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# THREE ESSAYS ON ENVIRONMENTAL RISK AND POLICY

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THREE ESSAYS ON ENVIRONMENTAL RISK AND POLICY

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DISSERTATION

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A dissertation submitted in partial fulfillment of the
requirements for the degree of Doctor of Philosophy in the
Graduate School at the University of Kentucky

By
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ABSTRACT OF DISSERTATION

THREE ESSAYS ON ENVIRONMENTAL RISK AND POLICY

This dissertation comprises three essays that investigate different facets of environmental hazards and their implications for policy and governance. While each essay examines a different topic area, they are all linked by examining how entities respond to incentives at the intersection of environmental risk and public policy. Each chapter informs a distinct literature within environmental policy and utilizes different methodologies to examine largely unexplored research questions.

In the first essay, I examine how individuals respond to the low-visibility, long-term environmental risk presented by radon. I employ radon zone data from the Kentucky Geological Survey and home information from Zillow to test whether home in areas with higher average radon sell for less than comparable homes in lower radon areas. I utilize a boundary discontinuity design to causally answer this question by comparing the selling price of similar homes on either side of a radon boundary. I find that homes with basements in high radon areas sell for between 5% and 7% less than comparable homes in low-radon areas. My findings suggest that current radon policy of mandatory disclosure and information campaigns is communicating the risk of radon to consumers.

In the second essay, I turn my focus to whether administrative fee structure affects incentives for constructing impervious surfaces. This paper proposes a novel theory, examines a little-studied administrative entity, and utilizes large datasets that are not often used in public policy research. Specifically, I look at whether variable rate user fees based on impervious surface cover which imposed by stormwater utilities lower the total amount of impervious surface cover. To causally examine this question, I use a stacked difference-in-difference design to look at two outcomes before and after imposition of a variable rate fee: footprint size of new residential construction and total impervious surface cover drawn from the National Land Cover Database. I find that variable rate fees do not affect impervious surface cover in stormwater utility districts.

In the third essay, I explore whether federal disaster policy induces moral hazard in local governments. I leverage the fact that when a disaster is declared affected counties in a state receive recovery funds, while the entire state becomes eligible for mitigation funding. The essay provides a theoretical framework of moral hazard in local government, descriptive analysis of mitigation uptake among local governments, and a preliminary examination of differences in mitigation uptake between counties which receive a disaster declaration and those that do not. Overall, I find no conclusive evidence on moral hazard but set the stage for an ongoing research agenda.

KEYWORDS: Environmental Policy, Natural Disaster Policy, Risk Management, Urban Policy, Regression Discontinuity, Difference-in-Differences

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08/08/2024

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THREE ESSAYS IN ENVIRONMENTAL RISK AND POLICY

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To my parents for always believing in me.

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Additionally, some data were provided by Zillow through the Zillow Transaction and Assessment Dataset (ZTRAX). More information on accessing the data can be found at http://www.zillow.com/ztrax. The results and opinions are those of the author(s) and do not reflect the position of Zillow Group.

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## CHAPTER 1. INTRODUCTION

Individuals and governments make conscious or subconscious risk assessments every day. Managing risk is an essential part of functioning in the world. Environmental risks are those that are borne of factors in the natural world and affect human wellbeing. Some of these risks manifest themselves in immediate and catastrophic ways, such as a tornado striking a community, while others, like the risk of cancer caused by exposure to radon, accumulate over a lifetime. Risk mitigation is the act of taking preventative steps to reduce the likelihood of an incident occurring or the damage caused when an incident does occur. Public policy serves a role in environmental risk mitigation through actions such as information campaigns, grant programs, or fees. All of these actions may change incentives for individuals and governments to engage in risk mitigation. In my dissertation I examine three distinct areas of environmental risk to determine whether and how public policy shapes the behavior of individuals or governments. I utilize a variety of methods, theories, and datasets to examine questions that have received little attention in the public policy world. While my background and training are firmly in the social science world of public policy, my work introduces data and concepts that are common in environmental science and serve as a bridge between the two literatures.

In Chapter 1, I examine individual response to the risk of radon exposure. Radon exposure is linked to a lifetime increase in the risk of cancer and residential radon exposure has been the focus of intense policy effort since the 1980s. The EPA has issued guidelines which include a threshold where they recommend residents invest in a mitigation system, and states have approached the issue with policies such as mandatory disclosure when selling home and information campaigns. I bring together radon potential data from the Kentucky Geological Survey and home sales data from Zillow (2023) to construct a causal model of individuals willingness-to-pay to avoid residential radon exposure. Kentucky radon policy is a combination of mandatory disclosure of residential radon levels, and information campaigns. A null finding would suggest that these policies are ineffective and more intensive efforts may be warranted. To examine the question, I construct a boundary discontinuity design which uses radon potential zones as the boundary. These are based on underlying geology and are not subject to sorting issues that arise in other discontinuity designs that utilize administrative boundaries. I compare comparable homes which happen to be sited either on the low or high-radon side of the boundary to construct a credible 'but for' scenario. I find that homes with a basement in high-radon areas sell for around 5% to 7% less than comparable homes in a low-radon areas.

In Chapter 2 I turn my focus to risks associated with impervious surface cover such as lower water quality and flooding. I propose a novel theory that the structure of fees used to fund stormwater utilities will also affect the built environment by raising the relative cost of impervious surfaces. Stormwater utilities employ a variety of fee structures to fund their operations – one of which is a variable rate fee imposed on a landowner and based on the impervious surface cover in a lot. I construct a dataset of stormwater utilities in the United States and spatially link home data from Zillow (2023) and impervious surface cover data from the National Land Cover Database. Leveraging these two datasets I employ a stacked difference-in-differences design to causally examine whether there are changes to the built environment within stormwater utility districts before and after imposition of a variable rate fee. The two outcomes I examine, footprint size of new residential construction and percent impervious surface cover growth rate, do not change following the introduction of a variable rate fee. This suggests that if policymakers are interested in curbing the growth of impervious surface cover, they will need to be intentional and design specific policies to do this.

Chapter 3 is an examination of how local governments, rather than individuals, respond to incentives related to environmental risk. Broadly, I look at how local governments engage with the most common pre-disaster mitigation program and more specifically examine the theory that federal disaster policy induces moral hazard in local governments. Current federal disaster policy serves as de facto insurance for local governments, if a sufficient threshold of damage is reached the federal government almost always provides disaster relief regardless of whether a local government engaged in mitigation before the disaster or engages in mitigation to lower the risk from future disasters. I engage in the first empirical examination of local government moral hazard in disaster policy since the 1990s. I leverage the fact that a disaster declaration authorizes recovery funding for specific counties in a state while also authorizing mitigation funding for the entire state, not just affected areas. Recovery funding is designed to return an area to “normalcy” and has explicit restrictions on if and when it can be used to engaged in mitigation. By examining the uptake of mitigation funding for counties which receive a disaster declaration and those that do not I am able to examine whether a declaration is associated with lower mitigation – which would suggest moral hazard. My findings suggest that while counties that receive a declaration are less likely to engage in mitigation on the whole, they utilize significantly more mitigation dollars when they do engage. There is considerable heterogeneity by disaster type and my findings are largely driven by the response to hurricanes, although declared counties also spend more on mitigation post-flooding than non-declared counties. Overall, there is no conclusive evidence to support or discount the moral hazard theory and more research is needed. This paper serves as the foundation of what I expect to be a fruitful research agenda.

In sum, my dissertation examines two areas which are relatively understudied in public policy literature – radon and municipal stormwater systems. While expanding the conversation in disaster policy. I bring in literature and datasets that have not been utilized in the world of public policy with a hope to push research forward and start to bridge the gap between fields. I push forward the study of intersection of public policy and environmental risk, which is important for individual health, financial wellbeing, and the general safety of residents and future generations.

