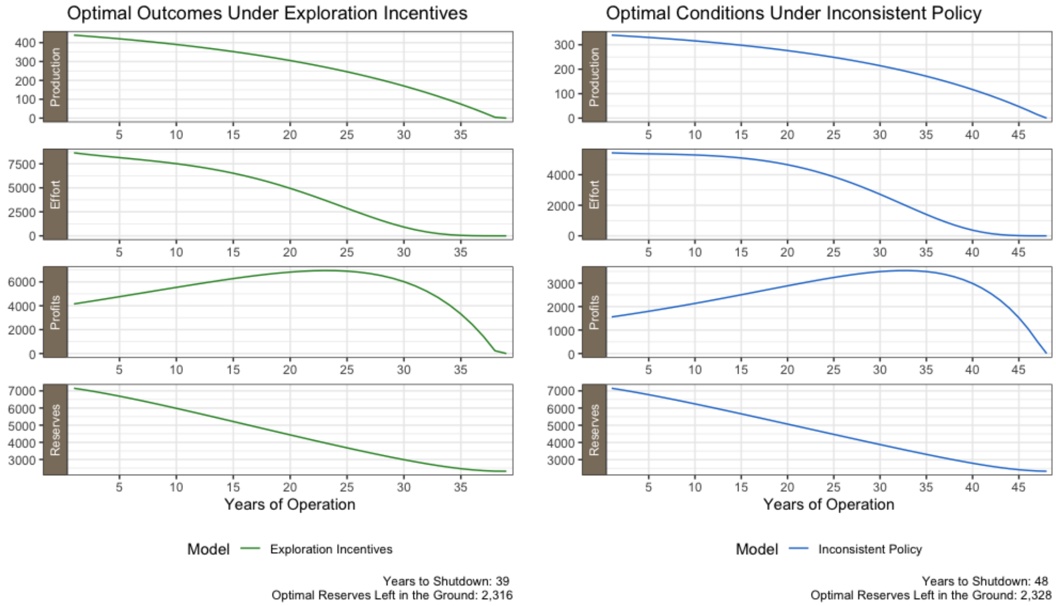
This results in the BAU leaving fewer reserves at the terminal period of production. The firm leaves $3,145$ million barrels in the ground at the terminal period of production under BAU which is about 2.7% fewer than under Carbon Tax. The carbon tax stranded 3,232-3,145=87 million barrels of oil. This is despite the model showing that carbon taxes actually increase the production time period by 7 years compared to the BAU results. This means that the firm produces more of its reserves under BAU in a shorter period of time than under the Carbon Tax while accruing more profits.

Figure 2.8 compares the model scenario where the firm is provided "Exploration Incentives" by the government (graph on left) with the scenario where the firm faces "Inconsistent Policy" (graph on right). Recall that Inconsistent Policy is when the firm receives government incentives to encourage exploration while also facing carbon taxes that penalize reserve production. Introducing the tax again increases the reserve left in the ground relative to the scenario of "Exploration Incentives" where there were no taxes. With exploration incentives in place, the carbon tax strands 12 million barrels of oil $(2,328-2,316)$. Policy inconsistency *decreases* the assets stranded by a carbon tax.

The application of a tax within an inconsistent policy framework still denudes overall rents which leads to the difference in profits but by leveraging the stock effects to reduce marginal production costs, the firm is able to produce more units than in Figure 7 when the firm faces a carbon tax without exploration incentives. Therefore, introducing a tax under inconsistent policy decreases the magnitude of stranded assets under a carbon tax than when the carbon tax is introduced without exploration incentives.

The nominal size of terminal period reserves are also lower for both scenarios in Figure 7. Consider the two scenarios where the firm does not face a tax. Under the BAU profile, the firm leaves $3,145$ million barrels of oil in the ground whereas the firm leaves $2,316$ million barrels of oil when it benefits from and responds to exploration incentives. The theory can explain this seemingly counter-intuitive result.

When the firm acquires more reserves, it becomes larger and more competitive by minimizing its production costs over larger reserve holdings. The stock effects of larger reserve holdings helps the firm remain competitive longer and produce more overall.


Optimal Outcomes Under Exploration Incentives

Optimal Conditions Under Inconsistent Policy

Years to Shutdown: 39
Optimal Reserves Left in the Ground: 2,316

Years to Shutdown: 48
Optimal Reserves Left in the Ground: 2,328

Figure 2.8: Comparing Production Dynamics: Exploration incentives without carbon taxes (right) and with carbon taxes (policy inconsistency; left)

This trend holds even when it faces a carbon tax. Under the Inconsistent Policy profile, the firm leaves $2,328$ million barrels of oil in the ground at the terminal period of production whereas the firm leaves $3,232$ million barrels of oil in the ground at the terminal period of production when it faces carbon tax without any exploration incentives. Therefore, historical policy that successfully encouraged the firm to explore more and acquire larger reserve holdings are less harmed by the shift in policy to tax production.

Other trends are validated in Figure 7 that parallel the impact of introducing taxes observed in Figure 6. When the firm only faces Exploration Incentives, it reaps 67% more profits than when it faces the tax under Inconsistent Policy (graph on right). Without the tax, the firm also maintains fewer reserves (-20%) than under inconsistent policy. This parallels the results we observe in Figure 7. We also see a repeat of the pattern observed in Figure 7 on the amount of time a firm will produce. Specifically, adding taxes to exploration incentives (Inconsistent Policy) increases the number of years a firm produces compared to when the firm just faces Exploration Incentives. All told, the firm produces more and reaps more profits without a tax.

2.6 Conclusion

This paper documents the effect of past energy policy on the magnitude of assets stranded by a carbon tax. To investigate the implications of this policy inconsistency, this paper modifies [93] by adding government terms to the model on the optimal exploration and production of an oil and gas firm. We then compared how many stranded assets remain in the ground across three policy regimes: one where the firm faces Carbon Taxes, one where the firm receives Exploration Incentives, and one where the firm faces both taxes and incentives (i.e. Inconsistent Policy).

Comparing simulated outcomes of those three policy regimes with a Business as Usual (BAU) environment illuminates the critical importance that stock effects play via lower marginal production costs on the size of stranded assets. We find that exploration incentives to achieve energy independence can induce the firm to acquire more reserves and taxes can raise the firm's price pathway, both of which (indirectly) change the timeline for production. Our results validate that taxes distort the decision-making on exploration in counter-intuitive ways.

When the firm is large (aka it has acquired a lot of reserves), its marginal cost of production is lower and the optimal exploration pathway indicates that it normally would not engage in high volumes of effort to explore. Because the tax reduces rents collected on each produced reserve, the firm explores more despite its low marginal production costs. This is because the firm can recapture those lost rents by offsetting the tax through the stock effects of becoming larger.

The size of reserves left in the ground under both Exploration Incentives and Inconsistent Policy is actually 24% and 20% smaller than BAU. This is due to the stock effects of nonrenewable resource production. Larger firms are better equipped to mitigate the negative impacts of a carbon tax than smaller firms through the impact of stock effects on marginal production costs. Yet this only results in 0.6% more lifetime profits and 1 additional year to produce for the larger firms. The big takeaway from this is that holding more reserves is a benefit under a carbon tax, not a negative, and positions the firm to profit slightly more on net than a smaller firm. This implies that Inconsistent Policy may actually position the firm to better absorb the tax.

A key policy implication of our result is that efforts to measure stranded assets created by carbon taxes must account for past policies that have incentivized exploration. Moving forward, government and inconsistent policy should be incorporated into the more sophisticated model structures such as [119] in order to more accurately measure the impact of carbon taxes on the size of stranded assets.

Chapter 3

Property Wealth Transfers, Convergence, and the Determinants of a City's Growth

Abstract

This paper studies growth and convergence across California cities after Proposition 13 normalized property tax rates and significantly reduced local government revenues while initiating a redistribution of wealth. Treatment is based on historical property tax rates and contained within county borders. This motivates two research questions. First, what are the determinants of growth in municipal revenues and expenditures? Second, do cities with lower initial property wealth grow more rapidly over time than those with higher initial wealth? This paper finds strong evidence of convergence across cities as measured by per capita property values. Moreover, I find little evidence that the transfer dampened the growth of household wealth in transfer cities. Digging into expenditure categories, I find significant variation in line item expenditure productivity. Investments that boost a city's core functionality induce strong growth while spending on services that may be better served by regional coordination strongly reduces growth. Increasing revenues spur growth when they do not inhibit the public's marginal propensity to consume while punitive revenue sources reduce it. Finally, the reduction of total revenues through proposition 13 resulted in smaller governments getting larger with larger governments shrinking even after cities returned to pre-treatment revenue totals.

3.1 Introduction

What drives growth? This question strikes at the heart of economics. Much focus has been spent on the growth of nations with several core, interlocking elements identified as necessary for long run growth. The development of a nation's stock of human capital drives gains in technology which increases efficiency which in turn can enable the development of human capital. This interplay of technology and human capital is a critical driver of growth due to technology's non-rival status complemented by its partial excludability through legal protections [103]. This implies a structural role for government in the determinants of growth.

Government policy can provide the institutional framework for clear and enforceable property rights, but must avoid rent-seeking to promote growth [4]. Efficiency is also critical.

Expenditures must be paid for by taxes which implies government spending may merely shift consumption away from the private sector [37]. Cities provide location-specific drivers of growth, but the characteristics of cities and their growth may be interrelated. Nice weather [96], a strong knowledge base [45], and higher quality of life amenities [111] are all correlated with stronger growth though likely confounded by each other. Agglomeration effects that have accrued in cities seem to lower transaction costs for both firms and labor [3], provide the opportunity to share inputs [69], and create the conditions under which external economies of scale induce spillover effects [54].

Public spending that leads to higher overall levels of educational attainment, life expectancy, and terms of trade while lowering fertility and infant mortality rates induce spillovers for productivity ([15] and [14]). Prior research on convergence at the city-level has shown some positive correlations between growth and total expenditures as well as spending on sanitation [44]. There is also strong evidence on convergence in per capita incomes across states and regions via differences in the rate of income growth based on initial levels [16].

This motivates the primary questions of this paper. First, what are the determinants of growth from the perspective of municipal spending? To study this, I exploit a landmark change in property tax policy in California in 1978 (Proposition 13) that normalized rates at 1%, restricted the property assessment process to an acquisition-based system, and capped yearly growth of rates at 2% per year when the property did not change hands. In addition to decreasing mobility ([86], [40], and [84]), Prop 13 altered local government revenue structures and increased homeowner tenure rates [74].

Second, using per capita property values, do convergence rates of wealth across cities follow the patterns in [44] and [13]? Specifically, do cities with higher initial per capita property values grow faster or slower than those with lower initial per capita values? As the introduction of proposition 13 initiated a transfer of wealth and increased household tenure rates ([86] and [40]), the ability to measure convergence as it is reflected in per capita property values (i.e. wealth) is unparalleled.

The property tax apportionment process is the policy mechanism that county governments use to distribute property tax revenues back to municipal governments to fund public services. It is a mechanism that incrementally extracts household wealth based on property values and redistributes it back to the community through a local government. As such, it is a potential mechanism for the redistribution of wealth overall.

This paper leverages a change in the apportionment process subsequent to the normalization of property tax rates in California under Proposition 13 in fiscal year (FY) $1978-79$. Prior to resetting every city's tax rate to 1% and restricting the future growth of rates to 2%, households faced rates that varied across city boundaries and could change at the whim of local governments' budget priorities each year. Not only did cities with historically high rates face the challenge of continuing to provide public goods to their constituents under a lower rate, but proposition 13 failed to consider its impacts on the apportionment process. Seeking a "do no harm" approach, the legislature decided that counties would collect taxes based on the new rate but use historical rates for apportionment. As cities with historical rates $< 1\%$ tended to be wealthier in terms of per capita property values with the opposite true for cities with historical rates $> 1\%$, this hastily made decision induced a transfer of wealth across municipal boundaries within the same county.

My model follows [44] and [13] with a simple OLS using per capita property values as dependent variable. To control for endogeneity, I transform per capita property into a 3 year forward moving average. Under this approach, this paper identifies strong evidence of convergence across cities. Specifically, the initially high premium in baseline per capita property values for wealthier cities shrank significantly compared to initially poorer cities. Because all cities in our study grew in nominal property values such that all cities grew in per capita terms, this convergence does not represent losses in wealth for any cities. This differs in how convergence results present in earlier papers where convergence is a function of income losses in richer areas that occur simultaneous to income gains in poorer areas. The convergence my paper presents is more of a "rising tides raise all boats" result. This is a key difference in my paper's results and is achieved using more granular government spending data.

Looking into the strategic decision-making of cities over line item revenues and expenditures, I find that expenditures that enhance a city's ability to provide for the basic functionality of municipal services (Public Works, General Government, and Public Safety) are more productive as measured by their impact on per capita property values while other services such as spending on local health initiatives reduce property values. Line item revenues that increase municipal budgets without impacting households' marginal propensity to consume increase household wealth while a city's increasing reliance on intergovernmental revenues significantly reduces per capita property values. Finally, increasing the collection of general taxes increases per capita property values.

I make four distinct contributions across a handful of research literature. This is the first paper to exploit the apportionment process subsequent to proposition 13 as an identification strategy to study the causal effect of municipal expenditures on growth. This was possible after I digitized a rich data set of expenditures and revenues by category, land valuations, and property tax rates from the annual California State Controller's Financial Transactions Concerning Cities and Counties covering fiscal years $1975 - 1993$. This paper joins a small body of research to use dis-aggregated data at the municipal level to study growth. Second, as a result of the data contribution, this paper affirms prior results on the convergence of cities, i.e. that wealth in poorer cities does catch up to the wealth of richer cities over time. Third, while a great deal of research looks at the effect of government expenditures and revenues on growth, the dominant approach is to leverage state boundaries as an identification strategy and deploy aggregated data.

My identification strategy is a treatment occurring within the top 10 most populous counties in the state of California using departmental (line item) expenditures and revenues. This presents the distinct advantage of leveraging a large number of cities (215) unaffected by confounding variations in state policy across differentiated economies. Finally, my paper also adds to the literature studying proposition 13 effects through the use of more granular data to determine how cities strategically prioritized the funding of government and deployed scarce investment dollars into the community.

The rest of this paper is structured as follows. Section 2 discusses the paper's identification strategy and section 3 presents a brief literature review. Section 4 summarizes the results of the model while section 5 delves into the data sources and study area. Section

6 outlines the model and key assumptions with section 7 providing the in-depth analysis. Section 9 presents the conclusion.

3.2 Identification

Key to this paper is the failure of Prop 13 to define the apportionment rates by which counties would distribute property revenues owed to municipalities to fund public services. The resulting flows of tax revenues shifted wealth out of households in cities with historically low rates into municipal coffers with historically high rates. Treatment is contained within counties. The identification of a clear shift in municipal revenues motivates a second research question. Using per capita property valuations as an indicator of wealth, does convergence across cities occur as found in [44] and [13]? Specifically, do cities with higher initial per capita property values grow slower than those with lower initial per capita values?

The property tax assessment and apportionment process is fairly straightforward. County assessors in California estimate the value of each property within their jurisdiction and then the county tax collector collects the taxes on each parcel based on the current tax rates. Prior to Prop 13, cities in California determined their own rates and could initiate changes each year at their discretion.

The county collected those revenues, kept any revenues attached to a separate county property tax rate, and returned revenues (apportionment) to each city based on the heterogeneous municipal rates that fiscal year. By normalizing all property tax rates to 1%, Prop 13 created a scenario where the apportionment process would be insufficient to fund the continuation of public services in cities with historical rates $> 1\%$.

Assembly bill (AB) 8 was the legislature's well-intentioned solution. It mandated the use of historical tax rates as the basis for apportionment. Taken together, prop 13 normalized tax rates for every city while AB 8 preserved the old apportionment process. This initiated a wealth transfer whose underlying mechanism is visualized in figure 3.3. This shows the apportionment process before prop 13/AB 8 (left) as one where city residents paid the county tax collector an amount based on the local tax rate and their city government received a proportional amount to provide city services.

When Proposition 13 normalized every household's tax rate to 1%, this increased tax bills in households with pre-Prop 13 rates $< 1\%$ and lowered bills where rates had been $> 1\%$. The state's solution to fix the apportionment process was that counties would simply use each city's average property tax rate from the 3 years prior as apportionment rates.

Because households all paid 1% rates under Prop 13 while their local municipality received apportionment funds based on historical rates, cities with historical rates $> 1\%$ (receiving cities) received relatively more in the apportionment process than their households paid into the system with the opposite occurring for cities with historical rates $< 1\%$ (transfer cities). As such, a transfer of wealth occurred, however Figure 2 (below) shows that both transfer and receiving cities clearly lost tax revenues as a result of the changes initiated by Prop 13.

Figure 3.3 shows the trends in tax revenues collected pre and post the passage of Prop 13. Note there is a distinct break because of Prop 13 whereupon the average city dropped precipitously and did not return to their pre-Prop 13 levels until $1984-85$, six years after the introduction of tax reform. Proposition 13 clearly altered the trajectory of local government revenues at the city-level and provides an opportunity to measure the causal impacts of city expenditures on growth. Simultaneously, the tax apportionment process initiated a transfer of wealth providing the opportunity to leverage this more granular data to attempt to confirm the findings on city-level convergence of growth from [44] and [13]. Specifically, do poorer cities catch up to wealthier cities over time?

There was little cities could do to alter this change in the apportionment process despite the fact that the most important revenue source for local governments had been cut in half [72]. Proposition 13 had also established a common rate of increase for all property tax rates in the state constitution, significantly limiting city governments' ability to compensate for the losses while the 3 weeks the legislature took to write and pass AB 8 did not allow for legislative gaming by cities. To further limit gamesmanship, AB 8 defined the historical tax rates as the three year historical average in FY $1975-76$ to $1977-78$.

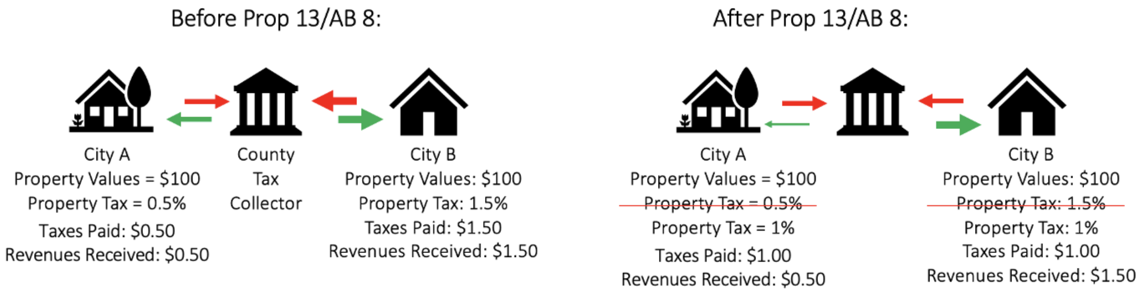


Figure 3.1: Changes in California's Property Tax Apportionment Process

3.3 Literature Review

Analysis shows proposition 13 immediately and intentionally limited tax growth at the municipal level though debate exists over its long run efficacy. With average taxes declining from \$11.21 per \$100 of assessment value $(1976-77)$ to \$4.69 $(1979-1980)$ [28], local governments raised revenues from non-tax sources (fees and charges) as well as sales tax ([56] and [66]). [42] finds evidence that cities fully compensated for lost property taxes from alternative revenue sources though [29] argues that the growth rate of total per capita revenues and expenditures declined. [98] finds total per capita expenditures and revenues remain constant after cities replace lost revenues with charges. Overall, taxpayer burdens declined statewide after proposition 13 [110] and limited overall municipal revenues [77] though perhaps less than promised [78].

The choices cities made over how to spend these limited funds are attractive conditions for identifying the determinants of growth from municipal expenditures. Scant consensus exists in the literature with some agreement that there are negative correlations between municipal expenditures and growth. One problem may be that trying to apply 'lessons learned' from studying one state or local government does not provide insight into other states or local governments. Or even the same city 20 years later. The impacts of local fiscal policies might just be location, time, or context-specific [101].