# CHAPTER 2. RESIDENTIAL RADON EXPOSURE: ANALYZING WILLINGNESS-TO-PAY AND POLICY IMPLICATIONS

## 2.1 Background

Radon is a colorless, odorless gas that is linked to an elevated risk of lung cancer by the U.S. Environmental Protection Agency (EPA) and World Health Organization (WHO). Radon is a natural byproduct of radioactive decay of elements in bedrock and soil which varies based on the underlying geology of an area. Importantly, radon is denser than air. This fact, combined with basements direct contact with radon emitting soil on up to five sides, mean that homes with basements tend to have more radon exposure and the radon settles in the basement which tend to be less ventilated than above-ground floors, leading homes with basements to generally have higher radon concentrations than those without (Casey et al., 2015; Fisher et al., 1998; Saadi et al., 2021). Homes with basements are more likely to have dangerous levels of radon than those without basements.

Despite the known dangers of radon, it has seldom been studied in the context of marginal willingness-to-pay (MWTP) and public policy. This is an important question because if consumers exhibit a willingness-to-pay to avoid radon exposure then current low-cost policy responses may be adequate in communicating risk.  One reason for the dearth of scholarship may be the relative lack of data concerning who knows about radon and the difficultly in assessing whether a particular consumer has been exposed to or aware of the threat.  This paper is an attempt to begin to fill in this gap in scholarship by identifying whether consumers exhibit a MWTP to avoid radon exposure.  The paper will first discuss the health effects and policy status of radon before presenting a theoretical framework, research design, results, and will close with a discussion of policy implications and possible next steps in radon scholarship.

2.1.1 *Health Effects*

Literature on the link between residential radon exposure and lung cancer arose in the early 1990s. The Iowa radon study, perhaps the most prominent study of residential radon exposure in the United States, examines women who resided in their homes for at least 20 years using test results from home radon kits to estimate their level of long-term exposure, finding that radon exposure is linked to increased cancer risk (Field et al., 2000). Pooled analyses of similar studies conducted in Asia, Europe, and North America establish a link between radon exposure and lung cancer (Lubin et al. 2004; Krewski, et al. 2005; Darby et al. 2005). These studies consistently find that long-term radon exposure increases the life-time risk of lung cancer, with one study finding a 34% increase in the risk of lung cancer for residents of counties with average radon concentrations over the EPA mitigation threshold of 4 pCi/l (Keith, 2012). Radon is especially harmful to smokers; the EPA estimates that radon exposure leads to 21,000 lung cancer deaths annually with 18,100 deaths being smokers (EPA, 2023).

Animal-based studies, another category of exposure research, generally expose animals to doses of radon far in excess of anything a human will encounter. These also show a link between lung cancer and radon exposure. Overall, there has been a substantial amount of evidence suggesting a link between radon exposure and lung cancer (Jostes, 1996). Other potential effects of radon exposure such as maternal or fetal complications have not been studied extensively. The Toxicology of Radon, a government review of all current research on radon, could find no studies concerning fetal effects in animals, and no studies on humans have found any association (Keith, 2012).

The most exhaustive review of literature on the effects of radon, the National Research Council Committee on the Biological Effects of Ionizing Radiation (BEIR IV), determined that residential radon exposure increases risk of lung cancer, these findings were echoed by Samet (2006), and the Toxicology Report for Radon in 2012. Importantly for the purposes of this study, the broad scientific and public conception of radon is as an environmental hazard which consumers should avoid. When purchasing a home, consumers are making decisions based on their perception of the risk that radon poses, which is established and communicated by health and policy professionals.

2.1.2 *Policy*

Residential radon exposure first rose to prominence as a policy issue in 1984 when a worker at the Limerick Nuclear Power Plant set off radiation detectors due to being exposed to high amounts of radon in his home. Prior to this event, radon had been thought to mainly be a risk for uranium miners. The Limerick incident led to action from the federal government, which instituted the first large scale survey of residential radon levels in the United States (Scheberle, 1994). While conducting this survey the EPA issued guidelines that set the maximum safe level of radon in a home at 4 picocuries per liter of air (pCi/L) (Mazur, 1987). There is no coercive power enforcing this standard; rather, the EPA recommends that residents have their homes checked for excess levels of radon. The EPA decided on 4 pCi/Lafter weighing the costs of remediation per life saved, as radon levels get lower it becomes increasingly costly to continue to lowering levels (Choi and Mazzone, 2014). The EPA estimates a cost of $700,000 per life saved at the 4 pCi/L level (NRC, 1999). The state-government run Kentucky radon program information webpage strongly recommends mitigation if levels above 4 pCi/Lare detected and suggests consideration of mitigation if levels are between 2 and 4 pCi/L. SWAT Environmental, the largest radon mitigation company in the country, uses the 4 pCi/Lcutoff as their mitigation suggestion. For these reasons, I use 4 pCi/L as the threshold between high and low radon throughout the paper.

The model used to establish the 4 pCi/L threshold employes a linear no-threshold model (LNT), this model assumes there is no level of radon exposure that is not harmful, that risks associated with exposure will increase in a linear fashion, and that exposure will lead to a heightened lifetime risk of cancer (George, 2015).  There is a debate within the epidemiology and toxicology community over the appropriateness of using this model.  One issue is that many studies that establish cancer risk using this model rely on the extrapolation of data gathered from extreme doses of radiation, such as exposure from the bomb dropped on Japan during World War 2.  However, the most recent Biological Effects of Ionizing Radiation (BEIR) Committee report weighed the available evidence and supported the LNT model (Cullom and Bateman, 2010).  Furthermore, in the case of radon the extrapolated data gathered from miners exposed to extreme doses has been given support through case control and animal-based studies (Keith, 2012).

On the federal level, radon policy is primarily limited to setting a recommended maximum threshold and facilitating the training of radon remediation professionals.  This was originally administered through a set of state grants and direct, EPA-run training facilities, a radon professional proficiency program, and informational materials provided to states, after 1998 the EPA programs were abolished, and two private firms now provide radon professional certification (Virginia Dept of Health, 2018).

States have a wide variety of policies that tackle the radon issue. Twenty-nine states require testing and disclosure of test results when selling a home. Kentucky, which does not require testing, has two laws that set up and outline the responsibilities of a state radon program. This program establishes standards for professionals, issues certificates to these professionals, and participates in the promotion of radon education (NCSL, 2018). Under this program the state provides free radon testing kits to residents and conducts information campaigns. Kentucky utilizes KGS radon potential maps to inform residents about the risk of radon. Chiavacci et al. (2020) found that the use of radon potential maps contributes to 75 residents of Kentucky a year avoiding exposure to high levels of radon. Research on more general community meeting, mailers, and radio PSAs are linked to a modest increase in testing (Desvousges et al., 1992).

Kentucky requires the disclosure of radon test results *if* a test has been conducted, however the state does not require testing. Additionally, misrepresenting prior radon readings is fraud under Kentucky statute. It is unclear the extent of testing in the state, though information on radon is included in the seller disclose of property condition form (**Figure 2.1)**, suggesting that property buyers have some level of exposure to the information through the disclosure form and potentially the home inspector. Individuals may not read the disclosure form, have an inspector point out the dangers of radon, or understand the dangers of radon. All of these facets may lead folks to not be aware of the potential risk of radon exposure. Unfortunately, I do not have any concrete data on the information given to potential buyers or the prevalence of testing when purchasing a home. Results that show a reduction in home prices for homes with the potential for high levels of radon will serve as an indication that current Kentucky policy is communicating risk with consumers

**RADON DISCLOSURE REQUIREMENT**

Radon is a naturally occurring radioactive gas that, when it has accumulated in a building in sufficient quantities, may present health risks, including lung cancer. The Kentucky Department for Public Health recommends radon testing. For more information, visit chfs.ky.gov and search "radon."