[101]'s rigorous survey presents no clear outcome on the impact of state/local taxation or spending on growth, though general 'rules of thumb' seem to exist. First, aggregate taxation at the state-level does not drive differences in growth across US states. Second, studies of tax policy's impact on growth are highly influenced by empirical strategies that underweight the process of identification. Third, studies of state-level taxes and expenditures present contradictory results of varying significance while studies on spending data are often narrowly focused on a couple of categories. Fourth, tax burdens have changed significantly over time while state-level tax policy has become more homogenous making studies across states less insightful across long periods of time. Fifth, state level dynamics do not occur in isolation and their analysis should consider neighboring state, national, and international

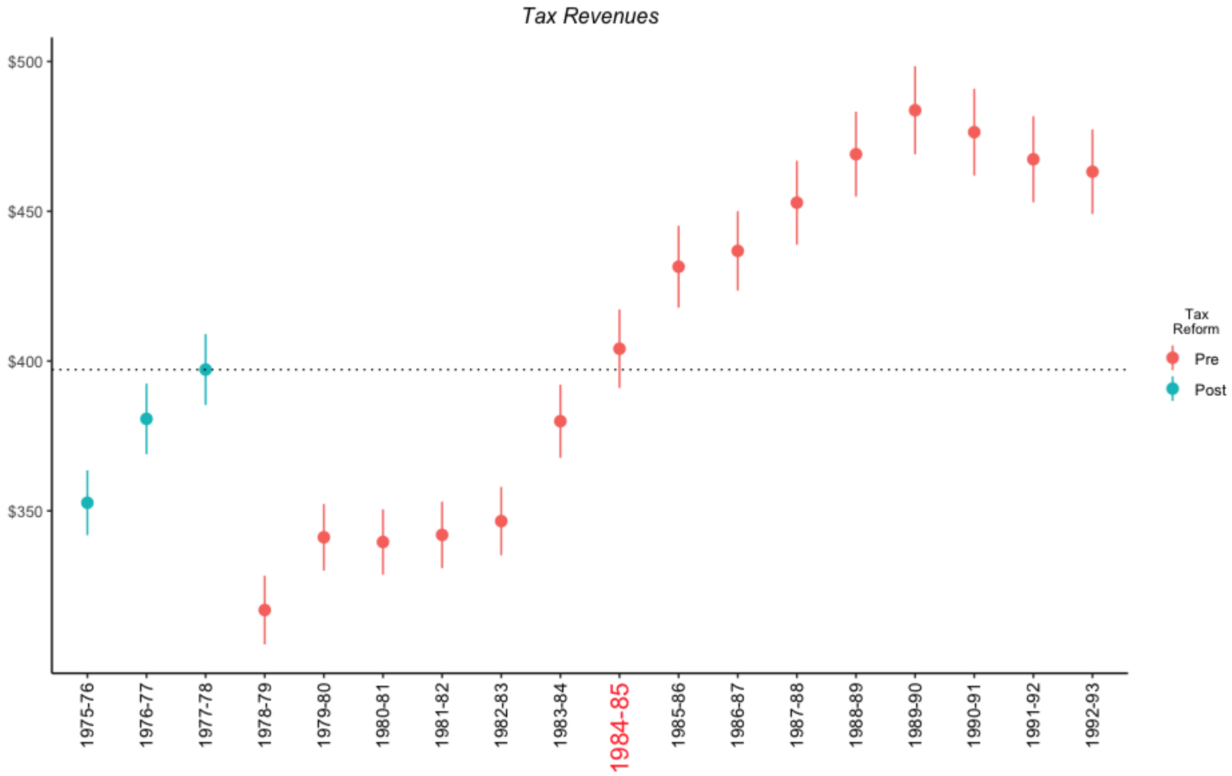


Figure 3.2: Changes in Per Capita Tax Revenues for All Cities After Proposition 13

economic dynamics occurring simultaneously. Finally, there is no universal, one-size fits all tax or expenditure policy tied to growth.

Where studies covered in the survey do hone in on identification with local data, most have exploited unexpected state policy changes to explore the impact of local spending across border counties. [101] points out the fallibility of this approach. Most critically, it is challenging to apply insights garnered along state borders to inform statewide policies as border counties do not typically contain either state's largest cities and are therefore, not representative.

There exists a wealth of literature on the effects of Prop 13 and this paper will only mention those that deal with growth. Looking at firm activity, proposition 13 was fairly good for growth. Reducing property tax rates by 1% was correlated with increases in the number of retail and service firms by 6% and a 9% rise in overall employment with payroll increases of 15% [123]. No response was detected in the manufacturing sector. At the same time, public sector employment and wage growth declined [94]. Taken together, these impacts on government size, overall employment, and total per capita revenues suggest distortive consumption spending by government may have decreased after proposition 13 while remaining expenditures skewed more productive.

3.4 Data

I digitized data from the Annual Report of Financial Transactions Concerning Cities of California covering the fiscal years $1975-76$ through $1992-93$. Issued by the California State Controller, it provides tables of data detailing municipal revenues and expenditures as well as city-level property assessment information for all cities within California[1]. This dataset covers California's 10 largest counties though coverage can be expanded with more effort. For now, the dataset includes Alameda, Contra Costa, Los Angeles, Orange, Riverside,

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[1] This onerous process took approximately $1,000+$ hours as the source materials presented significant challenges to automation and time constraints drove choices in defining our study set.

San Bernardino, San Diego, San Mateo, Santa Clara, and Ventura counties. All analysis is conducted in per capita real terms with 2019 as the baseline year.

I use historical property tax rates to identify the pathway of property tax revenues between cities of each county and estimate the impact of seven expenditure categories (General Government, Public Safety, Public Works, Health, Parks and Recreation, Libraries, Other) and seven revenue categories (Taxes, Licenses and Permits, Fines and Penalties, Money and Property, Intergovernmental Transfers, Service Charges, Other) on growth. Growth is measured in per capita property values and represents household wealth.

Following AB 8, I establish a three-year average of the fiscal years 1975−76 through 1977−78 to establish a baseline of city level expenditures and revenues as well as the property tax rates that underpinned the apportionment process enacted after the passage of proposition 13[2]. Additional data on Nominal and Real GDP as well as total state population in California was collected from the St. Louis Federal Reserve (FRED) website in order to establish 2019 as the baseline year for real values. Historical city-level populations were retrieved from the California State Association of Counties while state-level GDP was retrieved from the Bureau of Economic Analysis.

3.4.1 Study Area

Figure 3.3 maps out the counties within our study area. At the time of Prop 13's passage, our study area comprised 59% of California's total population. City-level expenditures and revenues in our study area totalled $\$15,034,499,594$ and $\$15,749,271,812$ in FY $1978-79$ which was 1.8% and 1.9% of the state's total \$824.7 billion GDP that year. California is quite large and is generally considered to be broken into 12 regions based on variations in geographic features, climate, and culture. The counties in our study area are the largest by population and represent four of these regions. Contra Costa, Alameda, Santa Clara, and San Mateo Counties are located in the Bay Area while Ventura and Santa Cruz counties

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[2] A format change in 1981 required the development of a strategy to reconcile the data. Please see the appendix for details on that process and details regarding the paper's treatment of cities formed just before and after the passage of proposition 13.

are considered the Central Coast. San Bernardino and Riverside counties are considered the Desert region while Los Angeles, Orange, and San Diego counties are Southern California. The current study area does not cover the North Coast, Sacramento Valley, Shasta Cascades, Gold Country, Sierra Nevada, or the San Joaquin Valley regions. However, the four regions that are covered are broadly representative of the demographic and economic characteristics of the entire state.

3.4.2 Removed Cities

A total of 49 cities were removed from our study area due to one of three reasons. Most of these cities were removed because they were either formed after the passage of Prop 13 (during the study period) so they were not subject to the transfer of wealth and apportionment process under AB 8 or they formed during the baseline years of $1975-76$ to $1977-78$ when apportionment rates were estimated. This includes forty cities that were formed after Prop 13 and five (La Cañada-Flintridge, Lancaster, Rancho Cucamonga, Lemon Grove, and La Habra Heights) that were incorporated during the baseline years.

Beyond the timing of city formation, several cities' primary function is not to serve residents and/or their population is artificially limited by city policy. This distorts their per capita property values. One situation arose in accounting for industrial havens within the county of Los Angeles. Vernon, CA is a small industrial haven formed within the boundaries of the city of Los Angeles that has a high concentration of business activity and a very small population ranging 85 to 150 over the study period with property values in the tens of millions. A similar issue was revealed with the cities of Industry and Irwindale. These two cities are also industrial havens just east of the city of Los Angeles. Finally, Colma is a city southeast of San Francisco in San Mateo County and is widely known as a ”cemetery city” for its policy priority to leverage open space for the siting of cemeteries. As such, it has over $1,000$ graves per resident and accompanying per capita property values are distorted.

Top 10 Most Populous
Counties in 1977-78

NorCal	Population	Property Values (Per capita)
Alameda	979,320	$7,232
Contra Costa	428,630	$5,936
San Mateo	511,460	$6,824
Santa Clara	1,094,205	$6,203

SoCal	Population	Property Values (Per capita)
Los Angeles	6,195,990	$6,405
Orange	1,481,425	$7,894
Riverside	346,840	$6,017
San Bernardino	436,640	$2,486
San Diego	1,283,330	$6,323
Ventura	377,225	$3,677

Share of California: 59%

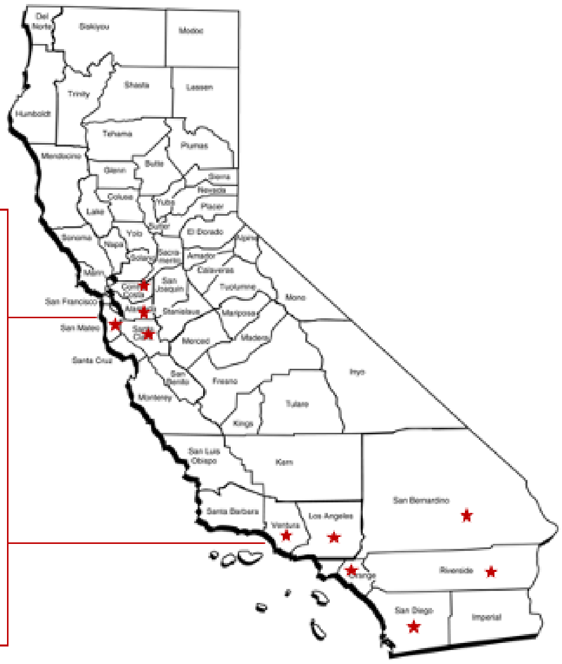


Figure 3.3: Study Area

After removing these cities, our study area consisted of 58 cities with historical property tax rates of less than 1%, 153 cities with rates higher than 1%, and 4 cities with rates equal to 1%. Also included is the integrated city-county government of San Francisco which consists of a city that is also the county. Its historical tax rates are over 7%, but it is included alongside cities with a tax rate equal to one percent as there is no change in apportionment given its integrated status.

3.5 The Model

Following earlier research on local growth ([44] and [13]), my model is a straightforward linear regression. Our measure of growth is per capita property values $PropValue_{it}$ for city i at time t. Cities i with historical property tax rates $\tau < 1\%$ are indicated by the variable $Transfer_{it}$ and cities i with historical $\tau > 1\%$ are indicated by $Receive_{it}$. Following [115] and [44], I use real per capita expenditures exp_{ijt} with j line items and revenues rev_{ikt} with k line items as independent variables. The per capita terms control for variations in demand for government services based on varying population totals.

$$\begin{aligned} PropValues_{it} = \beta_0 + \beta_1 \sum_{i=1}^{58} Transfer_{it} + \beta_2 \sum_{i=1}^{153} Receive_{it} + \\ \beta_3 \sum_{i=1}^{215} \sum_{j=1}^{8} exp_{ijt} + \beta_4 \sum_{i=1}^{215} \sum_{k=1}^{8} rev_{ikt} + \\ \beta_5 \sum_{i=1}^{215} FA_{it} + \beta_6 \sum_{i=1}^{215} FD_{it} + \beta_7 \sum_{i=1}^{215} Recession_t + \\ \beta_8 \sum_{m=1}^{10} NewGovSize_{mt} + \beta_9 CAGDP_t + \epsilon_{it} \end{aligned} \quad (1)$$

To control for endogeneity of government spending and reverse causality, this model uses a 3 year forward moving average for $PropValue_{it}$. This is informed by the use of a 5 year forward moving average in [37] and [108]. I reduce the forward moving average to 3 years to parallel the policy choices made under AB 8. Recall that AB 8 is the legislation that re-established the apportionment process subsequent to proposition 13. That bill established the baseline property values and tax rates for apportionment by using the 3 year average of fiscal years $1975-76$ through $1977-78$. To parallel that decision, I chose a 3 year forward moving average.

In either case, incorporating a forward moving average of $t+1$ through $t+3$ implies that reverse causality would only hold if governments were forward-thinking enough to spend money today in anticipation of accommodating for up to three year's worth of economic turbulence. This introduces serial correlation in the error terms which I account for by employing White's robust standard errors as outlined in previous research ([13] and [115]).

All values are expressed in terms of 2019 US dollars with expenditures and revenues scaled to $\$100s$ of dollars. Following AB 8, tax rates and property values are formed in that baseline year as the three year average covering $1975-76$, $1976-77$, and $1977-78$ to establish the direction of property value transfer which leaves us with $i=58$ for $Transfer_{it}$ and $i=153$ for $Receive_{it}$.

Equation 1 also includes several controls. Fiscal alignment FA_{it} is a ratio of Total Expenditures to Total Revenues. This controls for the level of alignment between a city's revenues collected and expenditures made while fiscal decentralization FD_{it} is the ratio of Intergovernmental Transfers received to Total Revenues collected. FD_{it} helps account for a city's lack of control over the portion of its revenues that may be predetermined by a higher level of government (state, federal) as a condition of their receipt.

Additionally, the equation also includes $NewGovSize_{mt}$ which is the Total Expenditures of excluded cities aggregated at the county-level - also presented as a ratio of that total relative to the statewide GDP. $Recession_t$ accounts for years in which the Federal Reserve identify the overall US economy as in a recession. Finally, $CAGDP_t$ accounts for per capita GDP at the state level.

While the data covers FY $1975-76$ through $1992-93$, the first three years are used to establish the baseline for FY $1977-78$ to identify the flow of property tax revenue transfers starting in FY $1978-79$. A format change in $1981-82$ demanded a rigorous effort to synchronize data across the format change. A discussion of this is included in the appendix. While synchronizing changes in the reporting of line item expenditures and revenues was successful, fundamental changes in how cities reported property values upended the effort to synchronize that data. The use of the 3 year forward moving average for expenditures and revenues limited the study period on the end as well. These issues and choices resulted in establishing a study period spanning the ten years of FY $1981-82$ through $1990-91$ for the regression analysis though this paper does use FY $1977-78$ through $1992-93$ for visualizing how cities chose to prioritize line item expenditures and revenues in their reported budgets.

3.5.1 Key Assumptions

This paper makes three key assumptions. First, cities have the option to contract with the county to provide constituent services like Public Safety, Libraries, or Education instead of providing them at the city-level. This paper assumes the quality of those services to be identical and the impact on growth by these services is assumed to be unrelated to what agency provides them. Second, this paper assumes minimal effects of population movements within counties due to the incentives of longer housing tenure under Proposition 13.

Prior to Proposition 13, changes in year over year property values could significantly change the size of a household's tax bill. Homeowners seeking lower bills could relocate to a lower tax city within the same county without affecting their employment status. By normalizing rates and establishing a common rate of growth, Proposition 13 made California an acquisition-value system which favors home ownership by residents with lower frequency moving preferences [86]. Research shows strong evidence of this lock-in effect [40] and decreased household moves in California by 3.3% while pushing overall housing prices up as much as 15% [41] with gains largest in coastal cities [121].

Finally, this paper does not consider expenditures on education as a driver of city-level growth. State legislature responses to declines in county and municipal revenues subsequent to Proposition 13 effectively transferred responsibility for funding schools to the state [31].

This shift in funding burdens to the state arguably increases the ability of this paper to identify which city-level expenditures foster growth.

3.6 Summary of Results

Using per capita property values as a metric of household wealth and measuring convergence as the change in each city's per capita property values relative to their county median, this paper finds strong evidence of convergence between wealthier and poorer cities over the study period as outlined later in Figure 7. In per capita terms, wealthier/transfer cities saw their per capita property values decline relative to county medians while poorer cities maintained their standing. Because county medians increased by $30 - 58\%$, this indicates that the relative decline in wealthier city's per capita property values is the result of convergence. This confirms findings by [44] and [13] and is strong evidence that the geo-spatial transfer of wealth based on property values does not harm the growth of wealth in transfer households.

When focusing strictly on the impact of the transfers on property values, there is strong evidence that the transfer of property tax revenues resulted in higher per capita property values for transfer cities, but mixed evidence on the impact for receiving cities. This is likely due to the fact that the cumulative impact of the transfer is rooted in the choices governments made when facing these overall declines in revenues. That is to say that transferring property tax revenues out of historically low cities forced those local governments to prioritize government spending with scarcer resources and identify alternative sources of funding after proposition 13. That said, this paper finds that transferring property tax revenues out of wealthier cities resulted in an estimated growth in per capita property values of $\$18,276 - \$71,135$ with all estimates statistically significant at the highest level.

Per capita property vales are estimated to have grown in receiving cities by $\$3,602 - \$23,397$ as a result of the transfer if controlling for expenditures with only the highest estimate statistically significant (with $p < 0.01$), but property values are found to *decrease* by $\$15,407 - \$18,540$ when controlling for line item revenues with all estimates significant ($p < 0.001$).

The mixed findings for receiving cities indicate that changes in wealth were not directly impacted by the transfer of property tax revenues. Logically, this makes sense as transfers were directed through the recipient municipality. The direct cause would be the strategic decision-making that occurred in response to the change in property tax revenues. However, looking at total property values (not per capita) reveals that both city types saw strong growth in overall property values with the poorer/receiving cities outpacing wealthier/transfer cities at the median (80.5% versus 74.8%).

I find strong evidence that line item expenditures and revenues differ in productivity. Raising Total Expenditures by \$100 per capita increases per capita property values by $\$5,964 - \$6,117$ with $p < 0.01$. Breaking that down by line items, the modeling finds that a 00 per capita investment in General Government increases per capita property values by $\$15,733 - \$18,143$ ($p < 0.01$). The same investment in Public Safety raises them by $\$2,262 - \$5,409$ with Public Works expenditures increasing values by $\$2,105 - \$3,620$, both across varying levels of significance. All three are indicative of a city's effort to provide basic services to household and business constituents which may lend to their innate productivity. Conversely, expenditures on Health, Libraries, and 'Other' expenditures *decrease* per capita property values by $\$38,096 - \$43,603$, $\$9,707 - \$10,290$, and $\$7,035 - \$8,286$ respectively. This likely reflects the long run nature of health and library investments that are more likely to accrue systemically. The scattershot focus of spending that falls into the generic Other category makes it prone to scattershot results. The other line item expenditures (Parks and Recreation) were mixed in sign and not statistically significant for any estimate.

Looking at our line item revenues, the productivity of revenues appears to be driven by their potential impact on households' marginal propensity to consume. Increasing revenues by \$100 per capita from Money and Property or Licenses and Penalties increases per capita property values by $\$26,480 - \$27,922$ and $\$14,251 - \$19,232$. This paper treats revenues accrued from Licenses and Permits as a signal for the overall direction of the local economy with Money and Property revenues an innately productive source of revenue as it extracts extra value from already existing public investments. I find that increasing revenues from Taxes and Service Charges by \$100 increase per capita property values by $\$10,655 - \$14,505$

and $\$4,122 - \$8,503$ with nearly all estimates statistically significant with $p < 0.05$. Note that each of these activities increases revenues without harming the private sector's marginal propensity to consume (MPC).

However, raising revenues from sources that would harm MPC such as Fines and Penalties are estimated to reduce per capita property values by $\$28,423 - \$43,861$ for every \$100 per capita increase with $p < 0.01$. I also find that increasing local government's reliance on Intergovernmental Transfers by \$100 *reduces* per capita property values by $\$26,449 - \$27,992$ at the 1% level of significance. These transfers can come with strings attached or specific targets that are not in synch with local needs and that may be the reason they are counterproductive.

Looking at the actual budget choices transfer and receiving cities made during the study period over expenditures and revenues, they took similar paths with key exceptions. Both prioritized the more productive expenditures such as Public Works and Public Safety while de-prioritizing investments on less productive expenditures such as Health, Libraries, and the Other category. Priorities deviated in the growth of general government expenditures with transfer cities increasing these investments by 8% at the median while receiving cities *decreased* them by 28%. Note that this line item is estimated to increase returns to property values. They also differentiated in their prioritization over Parks and Recreation with transfer cities increasing these investments by 45% while receiving cities remained relatively flat.

Both cities increased overall revenues with transfer cities more than doubling the pace of receiving cities. The primary driver of overall revenue growth in both cities came from three categories: Money and Property, Service Charges, and Taxes which are estimated to be far more productive than other line items. Both decreased their reliance on the least productive revenues (Intergovernmental Transfers, Fines and Penalties). They differed over Licenses and Permits as well as Other revenues with transfer cities *increasing* revenues from Licenses and Permits by 19% and receiving cities *decreasing* by 4% which implies stronger business formation and private sector activity in transfer cities or an increase in regulations. Transfer cities slightly reduced revenues from the Other category while receiving cities slightly increased.

3.7 Analysis

This paper uses changes in per capita property values as a proxy for wealth and growth. We begin with a consideration of line item revenues and expenditures as they evolved over the study period from a baseline three fiscal years prior to the passage of proposition 13.

3.7.1 Exploratory Data Analysis

Figure ?? is the first of several graphs depicting the evolution of revenues and expenditures spanning fiscal years $1975 - 76$ through $1992 - 93$. The first three years ($1975 - 76$ to $1977 - 78$) before the introduction of Prop 13 and property tax reform are depicted in green while the years ex post reform are depicted in red. Each row of graphs presents one line item expenditure or revenue with the far left column presenting the aggregate data for all cities in our study. The middle row shows trends in transfer cities and the far right column shows trends in receiving cities.

The dotted black line intersecting the y-axis indicates the revenue or expenditure total in the year prior to Prop 13. The year when each line item revenue or expenditure returned to its pre-Prop 13 level is indicated in red on the x-axis.

Figure 3.4 shows that total revenues and tax revenues declined precipitously after proposition 13. On average, most cities recovered to their pre-Prop 13 total revenues collected by fiscal year $1981-82$, but the impact on transfer vs. receiving cities varies. Transfer cities faced less of a decline in total revenues collected from Prop 13 because their pre-Prop 13 property tax rates were lower than 1%. This is supported by the difference in tax revenues collected where transfer cities returned to pre-prop 13 levels in FY $1983 - 84$ whereas cities receiving transfers failed to recover until the next fiscal year (FY $1984 - 85$). The difference in "time to recovery" is notable as is the clarity of treatment effects on cities based on how apportionment changed. Despite having historically higher property taxes, cities receiving property tax transfers after proposition 13 were more intensely affected by lost tax revenues than transfer cities.

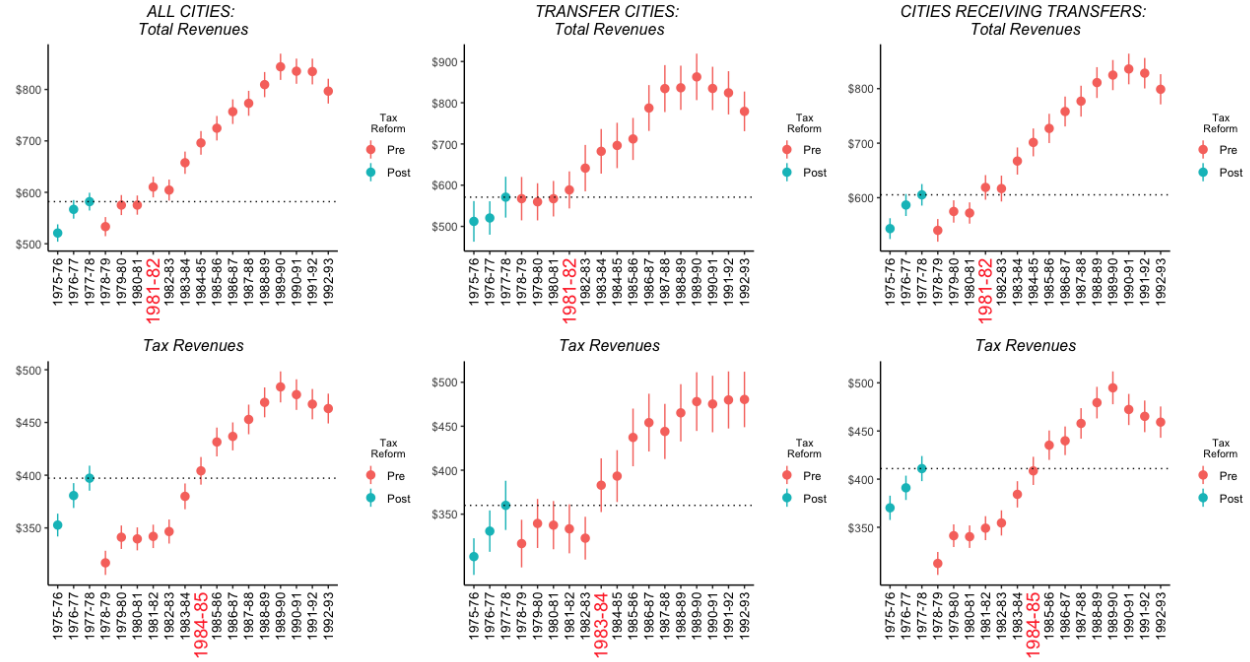


Figure 3.4: Changes in Total Revenues and Taxes Collected: Pre-Treatment (1975-76 to 1977-78) and Post-Treatment (1978-79 to 1992-93)

Not only did transfer cities recover more quickly, they ended up with higher per capita total revenues and taxes collected on average than cities receiving transfers. This is despite the fact that cities receiving transfers entered the study period in $1977-78$ with higher pre-Prop 13 levels in both categories. All told, we observe that total revenues recovered more quickly than tax revenues for both city types which indicates that cities strategically raised revenues by means other than taxes.

Figure 3.5 depicts the trends in city revenues from money and property as well as service charges. In both cases, cities increased their reliance on collecting revenues from these sources which was a driving force in filling the gap in lost tax revenues. Interestingly, transfer cities collected more revenues from money and property than receiving cities in the pre-Prop 13 era though both city types ended up with around \$55 in per capita revenues from this line item by the end of our study period. In neither case did the average city return to pre-Prop 13 levels.

Cities receiving transfers collected about \$5 more per capita in service charges than transfer cities at the start of our study period and maintained that edge to end up collecting just a bit more than \$150 per capita while transfer cities collected just above \$125 per capita in our final fiscal year. Where cities receiving transfers steadily increased their service charge revenues and never returned to pre-Prop 13 levels (on average), transfer cities initially saw service charge revenues drop below pre-treatment levels before returning to trend in fiscal year $1981-82$.

Additional graphs detailing the trends in revenues collected for fines and penalties as well as intergovernmental transfers are included in the appendix. In both cases, transfer and receiving cities saw declines in these line item revenues. Intergovernmental transfer dropped precipitously after Prop 13 which was an obvious result of the tax reform itself. Revenues collected from fines and penalties remained stable for both city types with both collecting around $\$14-\$16$ each year in per capita terms until the start of the $1990s$ where these revenues declined. The reasons for this drop-off are unclear and likely due to some shift in policy unrelated to the introduction of Prop 13. As such, both graphs are left in the appendix.

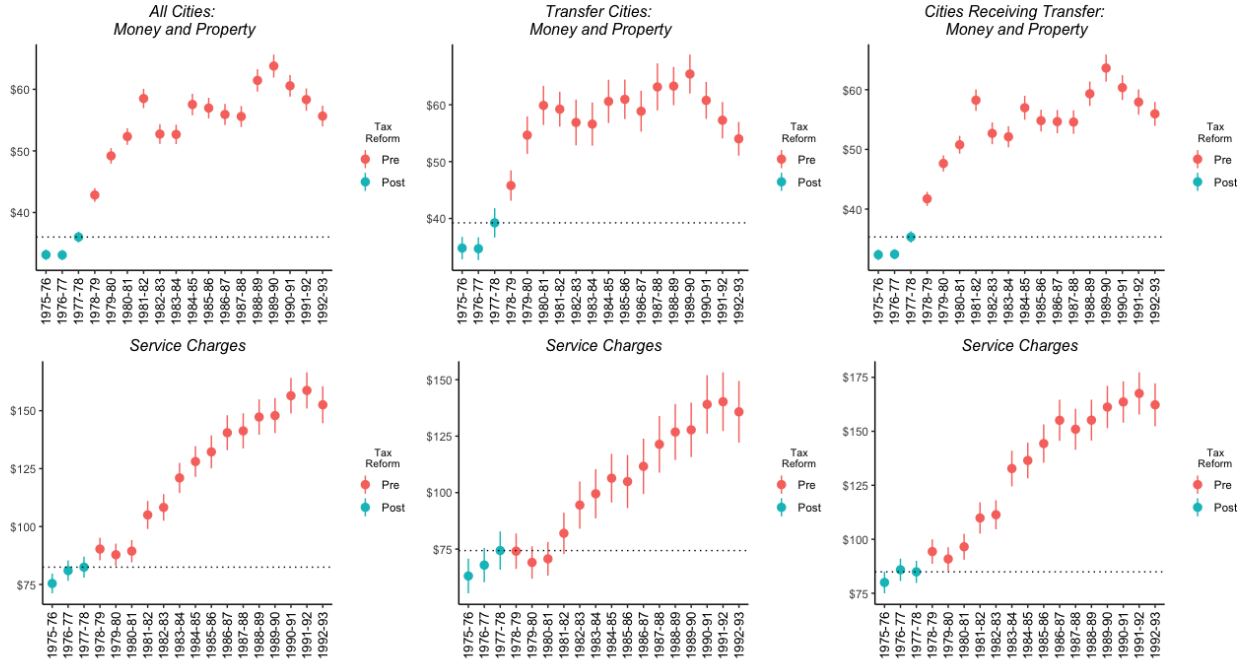


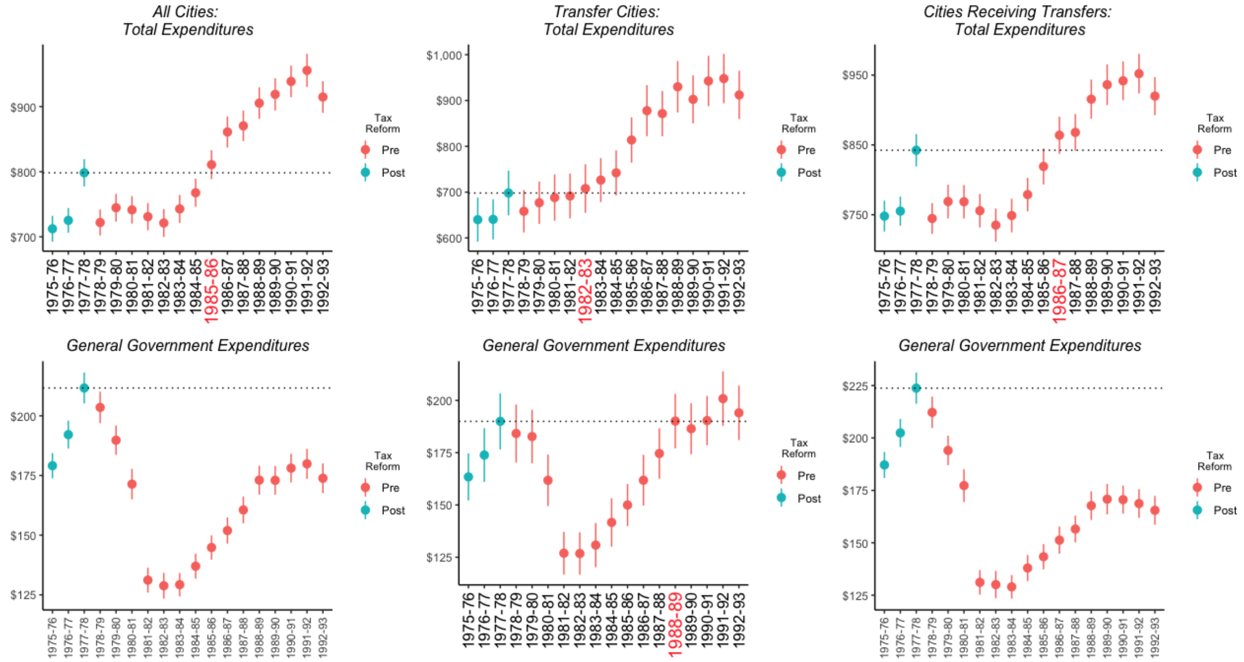
Figure 3.5: Changes in Revenues from Money and Property as well as Service Charges: Pre-Treatment (1975-76 to 1977-78) and Post-Treatment (1978-79 to 1992-93)

Figure 3.6 details total expenditures and general government expenditures. All cities immediately decreased spending by an average of almost $100 per capita after the implementation of Prop 13 with the average city returning to pre-Prop 13 levels in FY 1985 − 86.

With a leaner government prior to Prop 13, transfer cities took less of a hit here with total expenditures fell by about $30 per capita while receiving cities declined $100, on average. The timing of recovery for each city type varied a lot with transfer cities returning to pre-treatment total spending by FY 1982 − 83 (just one year after seeing their total revenues recover in figure 4) while cities receiving transfers didn't return to pre-Prop 13 total spending until FY 1986 − 87 (five fiscal years after total revenue collection recovered in figure 4). Both city-types delay returning to pre-treatment their total expenditures until after they saw a total recovery to their tax revenues implying that local governments prefer the consistency of taxes collected over line items that may be more likely to see year over year fluctuations like service charges as well as revenues from money and property.

Interestingly, while cities receiving transfers do not return to pre-Prop 13 levels of general government spending over the study period, transfer cities do so by FY 1988 − 89. By 1992 − 93, transfer cities are spending an average of $185 − 190 per capita on general government which is just about the same as they were entering into the study period while cities receiving transfers are spending around $170 per capita on average. This represents a decline of about 25% in the size of government for receiving cities while their total expenditures actually increased over the study period. This indicates that some right-sizing of local government may have occurred in cities with historically high property taxes.

Figure 3.7 illustrates a fascinating trend where all cities engaged in significant and sustained efforts to increase spending on public works projects and public safety measures. As we will see later in our analysis, most cities saw significant population increases over this time which may imply the existence of the reverse causality this paper addresses in its analysis. That said, the average city overall started off spending around $190 − $200 per capita on public works projects, briefly dropped below that level after the implementation of Prop 13 and returned to pre-treatment levels immediately after in FY 1978 − 79. This


All Cities: Total Expenditures

Transfer Cities: Total Expenditures

Cities Receiving Transfers: Total Expenditures

General Government Expenditures

General Government Expenditures

General Government Expenditures

Figure 3.6: Changes in Total Expenditures and General Government Expenditures: Pre-Treatment (1975-76 to 1977-78) and Post-Treatment (1978-79 to 1992-93)

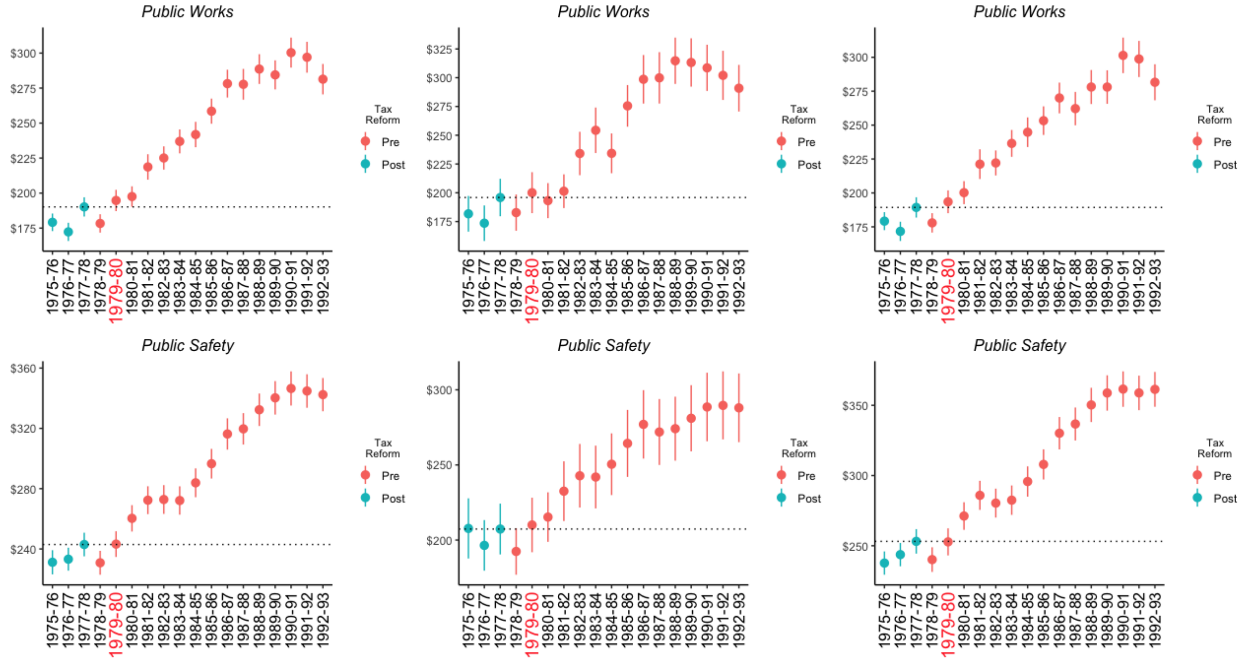


Figure 3.7: Changes in Public Works and Public Safety Expenditures: Pre-Treatment (1975-76 to 1977-78) and Post-Treatment (1978-79 to 1992-93)

indicates strong preferences for maintaining the day-to-day functionality of a city. Both city-types increased investments over the study period until around FY $1990-91$ when spending apparently leveled off during a recession.

A similar trend appears in public safety spending though historically higher tax cities (receiving cities) enter into the study period spending about $30 more per capita and end the study period spending about $75 more per capita. That isn't to say that either city skimped on these investments. Again, most cities immediately decreased per capita spending after Prop 13 and returned to pre-treatment levels the next fiscal year. This marked a period of sustained increases in investments into public safety with most cities steadily investing more each year into these efforts.

3.7.2 Convergence

Figure 3.8 displays changes in per capita property values (left) and population (right) for each city relative to the median of all cities within the same county. We look at population for context. Change is measured by comparing the relative values in the baseline year $(1977-78)$ to the relative value in the final year $(1992-93)$. Note that cities transferring revenues (tax rates $> 1\%$) are displayed in red while cities receiving transfers (tax rates $> 1\%$) are displayed in green.

It is clear that at the median, cities transferring revenues were wealthier in terms of per capita property values at the beginning of the study and this advantage dissipated over the study period. It is less clear upon first glance whether the households in cities receiving the property tax revenue transfers increased household wealth as measured by per capita property values. The evidence for convergence is more obvious when we consider the overall change in per capita property values at the county level in table 3.1.

Every county grew in term's of per capita property values by a range of $30-51\%$. This implies that while figure 8 appears to show that transfer cities declined in per capita property values, the decline is not a nominal decline but a decline relative to the county median. Table 1 shows strong overall growth of property values for all cities implying that progress towards convergence was achieved. Note that cities receiving transfers started off larger in terms of population and grew larger in terms of population over the study period. Taking population growth into consideration alongside per capita property values reveals that cities receiving transfers experienced strong growth overall.

While it is not clear based on this data whether the revenues transferred into receiving cities directly resulted in increases to household wealth, it is clear that the transfer of wealth out of cities did not prevent the continued growth of household wealth throughout the study period. From this perspective, the mechanism of property tax apportionment is a valid policy instrument option for governments that want to geospatially transfer household wealth.

The following analysis of multivariate least squares regressions is broken down into two sub-sections with the first focused on expenditures followed by revenues. Line item expenditures are considered separately from revenues due to post-regression analysis of multicollinearity when they were included together. This results in four modeling approaches with six different specifications for each model to total 12 model specifications in all.

The purpose of presenting 12 model specifications is to consider whether our results from any one specification are a function of the specification rather than the underlying result. Additionally, providing multiple specifications provides insight into the range of magnitude of impact on growth that our line item expenditures and revenues provide versus their impact as aggregate totals.

3.7.3 The Impact of Expenditures on Growth

This discussion on the impact of expenditures on growth is broken into two sections. First, I consider the estimated impact of per capita property values followed by a summary of which line item expenditures that transfer and receiving cities actually chose to prioritize.

Table 3.2 displays results from Models $1 - 6$. The dependent variable is per capita property values $PropValues_{it}$ at the city level i in year t. Model 1 regresses $PropValues_{it}$ on cities transferring revenues $Transfer_{it}$, cities receiving revenues $Receive_{it}$, as well as our line item expenditures. General Government expenditures include administration and

Figure 3.8: Evidence of Convergence in Per Capita Wealth: Comparing 1977-78 and 1992-93

Table 3.1: Changes in Per Capita Property Values at the County Level

County	1981 − 82	1992 − 93	%*Change*
Contra Costa	$77,541	$108,647	+40%
Los Angeles	$68,897	$95,309	+38%
Riverside	$81,886	$100,378	+30%
San Mateo	$93,374	$135,872	+46%
Ventura	$73,840	$98,423	+33%
Santa Clara	$85,308	$128,719	+51%
San Bernardino	$55,481	$75,542	+36%
Orange	$84,861	$115,388	+36%
San Diego	$68,909	$92,390	+34%
Alameda	$65,503	$98,955	+51%
San Francisco*	$86,278	$136,619	+58%

$\hat{*}$*San Francisco is a consolidated city - county*

Table 3.2: Per Capita Property Values and Line Item Expenditures

	(Model 1)	(Model 2)	(Model 3)	(Model 4)	(Model 5)	(Model 6)
Cities Transferring Revenues	\$49,907***	\$49,608***	\$71,135***			
	(7,444)	(7,352)	(10,845)			
Cities Receiving Transfers	\$3,602	\$3,669	\$23,397**			
	(6,446)	(6,454)	(9,591)			
EXPENDITURES						
General Government	\$16,901***	\$15,733***		\$18,143***	\$16,314***	
	(2,849)	(3,509)		(2,947)	(3,692)	
Public Safety	\$5,409***	\$4,419		\$3,780***	\$2,262	
	(1,357)	(2,796)		(1,380)	(2,914)	
Public Works	\$3,620**	\$2,651		\$3,609**	\$2,105	
	(1,663)	(2,788)		(1,628)	(2,851)	
Health	−\$38,096***	−\$38,537***		−\$42,957***	−\$43,603***	
	(7,285)	(7,591)		(7,665)	(7,954)	
Parks and Recreation	−\$1,092	−\$1,769		\$1,996	\$908	
	(2,283)	(3,239)		(2,314)	(3,344)	
Libraries	−\$10,021*	−\$9,707*		−\$10,290*	−\$9,799*	
	(5,777)	(5,678)		(5,819)	(5,723)	
Other	−\$7,394**	−\$8,195**		−\$7,035***	−\$8,286**	
	(2,900)	(3,626)		(2,714)	(3,564)	
Total Expenditures			\$6,117***			\$5,964***
			(542)			(554)
Total Revenues		\$895			\$1,390	
		(2,258)			(2,383)	
Additional Controls						
Fiscal Alignment	−\$580***	−\$480**	−\$524***	−\$700***	−\$543**	−\$615***
	(122)	(203)	(155)	(130)	(217)	(174)
Fiscal Decentralization	−\$2,276***	−\$2,250***	−\$2,015***	−\$2,562***	−\$2,518***	−\$2,312***
	(162)	(163)	(143)	(169)	(169)	(152)
Recession	−\$3,638	−\$3,610	−\$3,065	−\$3,613	−\$3,570	−\$2,723
	(2,355)	(2,343)	(2,502)	(2,470)	(2,452)	(2,636)
New City Expenditures (\$100s, by County)	\$560 (593)	\$567 (591)	\$850 (539)	\$209 (601)	\$226 (596)	\$652 (556)
CA GDP (per capita)	\$0*** (0.0)	\$0*** (0.0)	\$0*** (0.0)	\$0*** (0.0)	\$0*** (0.0)	\$0*** (0.0)
Constant	\$8,033	−\$2,966	−\$12,912	\$47,831***	\$30,410	\$47,261***
	(15,370)	(25,100)	(18,114)	(15,218)	(25,447)	(17,307)
Observations	3,010	3,010	3,010	3,010	3,010	3,010
R^2	0.530	0.530	0.476	0.486	0.487	0.426
Adjusted R^2	0.528	0.528	0.475	0.483	0.485	0.425
F Statistic	241.058***	225.474***	341.193***	235.697***	218.809***	370.951***

Some control variables not reported.
White's standard errors reported.
$^{*}p < 0.1$; $^{**}p < 0.05$; $^{***}p < 0.01$

payroll expenditures. Public Safety includes police, fire, emergency medical services (ems), and any disaster-related expenditures intended to provide for the safety of a city. Public Works expenditures would focus on investments in sewers, roads, and general infrastructure expenditures designed to keep the city physically operating. Health expenditures would include investments in hospitals, outreach, or anything targeting well being. Parks and Recreation include parks, playgrounds, trees, golf courses, and general investments into natural beauty and outdoor recreation. Libraries are just that, investments in Libraries, while the Other category catches one-offs and generalized expenses that don't neatly fit within a specific category.