| | | | | | |
|---|---|---|---|---|---|
| e. | 1) Are you aware of any testing for radon gas? | ☐ | ☐ | ☐ | ☐ |
| | 2) If yes, what were the results? | ☐ | ☐ | ☐ | ☐ |
| f. | 1) Is there a radon mitigation system installed? | ☐ | ☐ | ☐ | ☐ |
| | 2) If yes, is it functioning properly? | ☐ | ☐ | ☐ | ☐ |

*Figure 2.1* - Kentucky Sellers Disclosure of Property Condition Form.
Notes: Accessed at https://krec.ky.gov/Documents/402-SellersDisclosureofPropertyCondition.pdf

A number of studies examine the cost effectiveness of radon mitigation. A study published in the British Medical Journal compares the lost value of life through radon caused lung cancer deaths with the cost of various mitigation efforts. This effort estimated a baseline of deaths caused due to radon exposure and compared this with quality adjusted life years (QALY) that would be gained through various intervention methods. A cost effectiveness ratio was used to compare various proposals, with the authors finding that a nationwide requirement to insulate new homes from radon exposure would be highly cost effective, while a widespread policy of updating existing homes would be less cost effective (Gray et al., 2009). These findings echo earlier studies which have found that radon remediation programs are cost effective (Stigum et al., 2003; Coskeran et al., 2005). The cost effectiveness of efforts related to smokers is particularly strong due to the much higher rate of radon induced cancer amongst smokers. Radon is particularly acute concern in Kentucky which contains wide swaths of high radon potential areas and has the second highest smoking rate in the country at 23.4% (American Lung Association, 2020).

**2.2 Theory**

Rosen (1974) proposed a method of breaking the price of a product into its component parts which has become known as the hedonic pricing model. Central to this method is the theory that consumers choose the home that maximizes their utility, subject to their income. The price of an object reflects the sum of the implicit values of the observable characteristics of an object, and thus the marginal willingness to pay for a characteristic. Applying the hedonic model to homes, the price of a home is a function of observable characteristics ($Z_i$) and an error term ($\epsilon_i$), or $P_i = f(Z_i, \epsilon_i)$. In the context of a house, the price is made up of the value consumers place upon house characteristics such as the number of bedrooms or the presence of a basement as well as other observable characteristics that factor into purchasing decisions such as neighborhood crime rate or education quality. Hedonic pricing has been used extensively to study the value placed on environmental goods, such as clean air, hazardous waste, and clean water (Chay and Greenstone, 2005; Greenstone and Gallagher 2008; Poor et al., 2007). In the case of environmental goods an X term is added, $P_i = f(Z_i, X_i, \epsilon_i)$, with X being an environmental amenity (or, in this case, disamenity) such as radon or other pollutants.

At its core the hedonic model is a bidding model that is driven by exchanges between buyers and sellers in a common housing market. In an abstract scenario with no mitigation available, buyers within Kentucky that wish to avoid radon exposure may bid up the price in less exposed neighborhoods or bid down the price in more exposed neighborhoods of otherwise identical homes as sellers with high radon homes will need to lower their asking price to attract a buyer. Another key assumption of the hedonic model is that buyers are making their decisions based on the current, observable characteristics of a home or neighborhood and not on anticipated future characteristics. In this case this means that consumers are making their decision based on the information they currently possess on the effects of radon exposure and the radon levels in homes they are in the process of purchasing.

The invisible nature and long-run effects of exposure to radon make it a potentially undervalued hazard, as consumers will not be aware of the level absent a test or may discount the long-run risk of cancer. Currie et al. (2015) examine the effects of the opening of toxic plants, a very visible signal to buyers, and find plant openings cause an 11% decline in nearby home value. Similarly, Chay and Greenstone (2005) study the effect of a particulate matter, a visible source of air pollution, on housing prices and find that counties required to reduce air pollution under the Clean Air Act saw a resultant rise in home prices cause by the pollution abatement. Radon, on the other hand, has been nicknamed 'The Silent Killer' and its presence is revealed only through testing a home. Unlike these contexts, the invisible nature of radon and lack of a state or federal enforcement mechanism means that the information signal must be sent through communication by government actors and professionals in home inspection, real estate, and radon mitigation. This study contributes to the literature by examining whether this relatively low-cost policy mechanism conveys risk from an invisible hazard.

This study examines whether this policy mechanism is effective in communicating radon risk. In this case being effective is defined as the study uncovering a negative price response for homes with high radon levels, as consumers are assumed to generally avoid exposure to cancerous disamenities. I propose that if the policy is effective, homes with higher levels of radon will sell at a lower price, all other things equal, as consumers will exhibit a willingness-to-pay to avoid radon which will bid down the price of high radon homes. Additionally, prices will be bid down further in homes with basements in a high radon area as radon tends to pool in basements. A key assumption for this hypothesis is that individuals wish to avoid exposure to things that increase their risk of cancer. Furthermore, I assume that radon levels are not known prior to the seller disclosure, or a test conducted by the home inspector. This second assumption suggests that information is conveyed relatively late in the process when the simplest solution is for the buyer and seller to negotiate a solution such as a lower selling price. I argue this assumption is valid due to the relative scarcity of information on radon levels throughout Kentucky outside of the home purchase option. Consumers may know that radon is an issue due to the geology of the state but are not aware of specific demarcations of high and low radon areas. Furthermore, there is not a public database of radon test results, and the only public spatial radon information are county-level maps of radon potential zones – which I leverage for my research design. These maps do not include street level views but simply show the county as a whole with no political or built reference (streets, city borders, etc). Thus, a buyer looking at these maps will not know precise information on a home they are interested in purchasing, especially if it is close to a boundary between areas with different levels of radon potential.

Assuming that individuals generally wish to avoid exposure to cancer-causing gas, two factors may lead to the presence of high levels of radon not resulting individuals being willing to pay to avoid exposure: 1) a potential lack of information on radon and/or

2) a discounting of the long-run effects of radon exposure – a future problem effect. Discounting long-run effects has been proposed as an explanation for a seemingly irrational response to known health hazards. If this is an underlying cause of risky behavior the goal of policy intervention becomes to lead consumers to have a lower discount rate (Ortendahl, 2007). If this study finds a behavioral response that is evidence the current disclosure and information-based policy intervention is communicating risk. If I find no effect, I am not able to distinguish if consumers are not receiving information or if they are discounting future health effects.

Separately, the information effect and future problem effect will both serve to moderate any price differences between high and low radon homes. As an example, if an individual has perfect information about the radon level of homes and the dangers of radon exposure but they have a high discount rate for future problems they will not bid down the price of a home with high levels of radon as their internal value of mitigating that risk is quite low. Similarly, an individual that has a discount rate of 0% and as such values future risk at the same level as present risk but is unaware of the presence and danger of radon will also not bid down the price of a high radon home. This may occur if a risk averse person does not read the seller disclosure form or does not request a test during the inspection process, for example.

The general lack of data concerning the information possessed by individual buyers and sellers – such as the disclose form itself - or their long-run risk preferences makes it difficult to develop a satisfactory identification strategy to distinguish between these information and future problem explanations.  Thus, this research design is a first step in digging deeper into the economic and policy questions surrounding radon.

### 2.3 Research Design

To test my hypotheses, I use data on home sales and characteristics from the Zillow Z-Trax assessments and transactions database (2023), while the Kentucky Geological Survey (KGS) radon potential database is my source for radon data. KGS modeled radon zones based on the individual results of over 70,000 home radon tests, which were then linked with the specific type of rock underlying an area. Variations in the composition of underlying geology can lead to higher or lower levels of radon due to differences in radioactive elements present in bedrock (Hahn et al., 2015). **Figure 2.2** displays the mean radon levels throughout the state based on underlying geology. As can be seen there is significant variation across the state, notably in a diagonal swirl starting in west-central Kentucky.  I linked these data together with the Zillow data to provide a rich dataset concerning home prices, characteristics, and level of potential radon exposure.