Model 2 includes all of the previously mentioned variables, but includes Total Revenues. Model 3 presents all line item expenditures into one aggregate we call Total Expenditures. Models $4 - 6$ repeat models $1 - 3$ except they drop the indicator variables $Transfer_{it}$ and $Receive_{it}$. For Models $1-6$, we have $3,010$ observations with an adjusted R^2 that falls within the range of 42.6% to 52.8% with an F-statistic of $219 - 371$ that is statistically significant at the 1% level which implies that we can reject the null hypothesis that our coefficients are equal to zero.

Interestingly, the coefficients for the directional flow of the property tax revenues indicate a somewhat counter-intuitive result. Cities transferring revenues are estimated to see per capita property value increases of $\$49,906 - \$71,135$ as a result of the transfer (with $p < .01$ and relatively small standard errors. This is strong evidence that the incremental transfer of wealth based on property values does not harm the growth of wealth in transfer households. The results for cities receiving transfers were positive with only one estimate significant. Per capita property values in receiving cities increased by $\$23,3397$ with $p < 0.05$. In the case where these estimates were not significant, their standard of error was far larger than the estimate itself indicating a lot of uncertainty over the direct impact of these transfers on households. This uncertainty is confirmed in Table 3 when we control for line item revenues. Regardless, the broad takeaway is that transferring incremental property tax revenues is not necessarily harmful to the households in transfer cities.

Looking at our line item expenditures, there is evidence that investments into General Government, Public Works, and Public Safety spark growth in per capita property values with or without the inclusion of our indicator variables. Increasing per capita expenditures on General Government by \$100 increases per capita property values by an estimated $\$15,733$ to $\$18,143$ with $p < 0.01$. A \$100 investment in Public Works increases per capita property values by $\$3,609$ to $\$3,620$ with $p < 0.05$ while Public Safety investments increase values by $\$3,780 - \$5,409$ with $p < 0.01$. Increasing total expenditures by \$100 raises per capita property values by $\$5,964$ to $\$6,117$ with $p < 0.01$.

Estimates on the impact of health expenditures are strongly significant ($p < 0.01$) and strongly negative over the study period. A \$100 increase in spending on these types of services is estimated to *reduce* per capita property values by $\$38,096$ to $\$43,603$ across all model specifications. This likely reflects the long run nature of investments which are inherently less productive in the short run. Investments in mental and physical health are more likely to accrue systemically than they are to produce direct benefits to household wealth in terms of per capita property values. It is also worth noting that these investments are likely to attract less financially-solvent residents. Regardless, the results over this 10 year study period are conclusively negative.

Spending on Library Services is estimated to reduces per capita property values by $\$9,707$ to $\$10,290$ with $p < 0.05$ for every \$100 per capita increase. This result is possibly due to the overall low levels of city-investments into these services (average city spent \$0.18 per capita) or as a result of competition in the provision of government services with county departments that tend to provide the bulk of these services. The same can be said about investments in Parks and Recreation. Both of these expenditure types are challenging to interpret due to the prevalence of subcontracting within the state of California. Anecdotal evidence is that the largest cities within a county tend to invest in stand alone departments for both services as these investments can be viewed as "loss leaders" to attract more residents in an effort to raise the overall tax base while most cities end up contracting with the county to provide the same services. Data to reveal the underlying nature of the situation is available, but not digitized at this point in time leaving this as a potential area for future contributions.

Increasing expenditures on "Other" government efforts by \$100 per capita is estimated to reduce per capita property values by $\$7,035$ to $\$8,286$ with $p < 0.05$ which indicates that "one-off" spending efforts may lack the growth impacts of sustained spending on well-defined, coordinated spending.

The constant term is closer to zero, smaller than its standard error, and not statistically significant when the $Transfer_{it}$ and $Receive_{it}$ are included, but positive and strongly significant when they are excluded. There isn't a clear takeaway from this except to say it may be possible that the introduction of the transfer mechanism may have forced cities to more strategically prioritize line item expenditures with mixed results such that there was no shared constant outcome to report when including data on the direction of the property tax apportionment transfer. When it is excluded, per capita property values are estimated to have increased by $\$30,410$ to $\$47,831$ at the highest level of significance and regardless of city government spending priorities.

Looking at some of our controls does not produce surprising or large impacts to consider. Recall that Fiscal Alignment (FA) is the degree to which Total Expenditures and Total Expenditures align. An estimate of 100 implies that Expenditures equal Revenues are equal with $FA > 100$ indicating Expenditures are greater than Revenues and $FA < 100$ indicating Expenditures are less than Revenues. All estimates are statistically significant with a low magnitude of impact.

Fiscal Decentralization (FD) is a measurement of a city's dependence on intergovernmental transfers with higher scores indicating greater dependence. These estimates are also strongly significant and affirm prior research that greater dependence on transfers reduces growth. Additionally, recessions reduce per capita property values while new city formations as represented by their total aggregate expenditures by county tend to raise them which may be an agglomeration effect. Increasing the per capita California GDP is estimated to have a zero effect.

Post-estimate testing presented nearly identical results for Models $1 - 6$. Anova testing shows all variables are jointly significant across each specification. Both Anderson-Darling and Shapiro-Wilk tests for normality show we cannot reject the null hypothesis for any model at the 1% level implying the residuals are likely normally distributed. Graphing of residuals for each model across all specifications are in the appendix to illustrate normality. The Jarque-Bera test results reject the null at the 1% which implies that skewness and kurtosis do not significantly deviate from the expected values within a normal distribution of error terms.

The Farrar-Glauber test indicates some multicollinearity which is unsurprising, but it should be noted that the variance inflation factor (VIF) is within acceptable limits for all variables except for our indicator variables $Transfer_{it}$ and $Receive_{it}$ that account for the direction of property tax revenue flow. The VIF for the indicator variable $Transfer_{it}$ ($Receive_{it}$ was within the range of 11.8794 to 13.5211 (11.8665 to 13.4409) in models $1-3$. All other variable VIFs were below 10. This parallels results in earlier model specification strategies when I attempted to include line item revenues and expenditures within the same model which resulted in much stronger indications of multicollinearity. It should be noted that while the VIF estimates for $Transfer_{it}$ and $Receive_{it}$ are above 10, they are by nature collinear yet the magnitude is lower than I anticipated.

Actual Changes in Expenditures: Transfer vs. Receiving Cities

Our estimates showed that in terms of per capita property values, the most productive expenditure priorities appear to be General Government, Public Works, and Public Safety while expenditures on Health, Libraries, and the "Other" category resulted in large negative changes in per capita property values. Figure 3.9 visualizes the percentage change in each of these expenditure categories in cities transferring revenues (left panel) and cities receiving transfers (right panel) over the study period. "No change" on the graphs indicates that city-level expenditures or revenues were the same at the beginning of the study period as they were at the beginning of it after controlling for inflation.

City trends are somewhat similar across transfer and receiving cities for many categories. In terms of per capita property values, both transfer and receiving cities increased spending in Public Safety and Public Works which are estimated to be the more productive investments a city can make. Here transfer cities slightly prioritized Public Works investments more than receiving cities while the opposite is true for Public Safety. This may be influenced by the larger overall spending levels and population sizes of receiving cities just prior to this study. As transfer cities tended to grow larger in size at the bottom quartile of the distribution of cities by population, perhaps this period of time put upward pressure on building out Public Works infrastructure while continued strong population growth for receiving cities increased community stresses that resulted in their governments' prioritizing Public Safety over Public Works. Regardless, both cities increased their Total Expenditures with transfer cities slightly outpacing receiving cities. Regarding population growth, both General Government and Public Works spending reduced population counts with General Government about twice as negatively impactful as Public Safety.

Both cities de-prioritized spending on Health, Libraries, and the catch-all "Other" category with very similar disinvestment rates. Recall that investments made into Health reduced per capita property values by $\$36,276$ to $\$42,511$ for every \$100 and library expenditures negatively impacting per capita property values by about a third as much as Health. Similarly, Health spending is the strongest negative impact on population growth during this time which may account for the strongly negative constant estimates in the previous table when we include the indicator variable for property tax revenue flows.

City spending priorities deviated in the categories of General Government as well as Parks and Recreation. Transfer cities *increased* spending on General Government by 8% at the median while receiving cities *decreased* General Government spending by 28%. This paper views this as an indication that transfer city governments tended to grow larger in size than receiving cities whose General Government investments tended to shrink. This deviation in trends may be one reason that transfer cities experienced such strong per capita property value growth over the study period as compared to receiving cities. Table 2 shows that a \$100 increased in General Government spending raises per capita property values by $\$9,940$ to $\$18,879$.

Transfer (receiving) cities prioritized increases in Public Works more than anything else with the median city increasing these line item per capita expenditures by 62% (55%). Spending on Public Safety was the secondary priority for both with an increase of

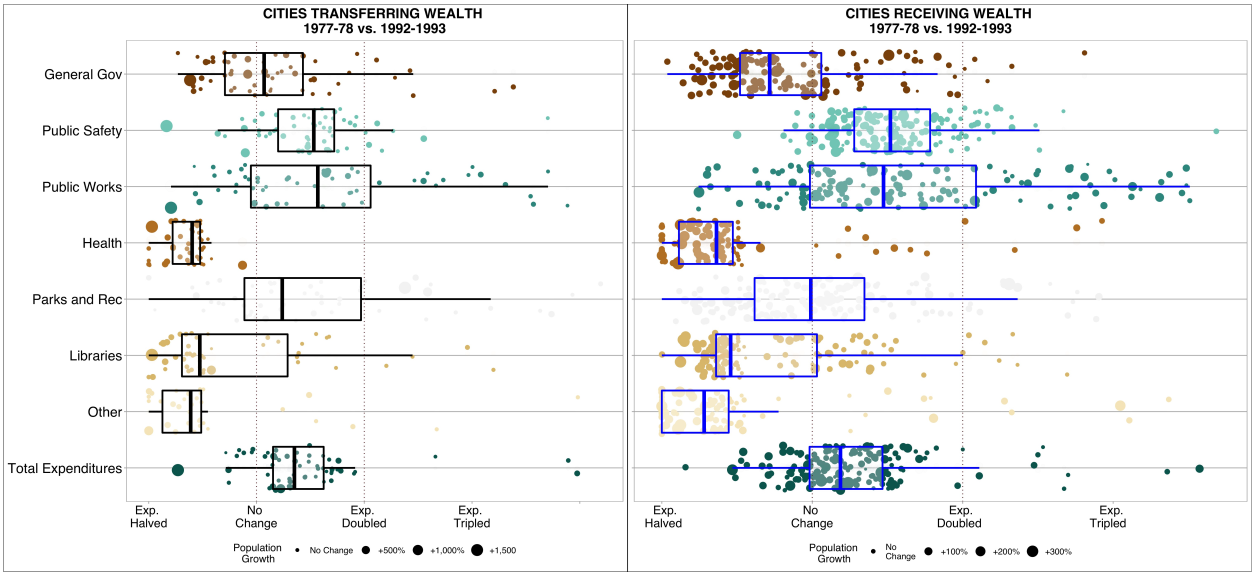


Figure 3.9: Actual Changes in City Expenditures: Comparing 1977-78 and 1992-93 for Transfer vs. Receiving Cities

54% (52%). This is the point at which city types differentiate their spending patterns. Both increase spending on Parks and Recreation but at significantly different magnitudes. The median transfer city increased its investment +45% while the median receiving city was basically flat. Recall that General Government spending is devoted to running the city with expenditures on things like public sector employment and administration and is estimated to be very productive in our modeling. Transfer cities *increased* this line item spending by +8% while receiving cities *decreased* theirs at the median by 28% which implies transfer cities grew in terms of government size while high tax cities shrank.

3.7.4 The Impact of Revenues on Growth

This discussion on the impact of revenues on growth parallels the structure for expenditures. First is a look at the output related to per capita property values followed by a summary of which line item revenues transfer and receiving cities actually chose to prioritize over the study period.

Table 3.3 displays results from Models 7 through 12. Again, the dependent variable is per capita property values $PropValues_{it}$. Models $7-10$ include indicator variables that track the pathway of property tax revenues transferred, $Transfer_{it}$ and $Receive_{it}$, as well as our line item revenues. Taxes are revenues generated from sales, use, utility, and other non-property based taxes. Licenses and Permits are fees collected from household or business endeavors that require local government permission to proceed (e.g. home remodeling or the formation of a business). Fines and Penalties are revenues collected as a result of a household or business receiving an infraction related to a local ordinance. Money and Property refers to the local government's ability to increase the rate of return on its investments via financial decision-making or by making publicly-owned property more productive. Service Charges are fees collected by the municipal government in exchange for some service performed such as solid waste revenues. Intergovernmental Transfers are revenues transferred from higher levels of government (county, state, or federal) to municipalities. These are often subject to special protocols or spending requirements. Other is a catch-all for revenues collected that do not fit easily within a category or are not routinely collected. Finally, Total Expenditures and Total Revenues are the aggregated total values of each type.

The model specification strategy mirrors that in models $1-6$. Model 7 includes all line item revenues. In model 8, I add Total Expenditures with the line item revenues. For model 9, revenues are aggregated into one total. Models $10-12$ drop the indicator variables $Transfer_{it}$ and $Receive_{it}$, but otherwise are the same as models $7-9$. Models $7-12$ have an adjusted R^2 that falls within a range of $51.8\% - 66\%.7$ with an F-statistic of $302 - 405$ that is statistically significant at the 1% level which implies that we can reject the null hypothesis that our coefficients are equal to zero.

The estimated coefficients for transfer and receiving cities validate the somewhat counter-intuitive results from models $1-6$ at a slightly lower magnitude. Cities transferring revenues are estimated to see per capita property value increase by $\$18,177 - \$33,548$ as a result of the transfer with estimates significant at the 1% level. This validates our earlier findings when expenditures were the independent variables that transfer cities appear to have grown because of the transfer - though I highly suspect this is also due to the cities' prioritization of specific line items. The signs of estimates for cities receiving transfers are now mixed and all statistically significant at the highest level with property tax transfers *decreasing* per capita property values by a range of $\$15,407$ to $\$18,276$. The flipping of signs underscores the importance of city choices over line item revenues and expenditures which will become clear when we consider which each city type appeared to prioritize.

Looking at our line item revenues, there is strong evidence that some revenues are more productive than others. Increasing revenues collected from general Taxes, Licenses and Permits, Money and Property as well as Service Charges by \$100 are estimated to increase per capita property values by ranges of $\$10,655$ to $\$14,505$, $\$14,251$ to $\$19,232$, $\$26,480$ to $\$27,922$, and $\$4,122$ to $\$8,503$ with estimates significant at the $1-5\%$ level. Raising Total Revenues by \$100 is estimated to increase per capita property values by $\$8,152$ to $\$8,289$ with $p < 0.01$.

Raising revenues through returns from investments in Money and Property are likely to be productivity-enhancing which could increasing the value of land around it. Increasing the

Table 3.3: Per Capita Property Values & Line Items Revenues

	(Model 7)	(Model 8)	(Model 9)	(Model 10)	(Model 11)	(Model 12)
Cities Transferring Revenues	$18,288***	$18,177***	$33,548***			
	(6,987)	(6,987)	(6,532)			
Cities Receiving Transfers	−$18,540***	−$18,276***	−$15,407***			
	(6,650)	(6,588)	(5,954)			
REVENUES						
Taxes	$10,655***	$13,092***		$11,434***	$14,505***	
	(1,108)	(3,258)		(1,156)	(3,297)	
Licenses and Permits	$14,251**	$16,595**		$16,296**	$19,232**	
	(6,980)	(7,412)		(7,344)	(7,714)	
Fines and Penalties	−$36,493***	−$28,423**		−$43,861***	−$33,565***	
	(9,955)	(12,403)		(10,459)	(12,793)	
Money and Property	$26,599***	$27,739***		$26,480***	$27,922***	
	(2,927)	(3,159)		(3,025)	(3,223)	
Service Charges	$5,806**	$8,503**		$4,122	$7,553*	
	(2,563)	(4,254)		(2,715)	(4,423)	
Intergovernmental Transfers	−$28,933***	−$26,449***		−$31,716***	−$28,542***	
	(4,310)	(4,613)		(4,683)	(4,952)	
Other	$2,510	$4,817		$3,320	$6,225*	
	(2,276)	(3,230)		(2,287)	(3,247)	
Total Revenues			$8,152***			$8,289***
			(781)			(810)
Total Expenditures		−$2,581			−$3,262	
		($2,873)			($2,900)	
Additional Controls						
Fiscal Alignment	$72	$328	−$260	−$12	$313	−$423**
	(133)	(219)	(182)	(137)	(223)	(193.494)
Fiscal Decentralization	$1,209***	$1,205***	−$668**	$1,136***	$1,133***	−$895***
	(350)	(347)	(276)	(373)	(369)	(277)
Recession	−$16,317***	−$16,214***	−$13,642***	−$15,876***	−$15,752***	−$12,816***
	(2,816)	(2,842)	(3,136)	(2,877)	(2,904)	(3,244)
New City Revenues	−$60***	−$61***	−$81***	−47.347***	−$49***	−$65***
	(13)	(14)	(17)	(12)	(13)	(16)
CA GDP	0***	0***	0***	0***	0***	0***
	(0.0)	(0.0)	(0.0)	(0.0)	(0.0)	(0.0)
Constant	−$66,298***	−$92,201***	−$74,566***	−$60,896***	−$93,602***	−$59,659***
	(18,370)	(27,005)	(20,500)	(17,426)	(27,674)	(20,007)
Observations	3,010	3,010	3,010	3,010	3,010	3,010
R^2	0.668	0.669	0.560	0.646	0.648	0.519
Adjusted R^2	0.666	0.667	0.559	0.644	0.645	0.518
F Statistic	322.992***	302.477***	358.750***	341.930***	317.362***	405.375***

Some control variables not reported.
White's standard errors reported.
$^{*}p < 0.1$; $^{**}p < 0.05$; $^{***}p < 0.01$

marginal productivity of land accrues vast returns to wealth [92], but it bears noting that these returns for a municipal government would increase its capacity to serve its constituents without directly reducing their own marginal propensity to consume. Ignoring the issue of moral hazard and the innate distortions to risk that city employees likely operate under in pursuit of investment returns from public dollars, the same can be said for the government's ability to increase its returns from money. Doing so does not directly affect city residents' capacity to consume as it is increasing returns from existing Money and Property holdings.

Two other line item revenues are estimated to increase property values though their causal relationship is in doubt as they are likely an indicator of economic activity and growth rather than a predictor of it. Increasing per capita revenues from Licenses and Permits (Service Charges) by \$100 are correlated with an increase in per capita property values of $\$14,251$ to $\$19,232$ ($\$4,122$ to $\$8,503$) with $p < 0.05$ ($p < 0.1$). Increases in applications for Licenses and Permits would be a leading indicator of business formation and investments in the development of property by the private sector and households while service charges may be a leading or lagging indicator of similar activities. In that capacity, neither is considered to have a causal relationship with growth in this paper.