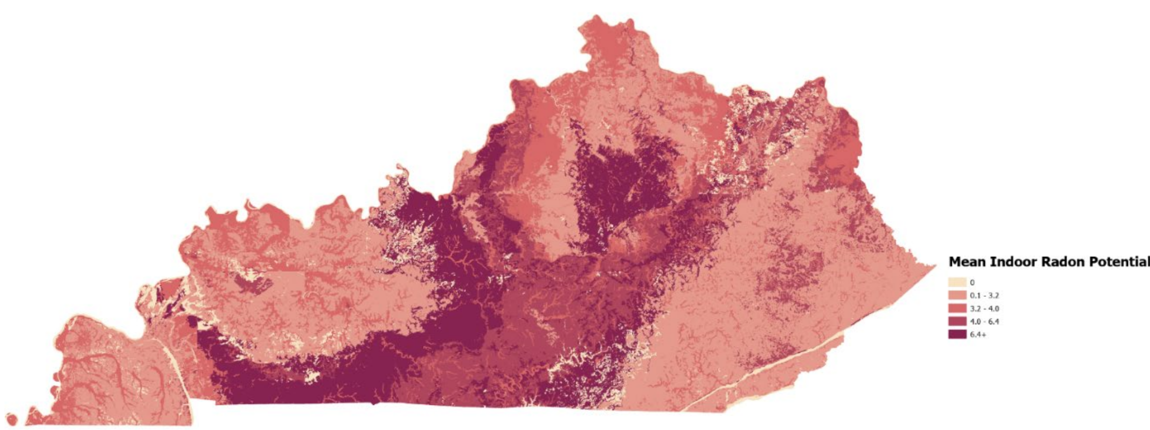


*Figure 2.2* - Kentucky Mean Indoor Radon Potential.
Notes: Mean radon potential is reported in pCi/L. A measure above 4 is considered high by the EPA. Data provided by the Kentucky Geological Survey. Figure created by author using ArcGIS.

I use all housing transactions in Kentucky after 2005. Non-arm's length transactions were dropped from the dataset to eliminate transactions with a price not set on the housing market. Additionally, all non-residential home sales are excluded because the focus in this study is residential radon exposure. I linked two Zillow datasets, one contains sales data, which include price and transaction type, the other is assessment data, which contains information concerning the physical characteristics of the home. Each transaction was linked with the most recent property value assessment *before* sale of the home. Homes that had no corresponding assessment were dropped, as were those missing housing characteristics included as covariates in the model such as the square footage of the home. The final sample contains 418,152 homes that are arm's length transactions, made after 2005, and do not have any missing variables of interest.

Zillow collects data from individual property value assessor offices which may have systematically not recorded one or more variables drawn from the assessment dataset, which means that some whole counties are missing from the dataset because of the county may be missing a control variable. The final dataset is missing several entire counties, such as Scott County (population 58,000), but contains the two most populous counties in the state – Jefferson and Fayette. **Figure 2.3** displays Kentucky with county borders (black lines), radon zones (lighter shade is low radon, darker shade is high radon), and each home sale (black dots). There are counties without any home sales – the counties without sales in southwest Kentucky have no variation in radon potential and are not a concern due to my research design, which is limited to homes close to a boundary, but the missing counties in central Kentucky, such as Scott, have variation in radon potential and their exclusion is unfortunate. Overall, the band of high radon areas that extends across much of central Kentucky is where the variation of interest lies and contains a large portion of the home sales that are included in the final dataset.

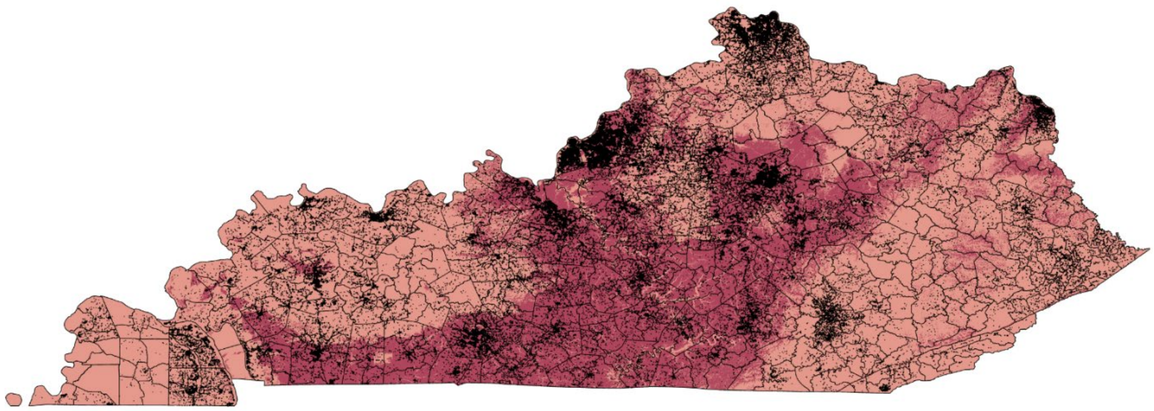

*Figure 2.3* – Statewide Sales, Counties, and Radon Potential
Notes: Sales indicated by black dots. County boundaries indicated by black lines. Radon potential indicated by shading with lighter shades representing areas with mean radon potential below 4 pCi/L and darker shades representing areas with mean radon potential at or above 4 pCi/L as calculated by the Kentucky Geological Survey. Sales data from Zillow (2023). Figure created by author using ArcGIS.

Each home address is geocoded using the U.S. Census Bureau Batch Geocode software. The geocoded homes were then matched with the KGS radon shapefiles using ArcGIS Pro. This is one of the first uses of the KGS dataset in a study of this type. The maps allow me to link each geocoded home to average radon levels that follow the contours of underlying rock formations. This provides a level of variation and allows for the use of a boundary regression discontinuity design.

**2.4 Empirical Design**

In order to establish a credible "but for" scenario I employ a regression discontinuity design (RDD) using a geographic boundary ($c$) as the identifying discontinuity. Where $c > 0$ means the home is in the treatment group (high radon potential) and $c < 0$ is the control group (low radon potential). In theory, this design allows me to compare homes that are similar in their unobservable qualities by restricting the sample to an absolute distance from the boundary. For instance, homes within 2,000 meters of either side of the boundary are close to each other they are theorized to be more similar than homes 20,000 meters from either side of the boundary and more likely to differ only in their radon potential, which is generated by underlying geologic formations that are unobserved by homeowners. As an illustration, **Figure 2.4** displays a close-up view of the high/low radon boundary. The distribution of homes (black dots) shows the distinct pattern of neighborhoods and streets (though they are not displayed) which cross over the radon boundary without respect to the underlying geology. By restricting the sample to these homes that are within proximity of the boundary I am in effect comparing homes that share unobserved similarities in demographics, public goods, or other (dis)amenities. The results can be viewed as a local average treatment effect for those observations that are in the vicinity of the boundary.

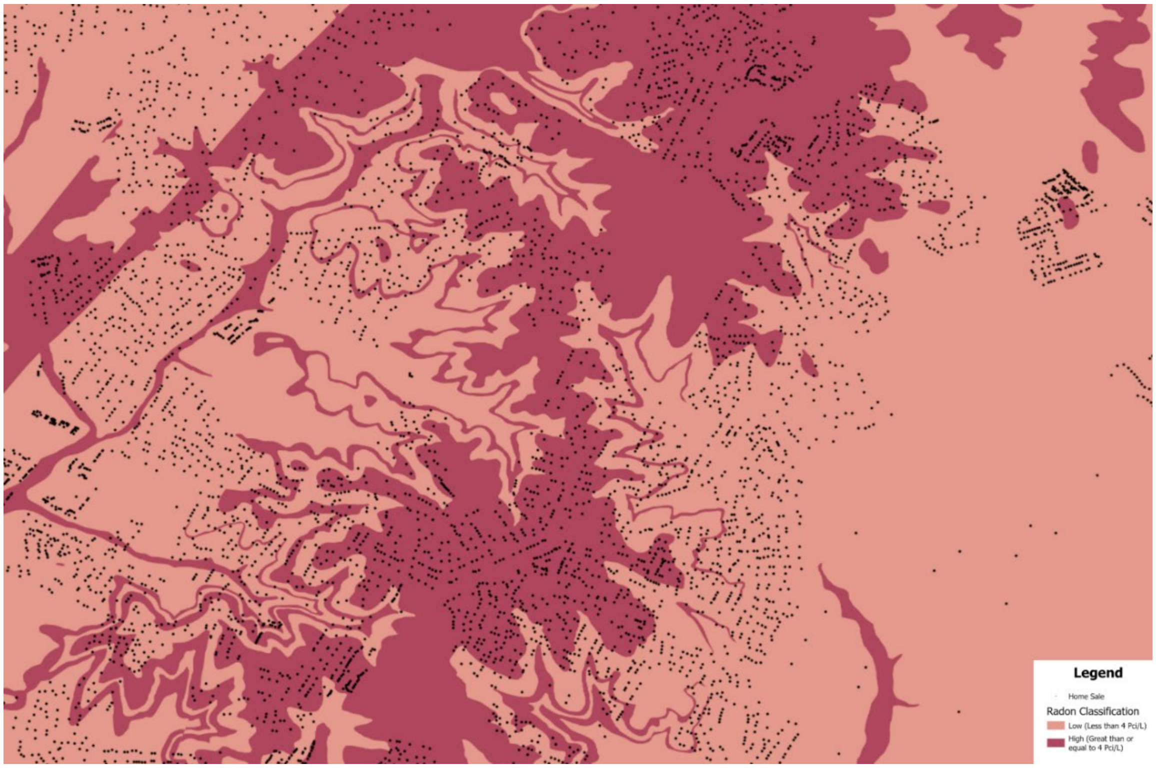


*Figure 2.4* - Close-Up View of Radon Boundary
Notes: Radon potential indicated by shading with lighter shades representing areas with mean radon potential below 4 pCi/L and darker shades representing areas with mean radon potential at or above 4 pCi/L as calculated by the Kentucky Geological Survey. Black dots represent a home sale in the dataset. Sales data from Zillow (2023). Figure created by author using ArcGIS.

This study uses mean radon level as determined by KGS to sort homes into either high (treatment) or low (control) radon areas. A high radon zone is any area with mean radon levels above 4 pCi/L as constructed by KGS using test kit results and data on Kentucky geology. This measure is a pure indicator of being in an area where the average test kit result is above the government labeled hazardous level threshold. This captures the information signal that homeowners receive, due to the fact that remediation is recommended on *any* level over 4 pCi/L. Both the EPA and the Kentucky state radon resources use the 4 pCi/L threshold as the demarcation between high and low radon levels.

Using Rubin's potential outcomes framework, the idea behind an RDD is that, due to the fundamental problem of causal inference, I cannot observe how radon affects the selling price of the same house, as a home cannot both be in a high potential zone ($D$=1) while simultaneously being in a low potential zone ($D$=0), as seen in (1).

(1) $\mathrm{E}[Y^0|D=1] - E[Y^0|D=0] = ?$

However, if there exists a continuously distributed sorting variable around an assignment threshold, I can establish good as random treatment and control groups. Treatment status is derived from EPA guidelines which recommend mitigation for concentrations above 4 pCi/L. This leads to the assumption that in general buyers will be recommended mitigation if concentrations above 4 pCi/L are detected, which in turn becomes the treatment threshold.

In the classic RDD design the likelihood of treatment jumps discontinuously from 0 to 1 at *c*.  The design is ideally a fuzzy RDD as the *likelihood* of assignment to treatment (radon levels above 4 pCi/L) discontinuously increases at the boundary, rather than assignment firmly going from control to treatment. This is due to the fact that there is considerable variation in radon levels in both the high and low areas, a home in the high radon area could have low levels and a home in the low area could have high levels, but *on average* levels are above or below 4 pCi/L. Sans a mitigation system, radon concentration depends on things such as the existence of a basement, the weather, and ventilation but being in a high area means the underlying rock is undergoing radioactive decay in a manner that leads to a higher probability of testing positive for high levels of radon. However, a fuzzy design would require that I have radon reading from individual houses, in a similar fashion to Angrist and Lavy (1999) which used actual and predicted class size in a fuzzy RD. Instead, I treat the discontinuity as sharp and assign all values $c > 0$ as belonging to treatment and $c < 0$ as control, the assignment mechanism can be seen in (2).

$$(2)\ D_i = \begin{cases} 1 \text{ if } c_i \geq c_0 \\ 0 \text{ if } c_i \leq c_0 \end{cases}$$

The assignment variable does not change until the threshold when it jumps from 0 to 1, which can be seen in **Figure 2.4** as the color changes from light (low) to darker (high). This introduces a potential issue with this research design, which is that it is possible for homes on the low radon side (control) to have a reading that would assign them to treatment; however, I assume that *on average* homes on the high side will have a reading above the threshold and homes on the low side will have a reading below the threshold. This assumption is supported by the way the KGS radon data are constructed. To reiterate, KGS took the results of home test kits across the state of Kentucky and mapped them to underlying geology – thus, areas with a mean value above 4 pCi/l means that the mean value of actual test kit results in that area is above 4 pCi/l (Haneberg et al., 2020).

This leads to a simple, formal linear model of the effect of treatment on home prices (3) in the Rubin framework.

$$(3)\ E[Y_{0i}|c_i] = \alpha + \beta c_i$$

$$E[Y_{1i}|c_i] = Y_{0i} + \rho$$

Where $\rho$ is the effect of radon readings over 4 pCi/L on home price. Which in turn can be written in the form of a linear regression (4), which is the baseline model:

(4) $Y_{i,t} = \alpha + \beta c_i + \delta(D_i{*}c_i) + \rho D_i + \lambda_t + \eta_{i,t}$ for all $|c_i| < b$

With $Y_i$ being the log selling price of house *i*, in year *t*, and $\beta$ representing a continuous linear function of distance to the border, while δ allows for differential effects of distance to the border for high/low radon, and $c_i$ is a running variable capturing the distance of a home to the radon borer. The $\rho$ term captures the effect of the discontinuity, as $D_i$ is a deterministic function of $c_i$ which allows me to capture the discontinuous jump at $c_0$. The model includes year fixed effects to capture common time trends affecting the housing market. *b* is the bandwidth, or distance from the high/low boundary with 1000 meters being the preferred distance but models between 50 and 5000 meters are presented.

I control for a vector of housing characteristics (**X'**) in order to minimize the potential bias from differences in homes in treatment and control, additionally I control for border segment (*s*) fixed effects, σ, to capture unobserved similarities in houses in close proximity to one another. The border segment fixed effect splits each border into one-mile segments with each home being assigned to the nearest border segment. This is done by taking all line segments that separate the high/low radon sides (seen for the whole state in **Figures 2.3, 2.5, and 2.6** and seen at a local scale in **Figure 2.4**) and using ArcGIS Pro to split each line into segments which are one mile in length. Each observation is then assigned to the nearest one-mile-long segment which then serves as an indicator of physical proximity for observations in the final sample. Thus, all homes within close proximity will be assigned to the same one-mile border segment. This assigned one mile segment serves as a local area fixed effect, which allows me to control for unobserved local features which may affect selling price such as crime. This can be seen in equation (5):

$$(5)\ Y_{i,t,s} = \alpha + \beta c_i + \delta(D_i * c_i) + \rho D_i + \beta_3 bs * D_i + \gamma \mathbf{X}'_i + \sigma_s + \lambda_t + \eta_{i,t,s} \qquad \text{for all } c_i < |b|$$

While all homes are at risk of high radon levels radon being heavier than air, the higher direct exposure to soil where radon originates in basements compared with above-ground floors, and general lack of ventilation in basements, such as is provided by an open door or window, leads to higher concentrations of radon being found in homes with basements (Fisher et al., 1998; Saadi et al., 2021). Additionally, the EPA recommends conducting a radon test at the lowest livable floor of a home which suggests that buyers purchasing a home with a basement in this study will most likely conduct the test in the basement (Li et al., 2022). Empirically, $\beta_3$ provides a measure of the interaction between high radon ($D_i$) and the presence of a basement (*bs*) which allows me to examine the additional price effect on homes with basements. If willingness-to-pay to avoid radon occurs, it is possible that it is only occurring in homes with basements.