Other results do not surprise. A \$100 increase in Intergovernmental Transfers is estimated to *reduce* per capita property values by $\$26,449$ to $\$31,716$ with $1\% - 5\%$ significance. As mentioned before, these revenues are often attached to specific spending requirements that are not necessarily reflective of local needs or preferences. Total Revenues increase growth by $\$8,152$ to $\$8,289$ with $p < 0.01$ which is reflective of the trade-off in productive and unproductive sources of revenues. Recessions decrease property values while increasing new city formations within the county decrease property values modestly which makes some intuitive sense. The constant term is negative overall with per capita property values *falling* $\$59,817$ to $\$93,602$ and statistically significant at the 1% level. Contrary to models $1 - 6$ where the sign flipped to positive when $Transfer_{it}$ and $Receive_{it}$ were excluded, all of the signs are negative for the constant with line item revenues.

Post-estimate testing presented the same pattern of results for Models 13 through 18 as for earlier models. Anova testing shows all variables are jointly significant across each specification while Anderson-Darling and Shapiro-Wilk tests for normality show we cannot reject the null hypothesis for any model at the 1% level. Jarque-Bera test results reject the null at the 1% which implies that skewness and kurtosis do not significantly deviate from expected values. The Farrar-Glauber test for multicollinearity again showed the $Transfer_{it}$ with a VIF ranging 12.8787 to 12.9671 and $Receive_{it}$ 12.7858 to 12.8139. Model 14 presents a bit more multicollinearity when we introduce Total Expenditures. Here, the VIF for Tax Revenues rises to a range of 16.5927 to 16.7734 with a VIF for Total Expenditures that is 33.5616 to 33.6537. Graphing of residuals is available in the appendix.

Actual Changes in Revenues: Transfer vs. Receiving Cities

Figure 3.10 visualizes the changing priorities of cities as they raised revenues in response to the precipitous drop in overall property taxes after the implementation of proposition 13. The data are visualized as the percentage change in line item revenues across our study period for cities transferring property tax revenues (left panel) and cities receiving revenue transfers (right panel). Both city types follow similar trends across line items.

The starkest change in revenues tool place in transfer cities where Total Revenues in the median city started off lower than in receiving cities in FY $1977-78$ but ended up higher in FY $1992-93$ resulting in a 24% increase in overall revenues for transfer cities and a 10% increase in receiving cities. The primary driver of overall revenue growth in both cities came from two categories: Money and Property as well as Service Charges. Here, receiving cities outpaced transfer cities. On average, they doubled their revenues from Money and Property while increasing Service Charge revenues by about 140%. Transfer cities grew theirs by about 180% and 110%. Both cities increased revenues from taxes over the study period with transfer cities jumping by 34% at the median and receiving cities by 17%. Note that Money and Property was estimated to present the largest positive gains to per capita property values with taxes the third largest. Service Charges presented positive impacts in table 3 thought statistical significance varied.

Both city types reduced the collection of revenues through Fines and Penalties while they saw declines in Intergovernmental Transfers. Recall that table 3 illustrated the unproductive nature of Fines and Penalties as they impact per capita property wealth. Transfer cities dropped 38% and receiving cities declined 29% at the median. Intergovernmental Transfers declined by 40% (48%) in transfer (receiving) cities.

The cities differed in their use of "other" revenues as well as Licenses and Permits. Recall in table 3 that Licenses and Permits is estimated to be one of the more productive line item revenues sources with an estimated increase of per capita property values of $14, 251 to $19, 232 for a $100 per capita increase in revenues from Licenses and Permits. In this category, transfer cities *increased* revenues by 19% whereas receiving cities *decreased* revenues by 4%. Revenues from the "other" category was the other line item where city types deviated with transfer cities slightly reducing them and receiving cities slightly increasing them though the category itself was not estimated to have much impact on property values as displayed in table 3 with little statistical significance.

Recalling the issue of convergence, it is clear from analysis into the impact line item expenditures and revenues had on these cities that some expenditures and revenues are more productive than others. Looking at the decision-making process over what each city type prioritized in both categories in response to the redistribution of property tax revenues reveals that strategic decision-making over line item budget matters limited the impact of this loss within transfer cities.

3.8 Conclusion

The gaps in the design of proposition 13 and subsequent unintended consequences of AB 8's apportionment process have provided us with insights into the potential efficiency of leveraging the property tax assessment and apportionment process. This paper provides evidence that the use of the apportionment process as a mechanism for redistribution does not harm households from which the revenues are extracted nor does it inhibit the government in the transfer city. Perhaps it is the incrementalism of this approach that underpins its efficiency. While the aggregate transfer of property tax revenues over our study period is no doubt large, the individual impact to each household is relatively minor.

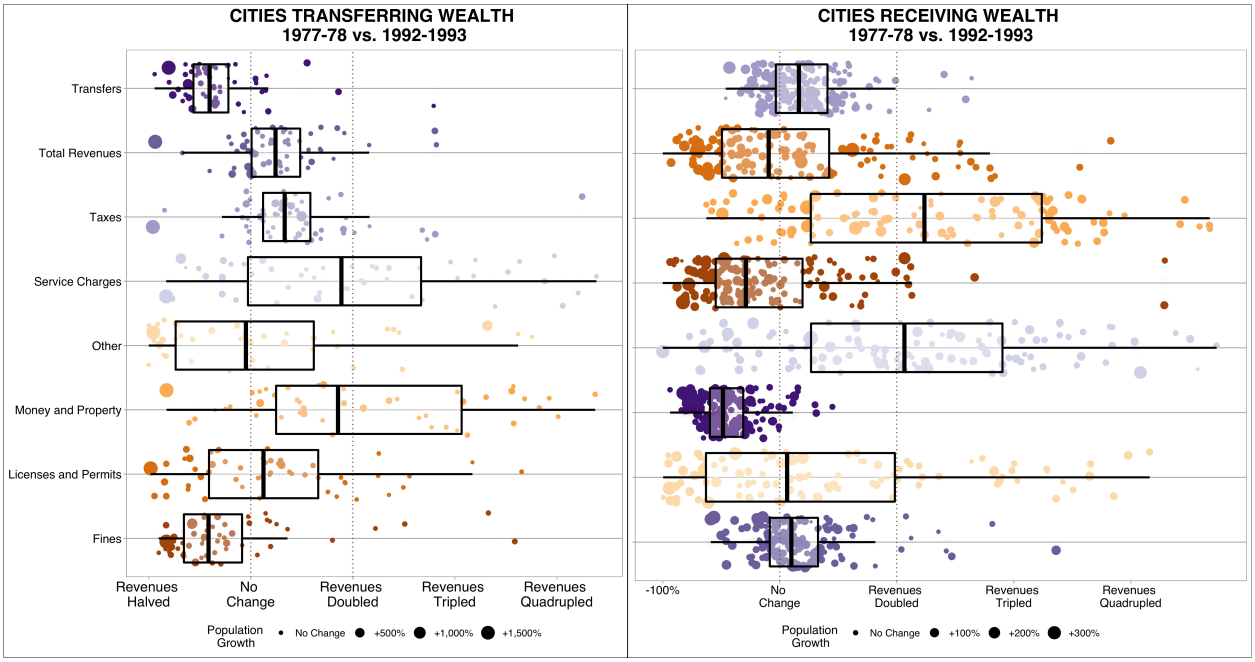


Figure 3.10: Changes in City Revenues: Comparing 1977-78 and 1992-93

The mixed results I found in sign and in significance regarding the impact of city governments receiving these transfers leaves a lot of uncertainty on the table. This is not terribly surprising given the accidental nature of this transfer. Had it been intentionally deployed based on a strategic plan to maximize its impact on property values or household wealth, then the results may have been more conclusive. Had it been a direct transfer between households, then the opacity of government revenues with respect to the dollar for dollar tracking of revenues and expenditures would not preclude knowing for sure what the impact had been on property values. This is beyond this paper's scope.

We do have strong indications that it does matter what line item revenues or expenditures a city prioritizes when the goal is to stimulate the growth of household wealth. None of it is too shocking. Spending on Public Works efforts and General Government will keep a growing city functional and is necessary when the population of your city grows. More people will flush more toilets, engage more intensely with bureaucracy, create more potholes. At the same time, maintaining a semblance of order in just the everyday flow of traffic in an increasingly dense population of people necessitates some attention to increasing investments in Public Safety. Spending money on long term investments into Parks and Recreation, Health, and Libraries may provide payouts that are beyond the study period this paper has chosen. Additional data may provide answers to this.

It also appears to matter how a city's prioritized streams of revenue affect households' marginal propensity to consume (MPC). Where Fines and Revenues are inherently not productive (for the most part), they may be crowding out more productive spending by the payees. On the contrary, increasing revenues from Money and Property are compounding the city's returns from the governments stewardship of public assets. This should be productive as long as the moral hazard of using public dollars in this manner does not distort the risk of these efforts to the taxpayer. In the limit, that seems likely.

[92] makes it clear that a majority of national wealth has accumulated in land values over the last 50 years with the results exacerbating inequality in the most powerful economies today. The incremental nature of the property tax assessment and apportionment process presents an attractive policy mechanism for gradually leveling this trend. Moreover, the

value of using the property tax apportionment process to geo-spatially move land wealth to limit the risk of climate change is quite attractive and it applies to any risk a city would face in this transition. It is easy to visualize the merit of this mechanism in coastal cities under rising sea levels, but consider the long run strangle that persistent drought or weather shocks may have on land valuations and it is self evident that some process of redistributing land wealth must be revealed.

The transfer of wealth is an oft-discussed solution in the debate over issues of income inequality, but income is only a flow in the stock of a household's wealth. Housing stock constitutes almost half of national capital stocks with increases in the value of housing the dominant driver of household wealth since the $1970s$ [92]. As coastal cities facing rising seas define their strategic responses, the potential need to physically change jurisdictional boundaries of local governments demands the identification of efficient mechanisms to transfer land wealth geo-spatially. The high risks posed by climate change to the wealth concentrated in coastal cities [65] also presents an increasingly salient catalyst for the mass migration of people [102]. If we consider land values a stock of wealth and incomes the flow, existing inequalities in the marginal distribution of incomes that dampen opportunity today [30] may reduce the ability of poorer households to extract familial wealth from housing stock at risk from rising seas. This presents the potential to stratify society in the future equilibrium under climate change and dampen long run national growth overall as the loss of land from rising seas exacerbates inequality and undermines mobility. This is where the concept of managed retreat can play a part. The incremental shifting of city boundaries pursued under a policy of managed retreat [112] provides a strategy that policymakers may choose to pursue in order to preserve as much of the current wealth of their city as possible. Existing policy mechanism related to the government's assessment and taxation of property values may provide a solution.

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Appendices

A Carbon Taxes

We consider a constant carbon tax τ that does not vary with the size of firm reserves. You will see that this functional form of the carbon tax affects the firm similarly to the $\tau(R_t)$, but is not as harmful to the firm. All other assumptions and functional forms remain in the format presented in [93]. Given initial conditions for reserves R_0 and cumulative reserve additions x_0, firms maximize welfare such that:

$$Max_{q,w} \quad \int_0^T [q_t p_t - C_1(R_t)q_t - C_2(w_t) - \tau q_t]e^{-\delta t}dt \tag{1}$$

$$s.t. \quad \dot{R}_t = \dot{x}_t - q_t \tag{2}$$

$$\dot{x}_t = f(w_t, x_t) \tag{3}$$

$$R_t \geq 0, q_t \geq 0, w_t \geq 0, x_t \geq 0 \tag{4}$$

The Hamiltonian for the optimization problem is:

$$H = q_t p_t e^{-\delta_t} - C_1(R_t)q_t e^{-\delta_t} - C_2(w_t)e^{-\delta_t} - \tau q_t p_t e^{-\delta_t} + \\ \lambda_1[f(w_t, x_t) - q_t] + \lambda_2[f(w_t, x_t)] \tag{5}$$

Since H is linear in q, each producer should produce either nothing or at some maximum capacity level. We derive our first order conditions starting with the reserves:

$$\frac{\partial H}{\partial R} \rightarrow \dot{\lambda}_1 - C_1'(R_t)q_t e^{-\delta_t}$$

Solve for the shadow value of additional reserves:

$$\dot{\lambda}_1 = C_1'(R_t) \tag{6}$$

Taking the first order condition for x_t:

$$\frac{\partial H}{\partial x} \rightarrow \dot{\lambda}_2 - \lambda_1 f_x - \lambda_2 f_x = 0$$

We simplify and solve:

$$\dot{\lambda}_2 = -(\lambda_1 + \lambda_2) f_x \tag{7}$$

We now take the first order condition with respect to production q_t:

$$\frac{\partial H}{\partial q} = p_t e^{-\delta_t} - C_1(R) e^{-\delta_t} - \tau e^{-\delta_t} - \lambda_1 = 0$$

And solve for the market clearing condition to find that the change in value of future profits from one additional unit of additional reserves is equal to the rents less the value of the tax:

$$\lambda_1 = [p_t - C_1(R) - \tau] e^{-\delta t} \tag{8}$$

A.1 Deriving the Price Pathway

We take the market clearing condition (equation 8) and differentiate it with respect to time.

$$\begin{aligned}\dot{\lambda}_1 = \dot{p} e^{-\delta_t} + p_t(-\delta_t) e^{-\delta_t} - C_1'(R_t) \dot{R} e^{-\delta_t} \\ - C_1(R_t)(-\delta_t) e^{-\delta_t} - \tau(R_t)(-\delta_t) e^{-\delta_t}\end{aligned}$$

We substitute for $\dot{R}$:

$$\begin{aligned}\dot{\lambda}_1 = \dot{p} e^{-\delta_t} + p_t(-\delta_t) e^{-\delta_t} - C_1'(R_t) \dot{R} e^{-\delta_t} \\ - C_1(R_t)(-\delta_t) e^{-\delta_t} - \tau(R_t)(-\delta_t) e^{-\delta_t}\end{aligned}$$

We set this equal to equation 6:

$$\begin{aligned} C_1'(R_t)q_t e^{-\delta_t} = \\ &\dot{p}e^{-\delta_t} + p_t(-\delta_t)e^{-\delta_t} - C_1'(R_t)[f(w_t, x_t) - q_t]e^{-\delta_t} \\ &\qquad - C_1(R_t)(-\delta_t)e^{-\delta_t} - \tau(R_t)(-\delta_t)e^{-\delta_t} \end{aligned}$$

Finally, we simplify and rearrange to solve for the price pathway with taxes:

$$\dot{p} = \delta_t[p_t - C_1(R_t) - \tau] + f(w_t, x_t)C_1'(R_t) \tag{9}$$

Equation 9 shows that the tax affects the price pathway in one way when taxes are τ. The tax slows the rise in prices by lowering rents.

A.2 Deriving the Optimal Pathway for Exploration

Finally, we differentiate the Hamiltonian with respect to w_t:

$$\frac{\partial H}{\partial w} \rightarrow C_2'(w_t)e^{-\delta_t} = f_w(\lambda_1 + \lambda_2)$$

We rearrange:

$$\frac{C_2'(w_t)e^{-\delta_t}}{f_w} = \lambda_1 + \lambda_2$$

We substitute 8 for λ_1 and rearrange:

$$\frac{C_2'(w_t)e^{-\delta_t}}{f_w} = p_t e^{-\delta_t} - C_1(R_t)e^{-\delta_t} - \tau e^{-\delta_t} + \lambda_2$$

Solving for λ_2:

$$\lambda_2 = \frac{C_2'(w_t)e^{-\delta_t}}{f_w} - p_t e^{-\delta_t} + C_1(R_t)e^{-\delta_t} + \tau e^{-\delta_t} \tag{10}$$

Substitute 8 and 10 into 7:

$$\begin{aligned}\dot{\lambda}_2 = -[p_t e^{-\delta_t} - C_1(R_t)e^{-\delta_t} - \tau e^{-\delta_t} + \\ \frac{C_2'(w_t)e^{-\delta_t}}{f_w} \\ - [p_t e^{-\delta_t} + C_1(R_t)e^{-\delta_t} + \tau e^{-\delta_t}]f_x\end{aligned}$$

Simplify:

$$\dot{\lambda}_2 = -[\frac{f_x}{f_w}]C_2'(w_t)e^{-\delta_t} \tag{11}$$

Take the time derivative of equation 10:

$$\begin{aligned}\dot{\lambda}_2 = \frac{[C_2''(w_t)\dot{w}e^{-\delta_t} + C_2'(w_t)(-\delta_t)e^{-\delta_t}]f_w - C_2'(w_t)e^{-\delta_t}[f_{ww}\dot{w} + f_{wx}\dot{x}]}{(f_w)^2} \\ - \dot{p}e^{-\delta_t} - p_t(-\delta_t)e^{-\delta_t} + C_1'(R_t)\dot{R}e^{-\delta_t} + C_1(R_t)(-\delta_t)e^{-\delta_t} \\ + \tau(-\delta_t)e^{-\delta_t}\end{aligned}$$

Substitute with 2, 3, and 9, reduce and group for $\dot{w}$ to find that the tax has canceled out:

$$\begin{aligned}\dot{\lambda}_2 = \dot{w}\frac{[C_2''((w_t)e^{-\delta_t}f_w + C_2''((w_t)e^{-\delta_t}f_{ww}]}{(f_w)^2} \\ - \frac{[\delta_t C_2'(w_t)e^{-\delta_t}f_w e^{-\delta_t} - C_2'(w_t)e^{-\delta_t}f_{wx}[f(w_t, x_t)]e^{-\delta_t}]}{(f_w)^2} \\ - C_1'(R_t)(q_t)e^{-\delta_t}\end{aligned} \tag{12}$$

Set 11 = 12:

$$
\begin{aligned}
-[\frac{f_x}{f_w}]C_2'(w_t)e^{-\delta_t} = \dot{w}\frac{[C_2''(w_t)e^{-\delta_t}f_w + C_2''(w_t)e^{-\delta_t}f_{ww}]}{(f_w)^2} \\
- \frac{[\delta C_2'(w_t)e^{-\delta_t}f_w e^{-\delta_t} - C_2'(w_t)e^{-\delta_t}f_{wx}[f(w_t,x_t)]e^{-\delta_t}]}{(f_w)^2} \\
- C_1'(R_t)(q_t)e^{-\delta_t}
\end{aligned}
$$

Reduce and solve for the equation of motion for exploration:

$$
\dot{w} = \frac{C_2'(w_t)[\frac{f_{wx}}{f_w}[f(w_t,x_t) - q_t] + \delta_t - f_x] + f_w q_t [C_1'(R_t)]}{C''(w_t) - C_2'(w_t)[\frac{f_{ww}}{f_w}]} \tag{13}
$$

We find that taxes τ do not affect the equation of motion for exploration directly.

B Exploration Incentives

We maintain the following variables. Price p_t, production q_t, proved reserves R_t, exploratory effort w_t, and additional reserves x_t. We introduce a government term $g(R_t)$ that represents policy incentives designed to stimulate the firm to explore more. As such, the government term varies positively with R, $g'(R_t) > 0$ and enters into the firm's production function for exploratory effort $\dot{x} = f(w_t, x_t, g_t)$.

$$Max_{q,w} \quad w = \int_0^t [q_t p - C_1(R_t)q_t - C_2(w_t)] \tag{15}$$

$$s.t. \quad \dot{R}_t = \dot{x}_t - q_t \tag{16}$$

$$\dot{x}_t = f(w_t, g_t, x_t) \tag{17}$$

$$\dot{g}_t = g(R_t) \tag{18}$$

$$R_t \geq 0, q_t \geq 0, w_t \geq 0, x_t \geq 0, g_t \geq 0$$

Forming the Hamiltonian:

$$H = q_t p_t e^{-\delta_t} - C_1(R_t)q_t e^{-\delta_t} - C_2(w_t)e^{-\delta_t} + \lambda_1[f(w_t, g_t, x_t) - q_t] + \lambda_2[f(w_t, g_t, x_t)] + \lambda_3[g_t(R_t] \tag{19}$$

Our first order conditions starting with the reserves:

$$\frac{\partial H}{\partial R} \rightarrow \dot{\lambda}_1 - C_1'(R_t)q_t e^{-\delta_t} + \lambda_3 g_R = 0$$

Solve for the shadow value of additional reserves:

$$\dot{\lambda}_1 = C_1'(R_t) q_t e^{-\delta_t} - \lambda_3 g_R = 0 \tag{20}$$

We take the first order condition with respect to reserve additions x_t:

$$\frac{\partial H}{\partial x} = \dot{\lambda_2} + \lambda_1 f_x + \lambda_2 f_x = 0$$

Simplify:

$$\dot{\lambda}_2 = -(\lambda_1 + \lambda_2) f_x \tag{21}$$

We take the first order condition with respect to production q_t:

$$\frac{\partial H}{\partial q} = p_t e^{-\delta_t} - C_1(R_t) e^{-\delta_t} - \lambda_1$$

And solve for rents to find that the change in value of future profits from one additional unit of additional reserves is equal to the rents:

$$\lambda_1 = p_t e^{-\delta_t} - C_1(R_t) e^{-\delta_t} \tag{22}$$

We take the first order condition with respect to government policyg_t:

$$\frac{\partial H}{\partial g} = \dot{\lambda}_3 + \lambda_1 f_g + \lambda_2 f_g + \lambda_3 g_R = 0$$

Rearranging:

$$\dot{\lambda}_3 = -(\lambda_1 + \lambda_2) f_x - \lambda_3 g_R = 0 \tag{23}$$

We take the first order condition with respect to exploratory effort w_t:

$$\frac{\partial H}{\partial w} = -C_2'(w_t)e^{-\delta_t} + \lambda_1 f_w + \lambda_2 f_w = 0$$

Simplify and substitute 22 for λ_1 and solve for λ_2.

$$\lambda_2 = \frac{C_2'(w_t)e^{-\delta_t}}{f_w} - p_t e^{-\delta_t} + C_1(R_t)e^{-\delta_t} \tag{24}$$

The shadow value of exploration is equal to the marginal discovery cost plus the current value average cost of production less the current value price.