Based on this research design two specific hypotheses are proposed:

H1: Mean radon level above 4 pCi/L will have a statistically significant negative effect on home selling price.

H2: Mean radon level above 4 pCi/L and the presence of a basement will have an additional statistically significant negative effect on home selling price.

The identifying assumption for RDD is the continuity assumption, that that all other relevant variables are continuous with respect to the assignment variable. Thus, there should not be discontinuous jumps at the boundary for anything other than the likelihood of having high radon levels in the home. This can be violated if homes differ systematically based on which side of the threshold they are on or if home buyers are aware of the threshold and sort on either side of it.

As discussed earlier in this section, it is unlikely that home buyers are specifically aware of the underlying geology while purchasing their home, however while they may not know precisely *where* radon levels are higher, they do receive the results of radon tests and disclosure of previous radon results when going through the home buying process. In general, buyers may be more likely to sort based on known boundaries, such as school districts and municipal borders, than on relatively unknown geological features which are not contiguous with these political borders.

The difference in means between homes in the general sample within 1,000 meters of the radon boundary, as well as the results of a series of t- tests, are displayed in **Table 2.1**, with results indicating homes that differ in a few aspects. In general homes on the high radon side appear to be larger in terms of square footage and rooms than those on the low side. Homes on the high radon side sell for more, have much larger lots, are newer than homes on the low radon side, and have more bedrooms and bathrooms, on average.

*Table 2.1* – Difference in Means, General Model

| Variable | High | Low | Difference | t |
|---|---|---|---|---|
| # of Observations | 158,204 | 54,704 | 103,500 | |
| Housing Characteristics | | | | |
| Price | 211,912.20 | 150,730.20 | 61,182.00 | (-6.88)*** |
| Lot Size (SqFt) | 108,683.70 | 111,201.40 | (2,517.70) | (-0.19) |
| Year Built | 1980 | 1968 | 12 | (-84.91)*** |
| Number of Stories | 1.33 | 1.25 | 0.08 | (-32.64)*** |
| Bedrooms | 2.15 | 1.63 | 0.52 | (-68.86)*** |
| Total Bathrooms | 2.08 | 1.63 | 0.45 | (-101.70)*** |
| Build Area (SqFt) | 1,872.93 | 1,531.66 | 341.27 | (-76.50)*** |
| Basement | 0.55 | 0.41 | 0.14 | (-58.91)*** |

Notes: Difference in means of housing characteristics of homes included in the final model. These are all observations within 1,000 meters of the high/low boundary and not missing any variables from final model. High and low radon potential classified by mean radon level above or below 4 Pci/L. All observations within 1,000 meters of high/low radon boundary. Data from Zillow (2023). *** $p < 0.001$.

Price is a function of observable and unobservable factors, which means larger lots and newer homes may drive the price up. Additionally, newer homes may have some characteristics that are not captured directly in what I observe but reveal themselves through the year built variable which may be associated with modern amenities. The lot size variable is large for both sides of the boundary. The sample may include a substantial quantity of large lots, or the Zillow data may be unreliable on this dimension. One explanation for the large lot sizes is that general model drops any observation not within 1,000 meters of the radon boundary (**Figure 2.5**). The remaining observations are heavily concentrated in a swath of central Kentucky which may contain homes with larger lots. The key takeaway is that differences in house attributes suggests an upward bias due to the fact that high radon area homes appear more attractive based on observables, which suggests that there may be an unobserved variable may be correlated with both high radon and selling price. With a hypothesized negative effect of radon on price an upward bias means any negative effects found may be an underestimate of the true price reduction.

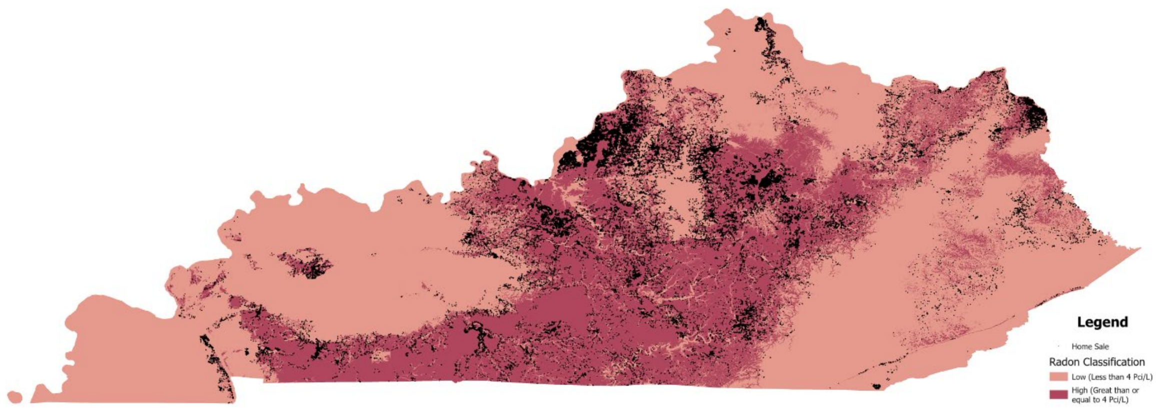


*Figure 2.5* - General Model Home Sales
Notes: Radon and Home Sales. Home sales included in the general model sample are indicated by black dots while radon potential is indicated by shading on the map, with darker shading representing high radon potential and lighter shading representing low radon potential. Includes all observations that are not missing any variables and are within 1,000 meters of the high/low radon boundary as defined as areas above and below 4 pCi/l. Sales data from Zillow (2023). Figure created by author using ArcGIS.

There may be unobserved differences on either side when using a boundary discontinuity design.  While I have tested for bunching and differences in observables there will always remain a chance that there is some public (dis)amenity visible to buyers that is correlated with being in a high or low radon area and is not included in the dataset. This is not as much of a concern in the research design compared to designs using political boundaries such as school district due to the use of a relatively unknown geologic boundary which runs through neighborhoods without respect to political or constructed boundaries. This suggests that unobservable characteristics are likely distributed as good as randomly with respect to the radon line as they would need to be tied to underlying geology. Unlike boundaries like school districts, in this case consumers do not have a readily identifiable boundary to sort between which may lead to systematic unobserved differences.

Even still I work to minimize the possibility of unobserved differences introducing bias. The selection of bandwidth is a key avenue to help alleviate concern about this potential source of bias. As the bandwidth is lowered, I examine homes much closer to each other that are less likely to differ based on unobservables, i.e.: with a range of 1000 meters I may capture homes within the same few blocks and exclude a whole neighborhood of much more attractive (or unattractive) homes that lie 5000 meters from the boundary. The tradeoff with a narrow bandwidth is a loss of precision that comes with using fewer observations, for robustness results will be presented for a series of bandwidths, though 1,000 meters is used in the general specification.

For an additional robustness check, I also run the model with a requirement that limits observations to only those areas that contain a minimum number of homes on both the high and low side of the boundary – I call this the restricted sample. Only one mile border segments which include at least 100 homes on the high side and 100 homes on the low side of the border are included in the model. This means that after each observation is assigned the nearest one-mile border segment I am only including those segments which have at least 100 homes on each side of the boundary assigned to the segment. 100 was chosen to balance the need for an adequate number of observations on each side of the boundary and a sufficient sample size (N = 12,480 for this specification). This model more accurately reflects a within neighborhood comparison because only those areas which have a relatively high density of homes to be compared with each other are included. This helps alleviate the concerns that areas with a large number of homes on either side of the boundary may be driving the results.