B.1 Deriving the Price Pathway

From equation 22, we take the partial with respect to time.

$$\frac{\partial(22)}{\partial t} = \dot{\lambda}_1 = \dot{p}e^{-\delta_t} + p_t(-\delta_t)e^{-\delta_t} - C_1'(R_t)e^{-\delta_t}\dot{R} - C_1(-\delta_t)(R_t)e^{-\delta_t}$$

Substitute equations 16 and 17.

$$\dot{\lambda}_1 = \dot{p}e^{-\delta_t} - \delta_t p_t e^{-\delta_t} - C_1'(R_t)e^{-\delta_t}[f(w_t, g_t, x_t) - q_t] + \delta_t C_1(R_t)e^{-\delta_t} \tag{22'}$$

Set 20 equal to $22'$ and rearrange to identify the "Equation of Motion for the Price Pathway".

$$\dot{p}_t = \delta_t[p_t - C_1(R_t)] + f(w_t, g_t, x_t)[C_1'(R_t)] - \frac{\lambda_3 g_R}{e^{-\delta_t}} \tag{25}$$

B.2 Deriving the Equation of Motion for Exploration

Take the derivative of equation 24 with respect to time.

$$\frac{\partial(10)}{\partial t} = \dot{\lambda}_2 = \frac{[C_2''(w_t)e^{-\delta_t}\dot{w} + C_2'(w_t)e^{-\delta_t}(-\delta_t)]f_w - C_2'(w_t)e^{-\delta_t}[f_{ww}\dot{w} + f_{wx}\dot{x} + f_{wg}\dot{g}]}{(f_w)^2}$$
$$- \dot{p}e^{-\delta_t} - p_t e^{-\delta_t}(-\delta_t) +$$
$$C_1'(R_t)\dot{R}e^{-\delta_t} + C_1(R_t)e^{-\delta_t}(-\delta_t)$$

Substitute 16, 17, and 25.

$$\dot{\lambda}_2 =$$
$$\frac{C_2''(w_t)e^{-\delta_t}\dot{w} - \delta_t C_2'(w_t)e^{-\delta_t}]f_w - C_2'(w_t)e^{-\delta_t}[f_{ww}\dot{w} + f_{wx}f(w_t, g_t, x_t) + f_{wg}g(R_t)}{(f_w)^2}$$
$$- [C_1'(R_t)f(w_t, g_t, x_t) + \delta_t p_t - \delta_t C_t'(R_t) - \frac{\lambda_3 g_R}{e^{-\delta_t}}]e^{-\delta_t} + \delta_t p_t e^{-\delta_t}$$
$$+ C_1'(R_t)[f(w_t, g_t, x_t) - q_t]e^{-\delta_t} - \delta_t C_1(R_t)e^{-\delta_t}$$

Rewrite and assume $f_{wg} = 0$[3]. Though government policy can directly stimulate exploratory effort by the firm through the first order condition, government has no second order effect on the efficacy of the firm's efforts to find reserves. Now regroup to isolate $\dot{w}$ and reduce:

$$\dot{\lambda}_2 = \frac{\dot{w}[f_w C_2''(w_t)e^{-\delta_t} - f_{ww}C_2'(w_t)e^{-\delta_t}]}{(f_w)^2} - \frac{C_2'(w_t)e^{-\delta_t}[\delta_t f_w + f_{wx}f(w_t, g_t, x_t)]}{(f_w)^2}$$
$$+ \lambda_3 g_R - C_1'(R_t)q_t e^{-\delta_t} \quad (26)$$

Recall equation 21: $\dot{\lambda}_2 = -(\lambda_1 + \lambda_2)f_x$. Substitute 24 and 22 into 21.

$$\dot{\lambda}_2 = -[p_t e^{-\delta_t} - C_1(R_t)e^{-\delta_t} + \frac{C_2'(w_t)e^{-\delta_t}}{f_w} - p_t e^{-\delta_t} + C_1(R_t)e^{-\delta_t}]f_x$$

---

[3] We have separately solved the equation without this assumption and the results are the same.

Simplify.

$$\dot{\lambda}_2 = -\frac{f_x}{f_w}(C_2'(w_t)e^{-\delta_t} \tag{27}$$

Set 26 = 27.

$$\begin{aligned} -[\frac{f_x}{f_w}(c_2'(w_t)e^{-\delta_t}] = \frac{\dot{w}[f_w C_2''(w_t)e^{-\delta_t} - f_{ww}C_2'(w_t)e^{-\delta_t}]}{(f_w)^2} + \lambda_3 g_R - C_1'(R_t)q_t e^{-\delta_t} \\ - \frac{C_2'(w_t)e^{-\delta_t}[\delta_t f_w + f_{wx} f(w_t, g_t, x_t)]}{(f_w)^2} \end{aligned}$$

Simplify.

$$\begin{aligned} -f_x c_2'(w_t) = \frac{\dot{w}[f_w C_2''(w_t) - f_{ww}C_2'(w_t)]}{f_w} + \frac{\lambda_3 g_R f_w}{e^{-\delta_t}} - f_w C_1'(R_t)q_t \\ - \frac{C_2'(w_t)[\delta_t f_w + f_{wx} f(w_t, g_t, x_t)]}{f_w} \end{aligned}$$

Rearrange to identify the "Equation of Motion for Exploration".

$$\dot{w} = \frac{C_2'(w_t)[\frac{f_{wx}}{f_w} f(w_t, g_t, x_t) + \delta_t - f_x] + f_w[C_1'(R_t)q_t - \frac{\lambda_3 g_R}{e^{-\delta_t}}]}{C_2''(w_t) - \frac{f_{ww}}{f_w}C_2'(w_t)} \tag{28}$$

The effective impact of government policy, $\frac{-\lambda_3 g_R f_w}{e^{-\lambda_t}} > 0$, is to boost exploratory efforts by the firm.

B.3 Signing the Shadow Value of Exploration Incentives λ_3

Recall equations 21 and 27 for $\dot{\lambda}_2$ as well as 23 for $\dot{\lambda}_3$:

$$\dot{\lambda}_3 = -(\lambda_1 + \lambda_2)f_g - \lambda_3 g_R \tag{21}$$

$$\dot{\lambda}_2 = -(\lambda_1 + \lambda_2) f_x \tag{23}$$

$$\dot{\lambda}_2 = -\frac{f_x}{f_w} C_2'(w_t) e^{-\delta_t} \tag{27}$$

Rearrange 21:

$$\frac{\dot{\lambda}_2}{f_x} = -(\lambda_1 + \lambda_2) \tag{29}$$

Substitute 24 into 29.

$$\frac{-\frac{f_x}{f_w} C_2'(w_t) e^{-\delta_t}}{f_x} = -(\lambda_1 + \lambda_2)$$

$$\frac{-C_2'(w_t) e^{-\delta_t}}{f_w} = -(\lambda_1 + \lambda_2) \tag{30}$$

Substitute 30 into 23.

$$\dot{\lambda}_3 = -\frac{f_g}{f_w} C_2'(w_t) e^{-\delta_t} - \lambda_3 g_R > 0 \tag{31}$$

C Inconsistent Policy

We now consider the impact of a carbon tax $\tau(R_t)$ alongside exploration incentives. As before, each unit of production is taxed at rate $\tau(R_t)$ where $\tau'(R_t) > 0$. We also introduce the government term $g(R_t)$ with $g'(R_t) < 0$ and $\dot{g} = y(R_t$. The impact of government policy affects the firm's decision to explore such that $\dot{x} = f(w_t, x_t, g_t)$. All other assumptions and functional forms remain in the format presented in [93]. Given initial conditions for reserves R_0 and cumulative reserve additions x_0, firms maximize welfare such that:

$$Max_{q,w} \quad \int_0^T [q_t p_t - C_1(R_t)q_t - C_2(w_t) - \tau(R_t)q_t]e^{-\delta t}dt \tag{32}$$

$$s.t. \quad \dot{R_t} = \dot{x_t} - q_t \tag{33}$$

$$\dot{x} = f(w_t, x_t, g_t) \tag{34}$$

$$\dot{R_t} = y(R_t) \tag{35}$$

$$R_t \geq 0, q_t \geq 0, w_t \geq 0, x_t \geq 0$$

The Hamiltonian for the optimization problem is:

$$\begin{aligned} H = q_t p_t e^{-\delta_t} - C_1(R_t)q_t e^{-\delta_t} - C_2(w_t)e^{-\delta_t} - \tau(R_t)q_t p e^{-\delta_t} + \\ \lambda_1[f(w_t, x_t) - q_t] + \lambda_2[f(w_t, x_t)] + \lambda_3[g(R_t] \end{aligned} \tag{36}$$

Since H is linear in q, each producer should produce either nothing or at some maximum capacity level. Our first order conditions starting with the reserves:

$$\frac{\partial H}{\partial R} \rightarrow \dot{\lambda}_1 - C_1'(R_t)q_t e^{-\delta_t} - \tau'(R_t)q_t e^{-\delta_t} + \lambda_3 g_R$$

Solve for the shadow value of additional reserves:

$$\dot{\lambda}_1 = [C_1'(R_t) + \tau'(R_t)]q_t e^{-\delta_t} - \lambda_3 g_R \tag{37}$$

Taking the first order condition for x_t:

$$\frac{\partial H}{\partial x} \rightarrow \dot{\lambda}_2 - \lambda_1 f_x - \lambda_2 f_x = 0$$

We simplify and solve:

$$\dot{\lambda}_2 = -(\lambda_1 + \lambda_2) f_x \tag{38}$$

We now take the first order condition with respect to reserve additions q_t:

$$\frac{\partial H}{\partial q} = p_t e^{-\delta_t} - C_1(R_t)e^{-\delta_t} - \tau(R_t)e^{-\delta_t} - \lambda_1 = 0$$

And solve for the market clearing condition to find that the change in value of future profits from one additional unit of additional reserves is equal to the rents less the value of the tax:

$$\lambda_1 = [p_t - C_1(R_t) - \tau(R_t)]e^{-\delta t} \tag{39}$$

C.1 Optimal Price Pathway

We take the market clearing condition (equation 39) and differentiate it with respect to time.

$$\begin{aligned}\dot{\lambda}_1 = \dot{p}e^{-\delta_t} + p_t(-\delta_t)e^{-\delta_t} - C_1'(R_t)\dot{R}e^{-\delta_t} \\ - C_1(R_t)(-\delta)e^{-\delta_t} - \dot{R}\tau'(R_t)C_1'(R_t)e^{-\delta_t} - \tau(R_t)(-\delta_t)e^{-\delta_t}\end{aligned}$$

We substitute for $\dot{R}$:

$$\begin{aligned}\dot{\lambda}_1 = \dot{p}e^{-\delta_t} + p_t(-\delta_t)e^{-\delta_t} - C_1'(R_t)[f(w_t, x_t) - q_t]e^{-\delta_t} \\ - C_1(R_t)(-\delta_t)e^{-\delta_t} - \dot{R}\tau'(R_t)C_1'(R_t)[f(w_t, x_t, g_t) - q_t]e^{-\delta_t} - \tau(R_t)(-\delta_t)e^{-\delta_t}\end{aligned}$$

We set this equal to equation 37, simplify, and rearrange to solve for the price pathway:

$$\dot{p} = \delta_t[p_t - C_1(R_t) - \tau(R_t)] + f(w_t, x_t, g_t)[C_1'(R_t) + \tau'(R_t)] - \frac{\lambda_3 g_R}{e^{-\delta_t}} \tag{40}$$

Equation 40 shows that the tax affects the price pathway in two ways. First, it slows the rise in prices by lowering rents. Second, because the tax is an increasing function of reserves, the tax also hastens the rise in prices through exploration. In other words, prices have to rise faster to account for the fact that exploration increases the tax rate.

C.2 Optimal Pathway for Exploration

Finally, we differentiate the Hamiltonian with respect to w_t:

$$\frac{\partial H}{\partial w} \rightarrow C_2'(w_t)e^{\delta_t} = f_w(\lambda_1 + \lambda_2)$$

We rearrange:

$$\frac{C_2'(w_t)e^{-\delta_t}}{f_w} = \lambda_1 + \lambda_2$$

We substitute 39 for λ_1:

$$\frac{C_2'(w_t)e^{-\delta_t}}{f_w} = p_t e^{-\delta_t} - C_1(R_t)e^{-\delta_t} - \tau(R_t)e^{-\delta_t}$$

Rearranging:

$$\frac{C_2'(w_t)e^{-\delta_t}}{f_w} = p_t e^{-\delta_t} - C_1(R_t)e^{-\delta_t} - \tau(R_t)e^{-\delta_t} + \lambda_2$$

Solving for λ_2:

$$\lambda_2 = C_2'(w_t)e^{-\delta_t} f_w - p_t e^{-\delta_t} + C_1(R_t)e^{-\delta_t} + \tau(R_t)e^{-\delta_t} \tag{41}$$

Substitute 39 and 41 into 38:

$$\begin{aligned}\dot{\lambda}_2 = -[p_t e^{-\delta_t} - C_1(R_t)e^{-\delta_t} - \tau(R_t)e^{-\delta_t} + \frac{C_2'(w_t)e^{-\delta_t}}{f_w} - p_t e^{-\delta_t} \\ + C_1(R_t)e^{-\delta_t} + \tau(R_t)e^{-\delta_t}]f_x\end{aligned}$$

Simplify:

$$\dot{\lambda}_2 = -[\frac{f_x}{f_w}]C_2'(w_t)e^{-\delta_t} \tag{42}$$

Take the time derivative of equation 41:

$$\begin{aligned}\dot{\lambda}_2 = \frac{[C_2''(w_t)\dot{w}e^{-\delta_t} + C_2'(w_t)(-\delta)e^{-\delta_t}]f_w - C_2'(w_t)e^{-\delta_t}[f_{ww}\dot{w} + f_{wx}\dot{x}]}{(f_w)^2} \\ - \dot{p}e^{-\delta_t} - p_t(-\delta_t)e^{-\delta_t} + C_1'(R_t)\dot{R}e^{-\delta_t} + C_1(R_t)(-\delta_t)e^{-\delta_t} \\ + \tau'(R_t)\dot{R}e^{-\delta_t} + \tau(R_t)(-\delta_t)e^{-\delta_t}\end{aligned}$$

Substitute with 33, 34, and 40 and reduce:

$$\begin{aligned}\dot{\lambda}_2 = \frac{C_2''(w_t)\dot{w}e^{-\delta_t} - C_2'(w_t)f_{ww}\dot{w}e^{-\delta_t}}{(f_w)^2}&\\ + \frac{-\delta_t C_2'(w_t)f_w e^{-\delta_t} - C_2'(w_t)f_{wx}[f(w_t, x_t.g_t)]e^{-\delta_t}}{(f_w)^2}&\\ - [C_1'(R_t)[f(w_t, x_t, g_t)] + \tau'(R_t)[f(w_t, x_t, g_t) - q + 1]&\\ + \delta_t[p_t - C_1(R_t) - \tau(R_t)] - \frac{\lambda_3 g_R}{e^{-\delta_t}}]e^{-\delta_t} + \delta_t p_t e^{-\delta_t}&\\ + C_1'(R_t)[f(w_t, x_t, g_t) - q]e^{-\delta_t} - \delta_t C_1(R_t)e^{-\delta_t}&\\ + \tau'(R_t)[f(w_t, x_t, g_t) - q]e^{-\delta_t} - \delta_t \tau(R_t)e^{-\delta_t}&\end{aligned}$$

Grouping for $\dot{w}$ and we reducing, we set it equal to 42:

$$\begin{aligned}-[\frac{f_x}{f_w}]C_2'(w_t)e^{-\delta_t} = &\\ \dot{w}\frac{C_2''(w_t)f_w e^{-\delta_t} - C_2'(w_t)f_{ww}e^{-\delta_t}}{(f_w)^2}&\\ - \frac{\delta_t C_2'(w_t)e^{-\delta_t}}{f_w} - \frac{C_2'(w_t)f_{wx}[f(w_t, x_t, g_t)]e^{-\delta_t}]}{(f_w)^2}&\\ - \tau'(R_t)e^{-\delta_t} + \lambda_3 g_R - C_1'(R_t)q_t e^{-\delta_t}&\end{aligned}$$

Reduce and solve for the equation of motion for exploration:

$$\dot{w} = \frac{C_2'(w_t)[\frac{f_{wx}}{f_w}[f(w_t, x_t, g_t) + \delta_t - f_x] + f_w[C_1'(R_t)q_t + \tau'(R_t)q_t - \frac{\lambda_3 g_R}{e^{-\delta_t}}]}{C_2''(w_t) - C_2'(w_t)(\frac{f_{ww}}{f_w})} \tag{44}$$

D Original Pindyck Model

Solving for the original Pindyck model:

$$Max_{q,w} \quad \int_{0}^{T} [q_t p_t - C_1(R_t)q_t - C_2(w_t)]e^{-\delta t}dt \tag{45}$$

$$s.t. \quad \dot{R}_t = \dot{x}_t - q_t \tag{46}$$

$$\dot{x}_t = f(w_t, x_t) \tag{47}$$

$$R_t \geq 0, q_t \geq 0, w_t \geq 0, x_t \geq 0$$

The Hamiltonian for the optimization problem is:

$$H = q_t p_t e^{-\delta_t} - C_1(R_t)q_t e^{-\delta_t} - C_2(w_t)e^{-\delta_t} + \lambda_1[f(w_t, x_t) - q_t] + \lambda_2[f(w_t, x_t)] \tag{48}$$

Since H is linear in q, each producer should produce either nothing or at some maximum capacity level. Our first order conditions starting with the reserves:

$$\frac{\partial H}{\partial R} \rightarrow \dot{\lambda}_1 - C_1'(R_t)q_t e^{-\delta_t}$$

Solve for the shadow value of additional reserves:

$$\dot{\lambda}_1 = C_1'(R_t)q_t e^{-\delta} = 0 \tag{49}$$

Taking the first order condition for x_t:

$$\frac{\partial H}{\partial x} \rightarrow \dot{\lambda}_2 - \lambda_1 f_x - \lambda_2 f_x = 0$$

We simplify and solve:

$$\dot{\lambda}_2 = -(\lambda_1 + \lambda_2) f_x \tag{50}$$

We now take the first order condition with respect to reserve additions q_t:

$$\frac{\partial H}{\partial q} = p_t e^{-\delta_t} - C_1(R_t) e^{-\delta_t} - \lambda_1 = 0$$

And solve for the market clearing condition to find that the change in value of future profits from one additional unit of additional reserves is equal to the rents less the value of the tax:

$$\lambda_1 = [p_t - C_1(R_t)] \tag{51}$$

D.1 Deriving the Price Pathway

We take the market clearing condition (equation 51) and differentiate it with respect to time.

$$\dot{\lambda}_1 = \dot{p} e^{-\delta_t} + p_t(-\delta_t) e^{-\delta_t} - C_1'(R_t) \dot{R} e^{-\delta_t} - C_1(R_t)(-\delta_t) e^{-\delta_t}$$

We substitute for $\dot{R}$:

$$\dot{\lambda}_1 = \dot{p} e^{-\delta_t} + p_t(-\delta_t) e^{-\delta_t} - C_1'(R_t)[f(w_t, x_t) - q_t] e^{-\delta_t} - C_1(R_t)(-\delta_t) e^{-\delta_t}$$

We set this equal to equation 6:

$$[C_1'(R_t) = \dot{p} e^{-\delta_t} + p_t(-\delta_t) e^{-\delta_t} - C_1'(R_t)[f(w_t, x_t) - q_t] e^{-\delta_t} \\ - C_1(R_t)(-\delta_t) e^{-\delta_t}$$

Finally, we simplify and rearrange to solve for the price pathway with taxes:

$$\dot{p} = \delta_t [p_t - C_1(R_t)] + C_1'(R_t) f(w_t, x_t) \tag{52}$$

Equation 52 shows that the tax affects the price pathway in two ways. First, it slows the rise in prices by lowering rents. Second, because the tax is an increasing function of reserves, the tax also hastens the rise in prices through exploration. In other words, prices have to rise faster to account for the fact that exploration increases the tax rate.

D.2 Deriving the optimal pathway for exploration

Finally, we differentiate the Hamiltonian with respect to w_t:

$$\frac{\partial H}{\partial w} \rightarrow C_2'(w_t)_2 e^{\delta_t} = f_w(\lambda_1 + \lambda_2)$$

We rearrange:

$$\frac{C_2'(w_t)e^{-\delta_t}}{f_w} = \lambda_1 + \lambda_2$$

We substitute 51 for λ_1:

$$\frac{C_2'(w_t)e^{-\delta_t}}{f_w} = p_t e^{-\delta_t} - C_1(R_t)e^{-\delta_t}$$

Rearranging:

$$\frac{C_2'(w_t)e^{-\delta_t}}{f_w} = p_t e^{-\delta_t} - C_1(R_t)e^{-\delta_t}\lambda_2$$

Solving for λ_2:

$$\lambda_2 = C_2'(w_t)e^{-\delta_t} f_w - p_t e^{-\delta_t} + C_1(R_t)e^{-\delta_t} \tag{53}$$

Substitute 51 and 53 into 50:

$$\dot{\lambda}_2 = -[p_t e^{-\delta_t} - C_1(R_t)e^{-\delta_t} + \frac{C_2'(w_t)e^{-\delta_t}}{f_w} - p_t e^{-\delta_t} + C_1(R_t)e^{-\delta_t}$$

Simplify:

$$\dot{\lambda}_2 = -[\frac{f_x}{f_w}]C_2'(w_t)e^{-\delta_t} \tag{54}$$

Take the time derivative of equation 53:

$$\begin{aligned}\dot{\lambda}_2 = &\frac{[C_2''(w_t)\dot{w}e^{-\delta_t} + C_2'(w_t)(-\delta_t)e^{-\delta_t}]f_w - C_2'(w_t)e^{-\delta_t}[f_{ww}\dot{w} + f_{wx}\dot{x}]}{(f_w)^2} \\ &- \dot{p}e^{-\delta_t} - p_t(-\delta_t)e^{-\delta_t} + C_1'(R_t)\dot{R}e^{-\delta_t} + C_1(R_t)(-\delta_t)e^{-\delta_t}\end{aligned}$$

Substitute with 46, 47, and 52 and reduce:

$$\begin{aligned}\dot{\lambda}_2 = &\frac{[C_2''(w_t)\dot{w}e^{-\delta_t} + C_2'(w_t)(-\delta_t)e^{-\delta_t}]f_w}{(f_w)^2} \\ &- \frac{C_2'(w_t)e^{-\delta_t}[f_{ww}\dot{w} + f_{wx}[f(w_t, x_x)]]}{(f_w)^2} \\ &- C_1'(R_t)(q_t)e^{-\delta_t}\end{aligned}$$

Grouping for $\dot{w}$:

$$\begin{aligned}\dot{\lambda}_2 = &\dot{w}\frac{[C_2''(w_t)e^{-\delta_t}f_w + C_2''(w_t)e^{-\delta_t}f_{ww}]}{(f_w)^2} \\ &- \frac{[\delta_t C_2'(w_t)e^{-\delta_t}f_w e^{-\delta_t} - C_2'(w_t)e^{-\delta_t}f_{wx}[f(w_t, x_t)]e^{-\delta_t}]}{(f_w)^2} \\ &- C_1'(R_t)(q_t)e^{-\delta_t}\end{aligned} \tag{55}$$

Set 54 = 55:

$$-[\frac{f_x}{f_w}]C_2'(w_t)e^{-\delta_t} = \dot{w}\frac{[C_2''((w_t)e^{-\delta_t}f_w + C_2''((w_t)e^{-\delta_t}f_{ww}]}{(f_w)^2} - \frac{[\delta_t C_2'(w_t)e^{-\delta_t}f_w e^{-\delta_t} - C_2'(w_t)e^{-\delta_t}f_{wx}[f(w_t, x_t)]e^{-\delta_t}]}{(f_w)^2} - C_1'(R_t)(q_t)e^{-\delta_t}$$

Reduce and solve for the equation of motion for exploration:

$$\dot{w} = \frac{C_2'(w_t)[\frac{f_{wx}}{f_w}[f(w_t, x_t) - q_t] + \delta_t - f_x] + C_1'(R_t)f_w q_t}{C''(w_t) - C_2'(w_t)[\frac{f_{ww}}{f_w}]} \tag{56}$$

E Transversality Condition

Assuming there is no cost of cumulative discoveries x in the terminal period of production T, the shadow value of additional exploration is zero such that:

$$\frac{C_2'(0)}{f_w(0)} = 0$$

$$\lambda_2(T) = 0$$

Given that, we know from equation (8) that at time T that $p_T = C_1(R_T)$. This represents the choke price after which additional production is not economical. This makes that the shadow price of production is zero, $\lambda_1 \to 0$.

Suppose that the marginal discovery cost is not zero such that $\frac{C_2'(0)}{f_w(0)} = \phi > 0$. At some time T_1 that occurs before the terminal period of production T, we observe that $w \to 0$ before $q \to 0$ so that $\lambda_2(T_1) = 0$.

Recall 51 and 53:

$$\lambda_1 = [p_t - C_1(R_t)] \tag{51}$$

$$\lambda_2 = C_2'(w_t)e^{-\delta_t} f_w - p_t e^{-\delta_t} + C_1(R_t)e^{-\delta_t} \tag{53}$$

From 51 and 53, we find that $p - C_1(R) = \phi$ and that $\phi e^{-\delta_t}$. Deriving with respect to t and substituting equation 49, we find that $C_1'(R)qe^{\delta_t} = -\delta\phi$. Rearranging, we find that as $w \to 0$ in time T_1:

$$p_t - C_1(R_t) \to \phi \tag{A}$$

$$\frac{-C_1' q_t}{\delta_t} \to \phi \tag{B}$$

The last additional unit of reserves should be discovered when marginal discovery costs ϕ equals:

- Net revenue obtained by extraction reserves to sell, and
- Storage values, i.e. PDV of all future extraction costs.

F Carbon Taxes as a Function of Reserves

We now consider the impact of a carbon tax $\tau(R_t)$ on the trade-off between exploration and production. Each unit of production is taxed at rate $\tau(R_t)$ where $\tau'(R_t) > 0$. All other assumptions and functional forms remain in the format presented in [93]. Given initial conditions for reserves R_0 and cumulative reserve additions x_0, firms maximize welfare such that:

$$Max_{q,w} \quad \int_0^T [q_t p_t - C_1(R_t)q_t - C_2(w_t) - \tau(R_t)q_t]e^{-\delta t}dt \tag{57}$$

$$s.t. \quad \dot{R}_t = \dot{x}_t - q_t \tag{58}$$

$$\dot{x}_t = f(w_t, x_t) \tag{59}$$

$$R_t \geq 0, q_t \geq 0, w_t \geq 0, x_t \geq 0 \tag{60}$$

The Hamiltonian for the optimization problem is:

$$H = q_t p_t e^{-\delta_t} - C_1(R_t)q_t e^{-\delta_t} - C_2(w_t)e^{-\delta_t} - \tau(R_t)q_t p e^{-\delta_t} + \\ \lambda_1[f(w_t, x_t) - q_t] + \lambda_2[f(w_t, x_t)] \tag{61}$$

Since H is linear in q, each producer should produce either nothing or at some maximum capacity level. We derive our first order conditions starting with the reserves:

$$\frac{\partial H}{\partial R} \rightarrow \dot{\lambda}_1 - C_1'(R_t)q_t e^{-\delta_t} - \tau'(R_t)q_t e^{-\delta_t}$$

Solve for the shadow value of additional reserves:

$$\dot{\lambda}_1 = [C_1'(R_t) + \tau'(R_t)]q_t e^{-\delta_t} = 0 \tag{62}$$

Taking the first order condition for x_t:

$$\frac{\partial H}{\partial x} \rightarrow \dot{\lambda}_2 - \lambda_1 f_x - \lambda_2 f_x = 0$$

We simplify and solve:

$$\dot{\lambda}_2 = -(\lambda_1 + \lambda_2) f_x \tag{63}$$

We now take the first order condition with respect to production q_t:

$$\frac{\partial H}{\partial q} = p_t e^{-\delta_t} - C_1(R_t)e^{-\delta_t} - \tau(R_t)e^{-\delta_t} - \lambda_1 = 0$$

And solve for the market clearing condition to find that the change in value of future profits from one additional unit of additional reserves is equal to the rents less the value of the tax:

$$\lambda_1 = [p_t - C_1(R) - \tau(R_t)]e^{-\delta t} \tag{64}$$

F.1 Deriving the Price Pathway

We take the market clearing condition (equation 64) and differentiate it with respect to time.

$$\begin{aligned}\dot{\lambda}_1 = \dot{p}e^{-\delta_t} + p_t(-\delta_t)e^{-\delta_t} - C_1'(R_t)\dot{R}e^{-\delta_t}& \\ - C_1(R_t)(-\delta_t)e^{-\delta_t} - \tau'(R_t)\dot{R}e^{-\delta_t} - \tau(R_t)(-\delta_t)e^{-\delta_t}&\end{aligned}$$

We substitute for $\dot{R}$:

$$\begin{aligned}\dot{\lambda}_1 = \dot{p}e^{-\delta_t} + p_t(-\delta_t)e^{-\delta_t} - C_1'(R_t)\dot{R}e^{-\delta_t}& \\ - C_1(R_t)(-\delta_t)e^{-\delta_t} - \tau'(R_t)\dot{R}e^{-\delta_t} - \tau(R_t)(-\delta_t)e^{-\delta_t}&\end{aligned}$$

We set this equal to equation 62:

$$\begin{aligned}
&[C_1'(R_t) + \tau'(R_t)]q_t e^{-\delta_t} = \\
&\qquad \dot{p}e^{-\delta_t} + p_t(-\delta_t)e^{-\delta_t} - C_1'(R_t)[f(w_t, x_t) - q_t]e^{-\delta_t} \\
&\qquad - C_1(R_t)(-\delta_t)e^{-\delta_t} - \dot{R}\tau'(R_t)C_1'(R_t)[f(w_t, x_t) - q_t]e^{-\delta_t} \\
&\qquad\qquad - \tau(R_t)(-\delta_t)e^{-\delta_t}
\end{aligned}$$

Finally, we simplify and rearrange to solve for the price pathway with taxes:

$$\dot{p} = \delta_t[p_t - C_1(R_t) - \tau(R_t)] + f(w_t, x_t)[C_1'(R_t) + \tau'(R_t)] \tag{65}$$

Equation 65 shows that the tax affects the price pathway in two ways. First, it slows the rise in prices by lowering rents. Second, because the tax is an increasing function of reserves, the tax also hastens the rise in prices through exploration. In other words, prices have to rise faster to account for the fact that exploration increases the tax rate.

F.2 Deriving the Optimal Pathway for Exploration

Finally, we differentiate the Hamiltonian with respect to w_t:

$$\frac{\partial H}{\partial w} \rightarrow C_2'(w_t)e^{-\delta_t} = f_w(\lambda_1 + \lambda_2)$$

We rearrange:

$$\frac{C_2'(w_t)e^{-\delta_t}}{f_w} = \lambda_1 + \lambda_2$$

We substitute 64 for λ_1:

$$\frac{C_2'(w_t)e^{-\delta_t}}{f_w} = p_t e^{-\delta_t} - C_1(R_t)e^{-\delta_t} - \tau(R_t)e^{-\delta_t} + \lambda_2$$

Rearranging:

$$\frac{C_2'(w_t)e^{-\delta_t}}{f_w} = p_t e^{-\delta_t} - C_1(R_t)e^{-\delta_t} - \tau(R_t)e^{-\delta_t} + \lambda_2$$

Solving for λ_2:

$$\lambda_2 = \frac{C_2'(w_t)e^{-\delta_t}}{f_w} - p_t e^{-\delta_t} + C_1(R_t)e^{-\delta_t} + \tau(R_t)e^{-\delta_t} \tag{66}$$

Substitute 64 and 66 into 63:

$$\dot{\lambda}_2 = -[p_t e^{-\delta_t} - C_1(R_t)e^{-\delta_t} - \tau(R_t)e^{-\delta_t} + \frac{C_2'(w_t)e^{-\delta_t}}{f_w} - p_t e^{-\delta_t} \\ + C_1(R_t)e^{-\delta_t} + \tau(R_t)e^{-\delta_t}]f_x$$

Simplify:

$$\dot{\lambda}_2 = -[\frac{f_x}{f_w}]C_2'(w_t)e^{-\delta_t} \tag{67}$$

Take the time derivative of equation 66:

$$\dot{\lambda}_2 = \frac{[C_2''(w_t)\dot{w}e^{-\delta_t} + C_2'(w_t)(-\delta_t)e^{-\delta_t}]f_w - C_2'(w_t)e^{-\delta_t}[f_{ww}\dot{w} + f_{wx}\dot{x}]}{(f_w)^2} \\ - \dot{p}e^{-\delta_t} - p_t(-\delta_t)e^{-\delta_t} + C_1'(R_t)\dot{R}e^{-\delta_t} + C_1(R_t)(-\delta_t)e^{-\delta_t} \\ + \tau'(R_t)\dot{R}e^{-\delta_t} + \tau(R_t)(-\delta_t)e^{-\delta_t}$$

Substitute with 58, 59, and 65 and reduce:

$$\begin{aligned}\dot{\lambda}_2 = \frac{[C_2''(w_t)\dot{w}e^{-\delta_t} + C_2'(w_t)(-\delta_t)e^{-\delta_t}]f_w}{(f_w)^2} \\ - \frac{C_2'(w_t)e^{-\delta_t}[f_{ww}\dot{w} + f_{wx}[f(w_t, x_x)]]}{(f_w)^2} \\ - C_1'(R_t)(q_t)e^{-\delta_t} - \tau'(R_t)(q_t)e^{-\delta_t}\end{aligned}$$

Grouping for $\dot{w}$:

$$\begin{aligned}\dot{\lambda}_2 = \dot{w}\frac{[C_2''((w_t)e^{-\delta_t}f_w - C_2''((w_t)e^{-\delta_t}f_{ww}]}{(f_w)^2} \\ - \frac{[\delta_t C_2'(w_t)e^{-\delta_t}f_w e^{-\delta_t} - C_2'(w_t)e^{-\delta_t}f_{wx}[f(w_t, x_t)]e^{-\delta_t}]}{(f_w)^2} \\ - C_1'(R_t)(q_t)e^{-\delta_t} - \tau'(R_t)(q_t)e^{-\delta_t}\end{aligned} \tag{68}$$

Set 68 = 67:

$$\begin{aligned}-[\frac{f_x}{f_w}]C_2'(w_t)e^{-\delta_t} = \dot{w}\frac{[C_2''(w_t)e^{-\delta_t}f_w - C_2'(w_t)e^{-\delta_t}f_{ww}]}{(f_w)^2} \\ - \frac{[\delta_t C_2'(w_t)e^{-\delta_t}f_w e^{-\delta_t} - C_2'(w_t)e^{-\delta_t}f_{wx}[f(w_t, x_t)]e^{-\delta_t}]}{(f_w)^2} \\ - C_1'(R_t)(q_t)e^{-\delta_t} - \tau'(R_t)(q_t)e^{-\delta_t}\end{aligned}$$

Reduce and solve for the equation of motion for exploration:

$$\dot{w} = \frac{C_2'(w_t)[\frac{f_{wx}}{f_w}[f(w_t, x_t) - q_t] + \delta_t - f_x] + f_w q_t[C_1'(R_t) + \tau'(R_t)]}{C''(w_t) - C_2'(w_t)[\frac{f_{ww}}{f_w}]} \tag{69}$$

G Annual Reporting Format Change

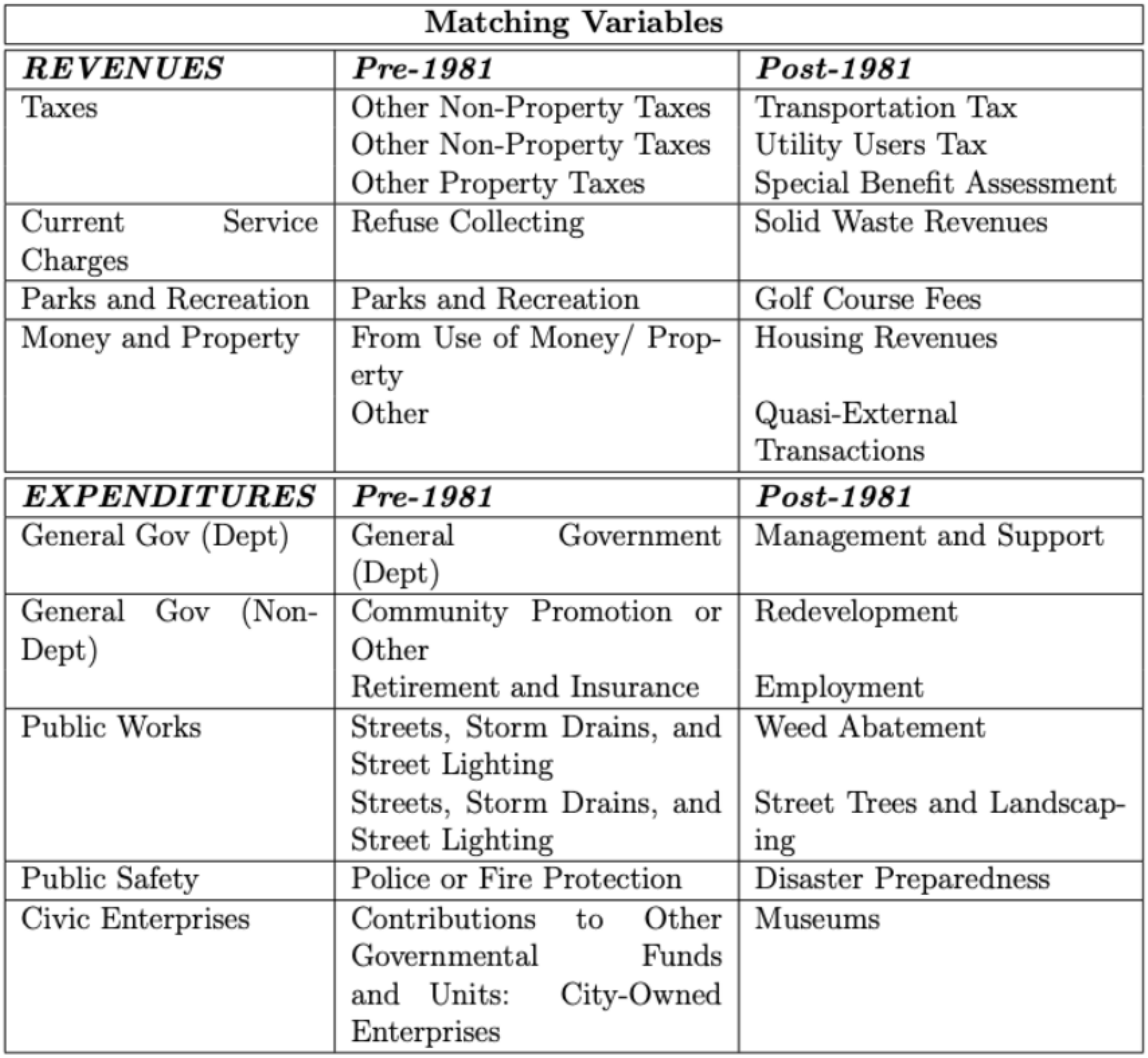
Prior to 1981, data was reported across 19 tables for each municipality by the state of California. At the time, revenue data was available in table 4, expenditures in table 5, and property assessment in table $19A$. Subsequent to the format change, all municipal data was presented in 1 table. Some granularity was lost though most data was easily reconciled across the formats. Table **??** below details cases where some thought was necessary to reconcile the different formats due to the introduction of new variables.

Revenues

Transportation Tax is included in the variable "Taxes" as 'Other Non-Property Taxes" because it is likely a local sales tax surcharge imposed under California's 1971 Transportation Development Act that allows municipalities the right to increase sales tax by 0.25% to fund local transportation projects [43]. Prior to the format change, revenues and expenditures related to Transportation Systems was presented in table 1, but the revenues listed are service-oriented and no Transportation Tax is listed.

Likewise, the Utility Users Tax (UUT) provided after the format change is also included in "Taxes" as "Other Non-Property Taxes". Water, electric, and gas utility data was listed in their own tables $(6-8)$ prior to the format change. Cursory research shows that most UUT were approved before 1986, applied to all utilities, and was heavily relied upon to replace lost property tax revenues subsequent to 1979's prop 13. It is levied by a city, county, or district, but collected by the utility before being remitted to the government levying the tax [2]. As such, it is treated as "Other Non-Property Tax" revenue for the municipalities.