The difference in observables between high and low radon homes in the restricted sample is shown in **Table 2.2**. This model only includes observations in border segments that have at least 100 homes on the high radon side and 100 homes on the low radon side. On most dimensions the homes in this sample are more similar on observables than the expanded sample. Homes on each side have a similar number of stories, bedrooms, bathrooms, and likelihood of having a basement. The largest difference comes from lot size where homes on the high side of the boundary have lots that are 9,000 square feet larger on average than the low side. This is the opposite of the full sample where low radon homes have lot sizes where are about 2,000 square feet larger on average. Additionally, the average selling price for high radon homes is $13,000 more than low radon homes, which is much closer than the $61,000 difference of the expanded sample. The similarities on observables other than lot size suggests that this model is more effective at providing an apples-to-apples comparison. The sample size is 12,480 observations with these restrictions.

*Table 2.2* - Difference in Means, Restricted Sample

| Variable | High | Low | Difference | t |
|---|---|---|---|---|
| # of Observations | 5,583 | 6,897 | -1,314 | |
| Housing Characteristics | | | | |
| Price | 136,300.20 | 123,220.40 | 13,079.80 | (-4.85)*** |
| Lot Size (SqFt) | 18,598.66 | 9,008.34 | 9,590.32 | (-1.32) |
| Year Built | 1972 | 1967 | 5 | (-9.89)*** |
| Number of Stories | 1.33 | 1.27 | 0.06 | (-7.90)*** |
| Bedrooms | 1.44 | 1.41 | 0.03 | (-1.10) |
| Total Bathrooms | 1.69 | 1.59 | 0.1 | (-7.19)*** |
| Build Area (SqFt) | 1,489.08 | 1,388.76 | 100.32 | (-9.45)*** |
| Basement | 0.33 | 0.32 | 0.01 | (-1.96)* |

Notes: Difference in means of housing characteristics of homes included in the restricted sample. These are all observations within 1,000 meters of the high/low boundary, not missing any variables from final model, and the nearest mile-long border segment contains at least 100 observations on the high side and 100 observations on the low side. High and low radon potential classified by mean radon level above or below 4 pCi/L. All observations within 1,000 meters of high/low radon boundary. Data from Zillow (2023). *** $p < 0.001$.

**Figure 2.6** displays a plot of the frequency of home sales by distance to the radon boundary. Sales remain generally consistent throughout the distance to the boundary, though there is a higher concentration of sales on the high radon side which is to be expected given the distribution of sales seen in **Table 2.1**. However, the question remains to be answer why there is such an unbalance distribution of home sales on either side of the boundary.

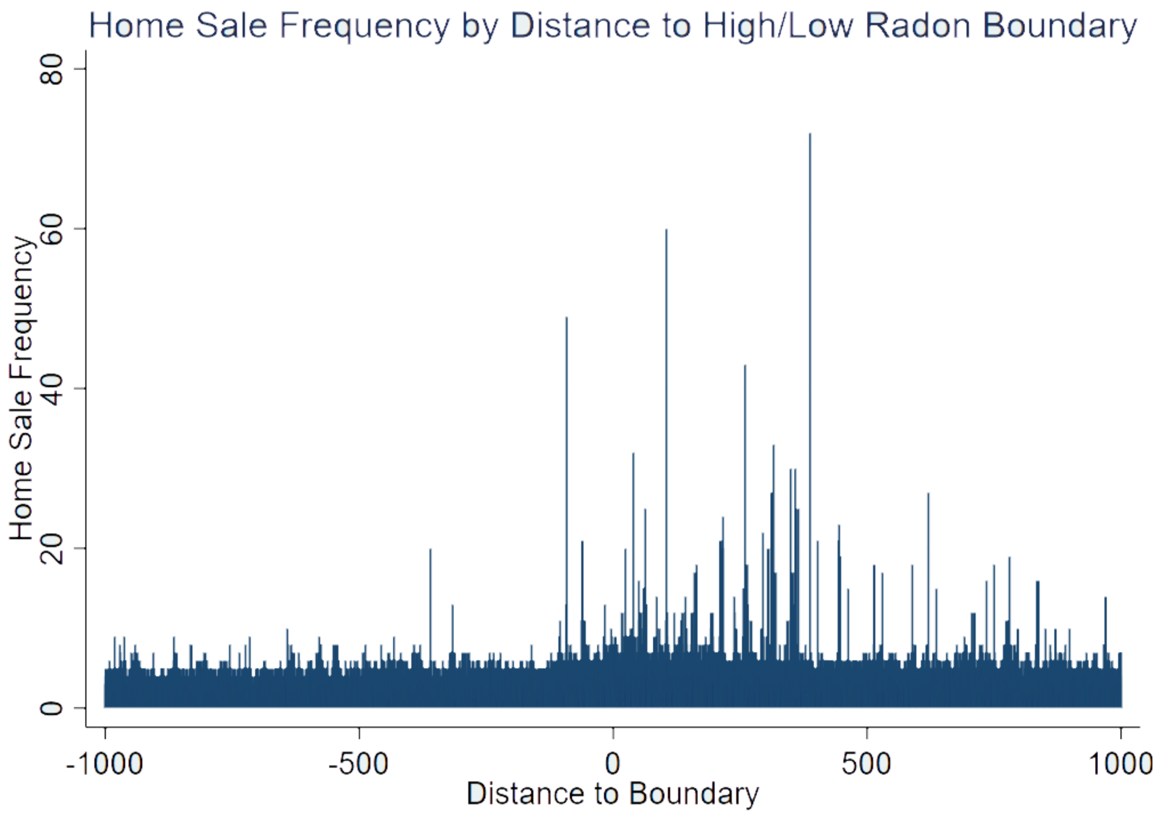


*Figure 2.6* - Home Sale Frequency in Final Sample by Distance to Border
Notes: Plot of home sale frequency by distance to high/low radon boundary. Red indicates high radon (average over 4 pCi/L), blue indicates low radon (average under 4 pCi/L) as defined by KGS. High radon defined as distance measured in meters. Sales data from Zillow (2023).

A visual examination of the underlying data provides some clues as to the potential answer. **Figure 2.5** displays each home in the final sample (not missing house characteristics data) overlayed on mean radon zones, with the darker shade indicating a high radon area. As can be seen, the final sample simply includes a large number of observations in a high radon area as many of the population centers tend to occur in high radon areas. Further compounding the issue is that only observations within $c_i$ are included, meaning that low areas with a large number of home sales in northern, western, and southeastern Kentucky are not included due to the fact that a boundary is not nearby. The high radon zones tend to swirl through central Kentucky. A comparison of **Figures 2.3 and 2.5** illuminates the geographic concentration of excluded observations with large portions of western, northern, and parts of eastern Kentucky dropping a notable quantity of observations. The remaining observations are concentrated in central Kentucky. Overall, the distribution of home sales along the running variable is generally consistent throughout, though there is an overall higher frequency of sales on the high side of the boundary which may be due to the nature of home location and radon zones throughout the state and is not a reason for concern for the validity of the model.

**Figures 2.7 and 2.8** show binned plots of the residuals plotted against distance to the radon boundary, after running the full sample (**Figure 2.7**) and the restricted sample (**Figure 2.8**). If there is an unobserved factor that is differentially influencing price, I would expect to see a discontinuous change in residuals as one crosses the radon boundary. **Figure 2.7** shows more observations on the high side, as expected, as well as higher variation in the distribution of bins on the high side compared to the low side. The distribution of bins on the high side suggests the possibility that there is some unobserved factor that is influencing prices on the high side of the boundary. **Figure 2.8** with the restricted data helps alleviate concerns of bias as the pattern remains generally consistent throughout the distribution. Overall, these graphs suggest that while homes on the high side in the full sample may be different on unobservables, the restricted sample should alleviate these concerns. Results from both samples are presented and return consistent results.