Table 1: Variable Alignment Across Formats



Matching Variables		
REVENUES	***Pre-1981***	***Post-1981***
Taxes	Other Non-Property Taxes Other Non-Property Taxes Other Property Taxes	Transportation Tax Utility Users Tax Special Benefit Assessment
Current Service Charges	Refuse Collecting	Solid Waste Revenues
Parks and Recreation	Parks and Recreation	Golf Course Fees
Money and Property	From Use of Money/ Property Other	Housing Revenues Quasi-External Transactions
EXPENDITURES	***Pre-1981***	***Post-1981***
General Gov (Dept)	General Government (Dept)	Management and Support
General Gov (Non-Dept)	Community Promotion or Other Retirement and Insurance	Redevelopment Employment
Public Works	Streets, Storm Drains, and Street Lighting Streets, Storm Drains, and Street Lighting	Weed Abatement Street Trees and Landscaping
Public Safety	Police or Fire Protection	Disaster Preparedness
Civic Enterprises	Contributions to Other Governmental Funds and Units: City-Owned Enterprises	Museums

Special Benefit Assessments existed prior to the passage of Proposition 13. However, the California State Legislature expanded local government powers to introduce special benefit assessments (see link). I include Special Benefit Assessments in the category of ”Taxes” as ”Other Property Taxes” based on the earlier organization of data. While the earlier format included Table 18C for ”Special Assessment Act Bonds, An Obligation of Benefited Property”, a ”Special Benefit Assessment” is a property-based assessment to fund services such as police, fire, library, and parks [1].

Finally, Housing Revenues is a line item included after the format change which is reconciled as ”Money and Property” revenues as ”From Use of Money Property” while ”Quasi-External Transactions” are included as ”Other”.

Expenditures

”Management and Support” was reconciled as ”General Government - Departmental” spending as it aggregates data that had been listed by function (city clerk, city treasurer, city attorney, etc...) prior to the format change. ”Redevelopment” is considered ”General Government - Non-Departmental” under ”Community Promotion or Other” while ”Employment” expenditures are also included in this category as an amalgam of ”Retirement and Insurance”. Both ”Weed Abatement” and ”Street Trees and Landscaping” are reconciled as ”Public Works” under ”Streets, Storm Drains, and Street Lighting” as that makes the most common sense.

”Disaster Preparedness” is reconciled as ”Public Safety” under ”Police or Fire Protection” as first responders typically coordinate disaster response under the Incident Command System [19]. Finally, ”Museums” was reconciled as ”Civic Enterprise” under ”Contributions to other Government Funds and Units: City-Owned Enterprises” simply because that was the author’s best ’guesstimate’.

Some changes in accounting occur after the reporting format change in 1981. ”Construction and Engineering Regulation Enforcement” and ”Regulation Enforcement” are line items that exist after the format change as well that this paper reconciles as "Public Works" expenditures.

G.1 Cities Formed After Prop 13

Forty cities were formed within the study area after the passage of Prop 13 in 9 out of the 10 counties . Additionally, seven other cities were formed just before the passage of Prop 13. As such, these cities were removed from the study area and reported as aggregate county totals (described below). Only Santa Clara County maintained its original cohort of cities across the entire span of the study period.

To account for the incorporation of new cities within those 9 counties, expenditure and revenue data for those cities are aggregated into per capita expenditure EXP_{new} and per capita revenue REV_{new} estimations at the county-level. These totals will be set apart from all other data and act as a control for equilibrium changes in local governance that occur outside of the study group's boundaries but affect the aggregate flows of property tax revenues.

Critical to making this choice is the recognition that the formation of new cities after Prop 13 does not affect the apportionment rates for the study group as set by AB 8. The process of setting property tax rates for every city is set at 1% in the initial year of purchase and grows at a rate of 2% each year according to Prop 13. However, because newly formed cities during the study period no historical tax data prior to Prop 13, their apportionment process is not subject to AB 8 and does not induce a transfer of wealth.

The following summarizes the rational for these decisions:

- 47 cities are formed just before or after prop 13, but no cities are disbanded.
- The rate of property tax growth is 2% for all properties.
- The AB 8 apportionment rates only apply to cities that existed prior to Prop 13.

These three points underpin the identification of the cities in my study cohort. The creation of new cities after Prop 13 does not change the initial treatment of the cohort though it is likely that the creation of new cities affected the aggregate flow of property tax revenues along two pathways.

Think of new cities as either increasing the size of the property tax revenue 'pie' on the aggregate or decreasing the size of each 'slice'. To the extent that new cities form in formerly unincorporated areas of a county, historically depressed property values may rise and grow the size of property tax revenues across the county overall. To the extent that newly formed cities fractionalize an existing city's population, the flow of property tax revenues may change without growing the size of the total collected revenues.

Therefore, this paper aggregates per capita expenditures and revenues of newly formed cities into one sum. Changes in the size of captures the general changes in revenues that are directed to newly formed governments within our study area.

G.2 Distribution of Model Residuals

Figures 1 and 2 visualizes the distribution of residuals for all 24 model specifications.

G.3 Visualizing Revenue and Expenditure Pathways

Line item revenues for Fines and Penalties as well as Intergovernmental Transfers in figure 13 while line item revenues for as well as Licenses and Permits as well as Other Revenues are displayed in figure 3. Line item expenditures for Health, Libraries, and Other Expenditures are presented in figure 4.

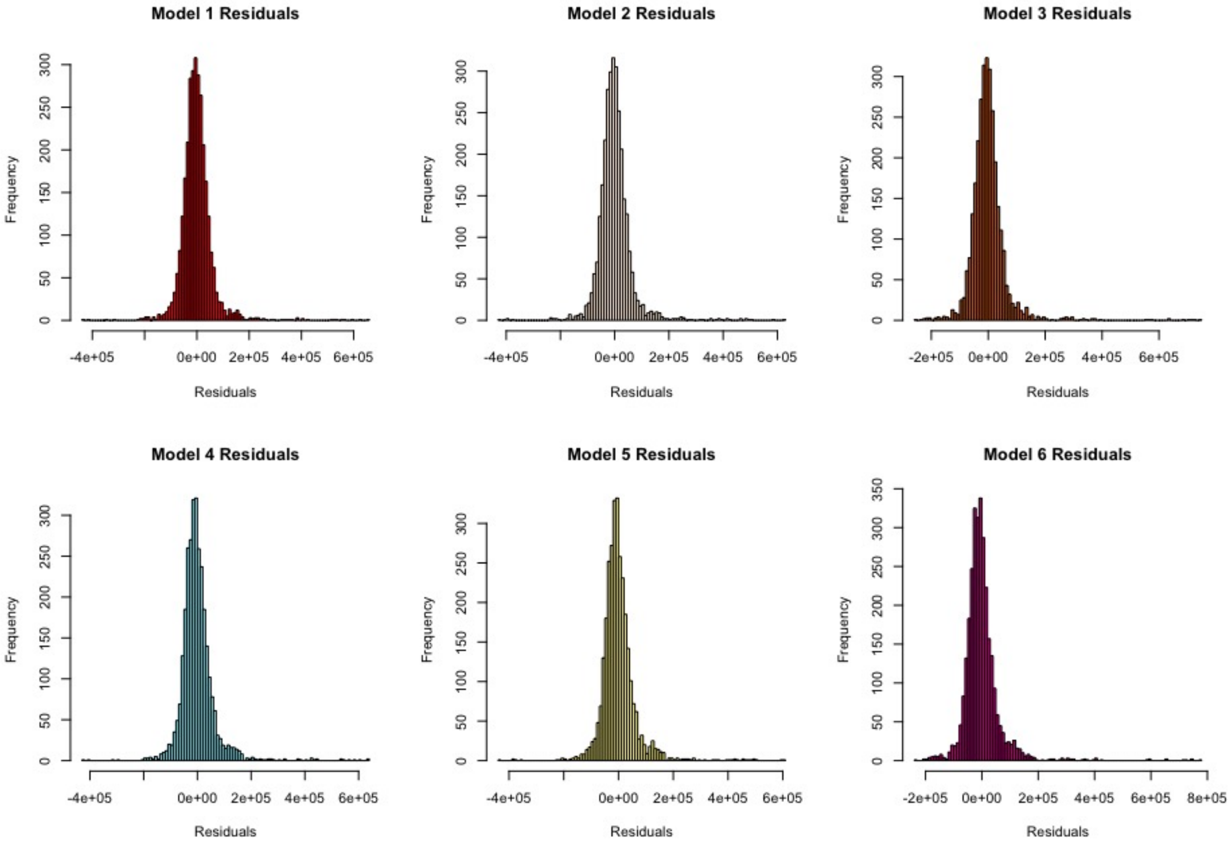


Figure 1: Distribution of Models Residuals with Expenditures

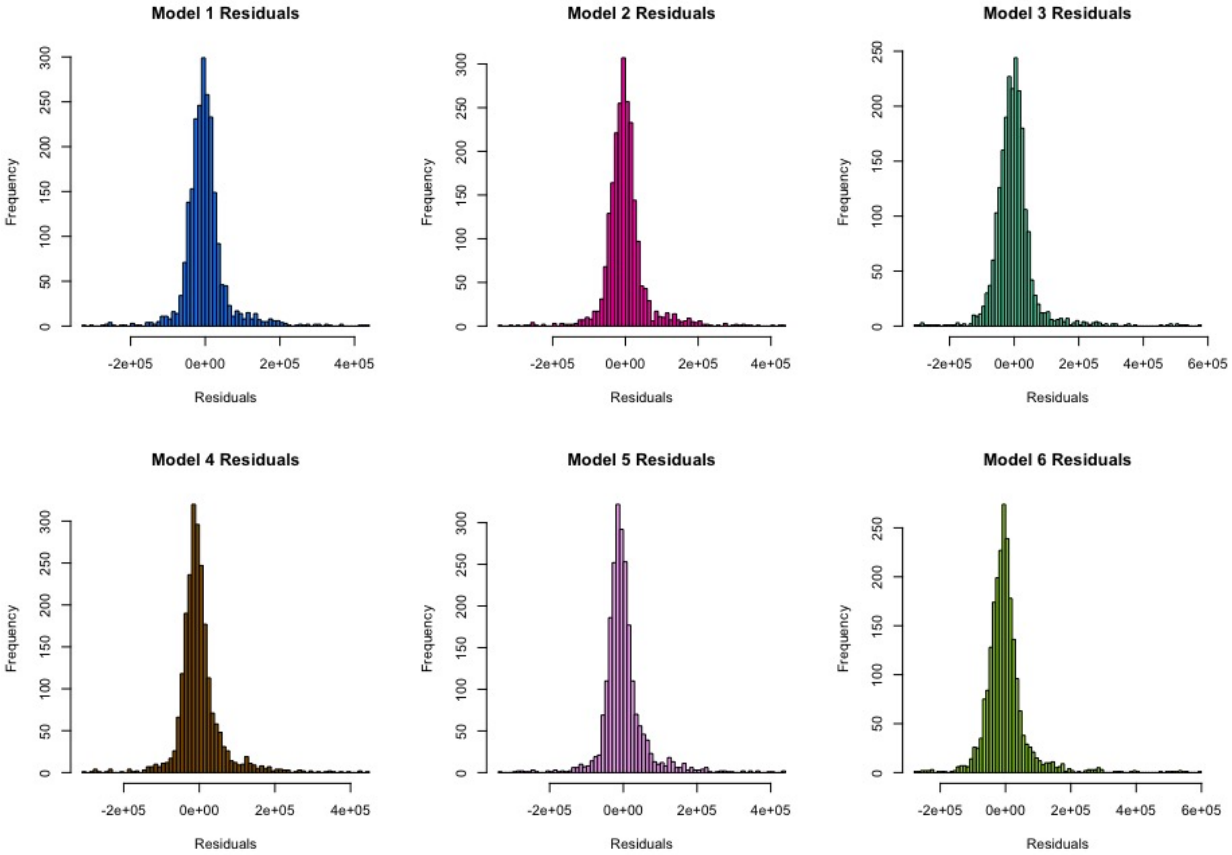


Figure 2: Distribution of Models Residuals with Revenues

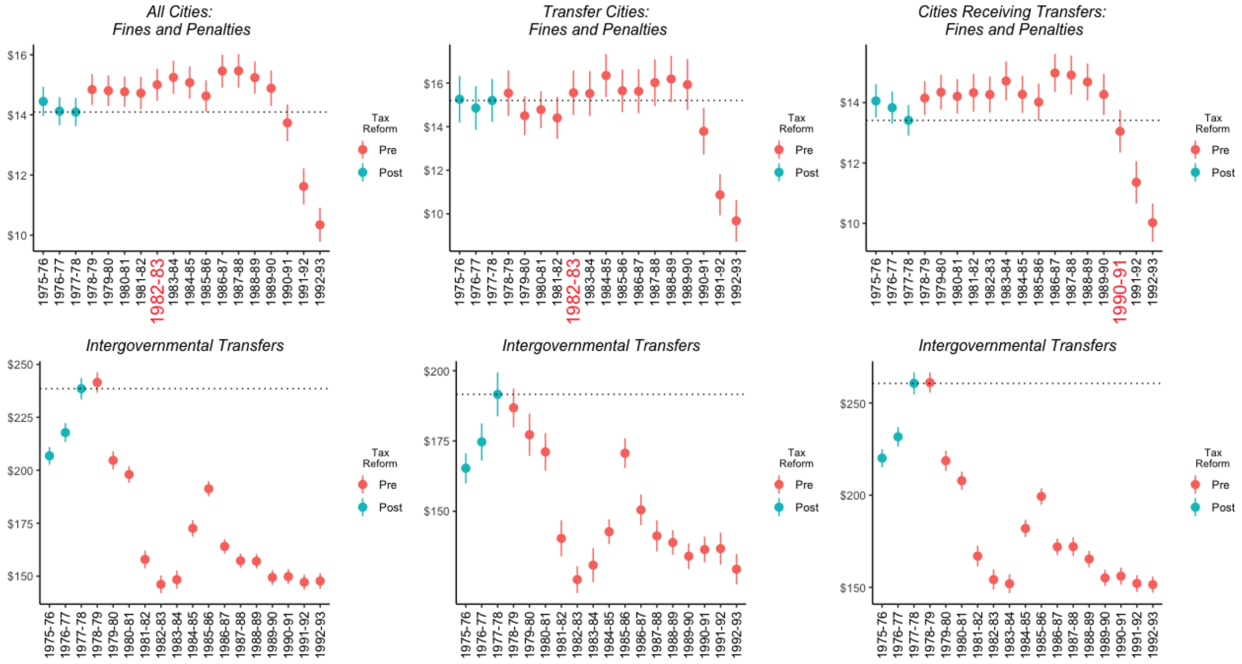


Figure 3: Changes in Revenues Collected from Fines and Penalties as well as Intergovernmental Transfers: Pre-Treatment (1975-76 to 1977-78) and Post-Treatment (1978-79 to 1992-93)

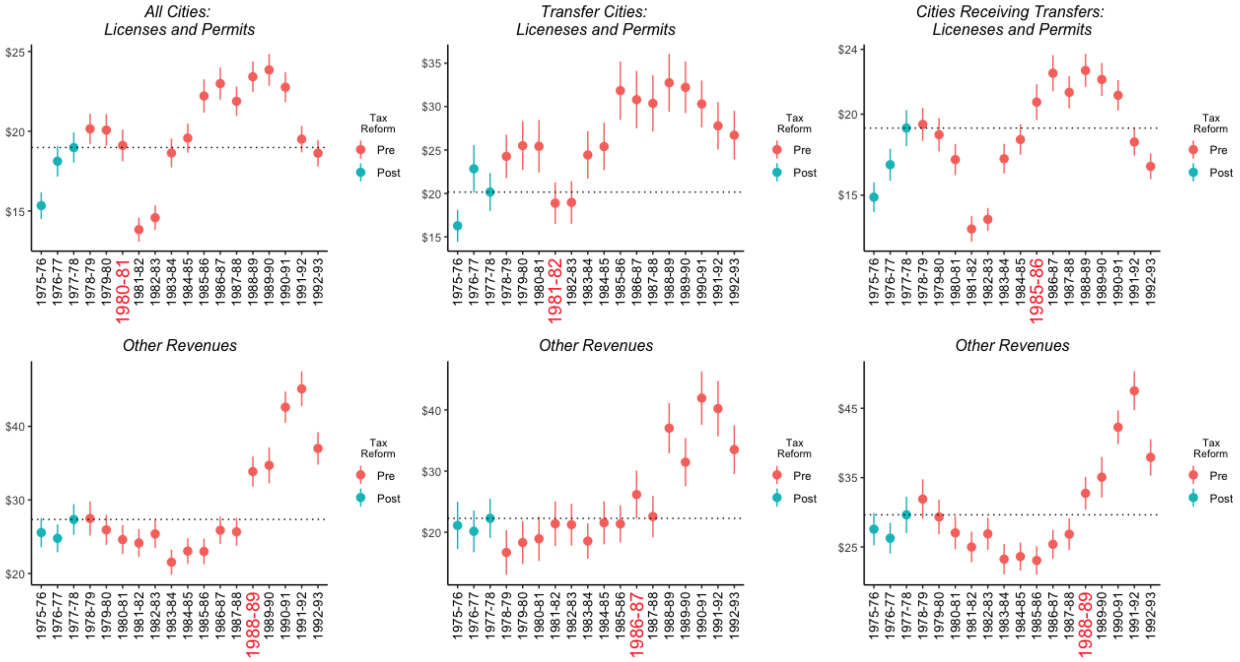


Figure 4: Changes in Revenues Collected from Licenses and Permits as well as Other Revenues: Pre-Treatment (1975-76 to 1977-78) and Post-Treatment (1978-79 to 1992-93)

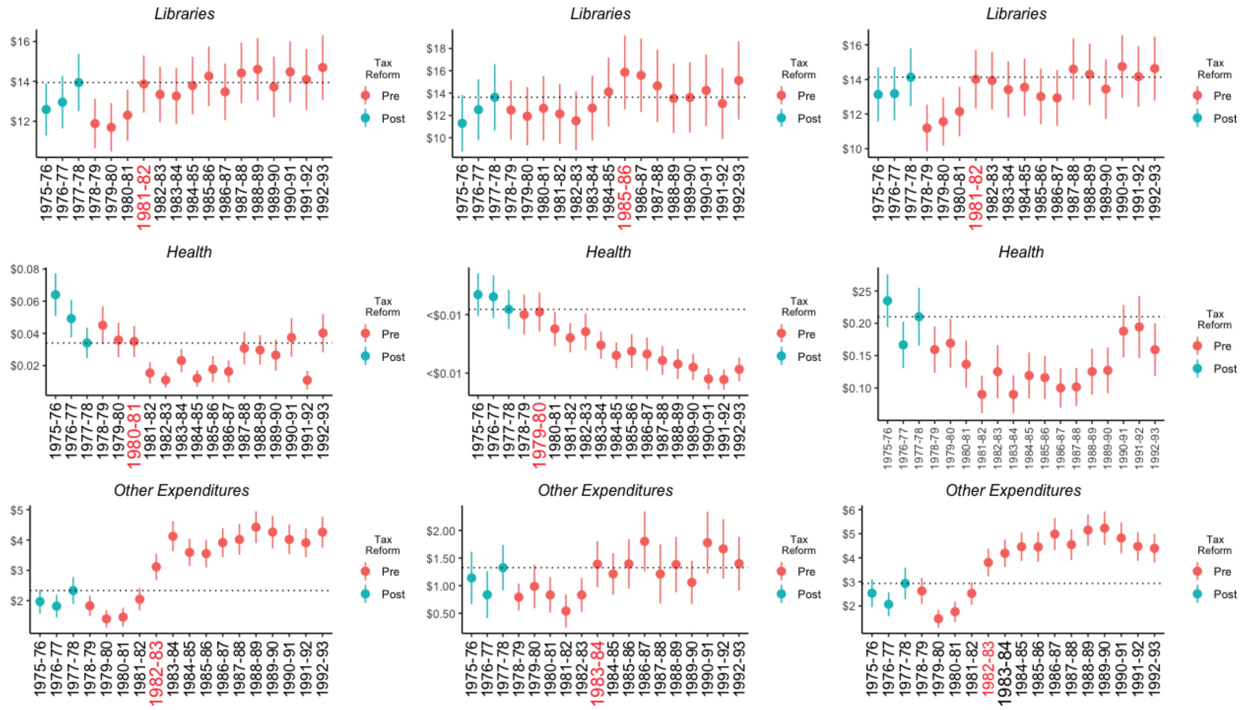


Figure 5: Changes in Revenues Collected from Licenses and Permits as well as Other Revenues: Pre-Treatment (1975-76 to 1977-78) and Post-Treatment (1978-79 to 1992-93)

Vita

Odysseus grew up in the swampy backwoods of rural Floribama in a single-wide trailer fit for none. As a youth, he was once lost at sea and in the woods, but managed to find his way to Los Angeles where he met his lovely wife and became a middle school teacher in the Echo Park neighborhood where he sidetracked his way into California politics. In 2015, he heard a rumor that colleges would pay you a stipend to get a PhD in fields like economics, so he got one and moved his wife and three small daughters to study in Tennessee.

He is a now an economist providing technical analysis and strategic thinking for Deloitte, LLP. There, he manages teams and projects for federal clients including USAID as well as the Departments of State, Energy, and Transportation. Odysseus splits his time between analyzing Ukraine's macroeconomic and fiscal health under wartime conditions and supporting the energy transition as it relates to the development of critical mineral supply chain opportunities.

Prior project work dealt with EV adoption for the Virginia Department of Transportation's 5-Year NEVI Formula Funding Plan, cost-minimization model for the NYC Bus Company's fleet electrification charging strategy, as well as the design of a framework for geospatially measuring the environmental, economic, and social benefits of federal investments under Justice40.

Some say he may try to learn piano. These rumors are not yet confirmed.