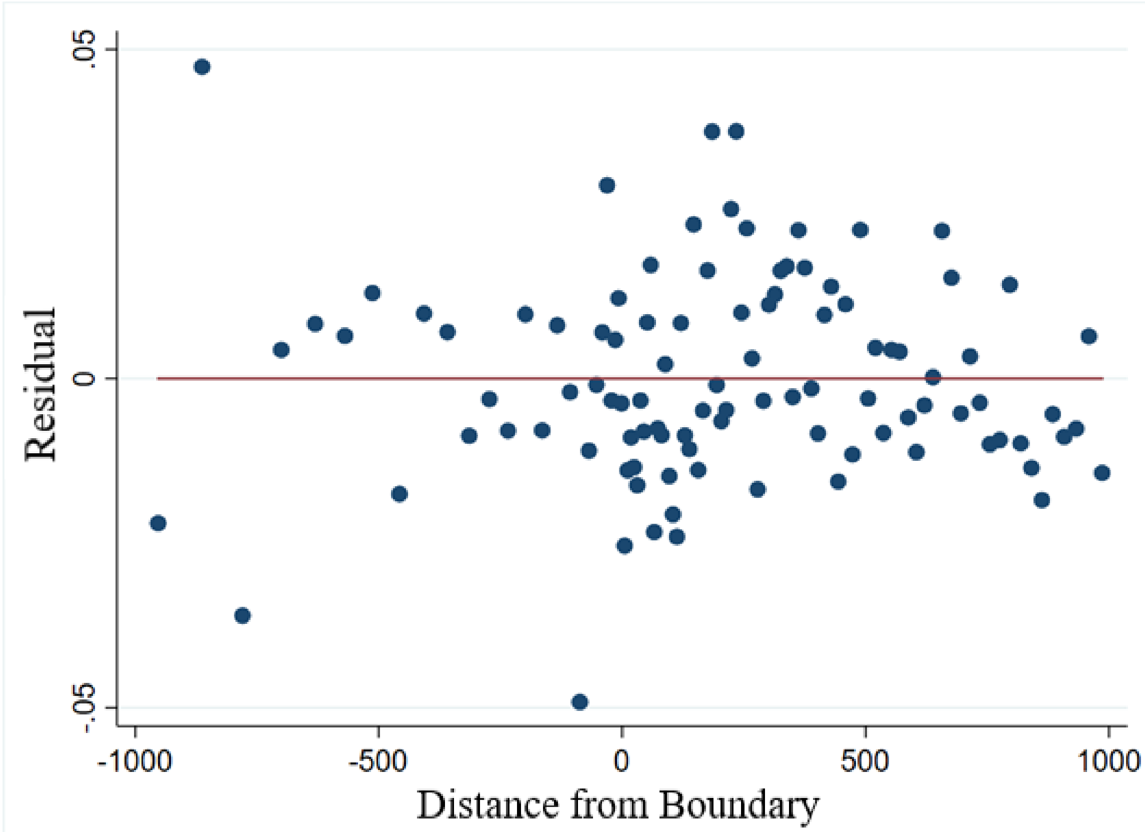


*Figure 2.7* - Bin Scatter Plot of Residuals of General Model
Notes: Dots represent binned residuals of results of general 1000-meter bandwidth model binned by distance to radon boundary. Sample is split into 60 equally sized bins. Red line represents line of best fit. Sales data from Zillow (2023).

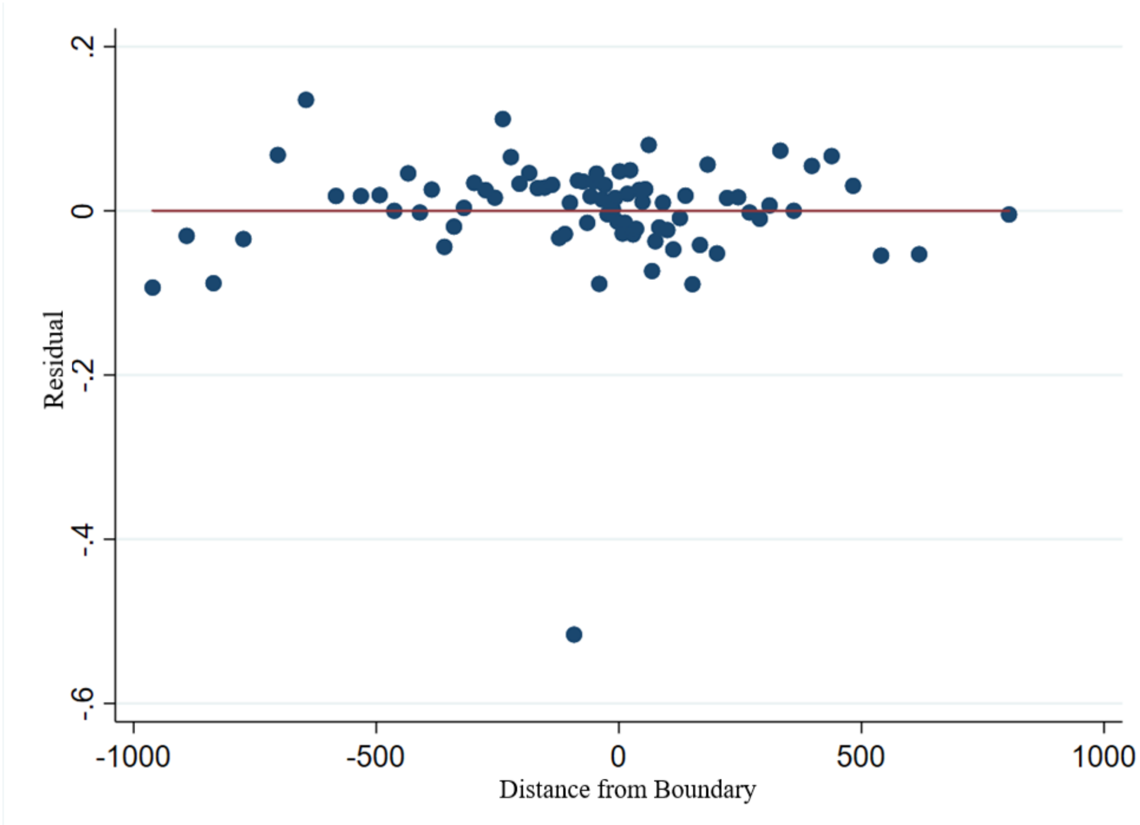


*Figure 2.8* - Bin Scatter Plot of Residuals of Restricted Sample
Notes: Dots represent binned residuals of results of restricted 1000-meter bandwidth model binned by distance to radon boundary. Model restricted to mile segments that contain at least 100 homes on the low radon side (less than 4 pCi/L) and 100 homes on the high radon side (over 4 pCi/L) of the boundary. Sample is split into 60 equally sized bins. Red line represents line of best fit. Sales data from Zillow (2023).

**2.5 Results & Discussion**

**Table 2.3** presents a progression of the general model using a 1,000-meter bandwidth and gradually adding in control variables. High radon areas themselves have an opposite and statistically significant effect on home prices than predicted, but the interaction between high radon area and having a basement has a negative and statistically significant effect on home selling price. The radon-basement interaction negative effect appears in all iterations of the model. Homes in high-radon areas with no basement sell for about 6% more than comparable homes in low-radon areas, while homes in low-radon areas with a basement sell for about 23% more than comparable low-radon homes without a basement. However, homes in high-radon areas with basements sell for about 6% *less* than expected.

*Table 2.3* - Progression of General Model Results

| VARIABLES | (1)<br>1 | (2)<br>2 | (3)<br>3 | (4)<br>4 | (5)<br>5 | (6)<br>6 | (7)<br>7 | (8)<br>8 | (9)<br>9 | (10)<br>10 | (11)<br>11 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| High Radon | 0.0570*** | 0.0429*** | 0.0493*** | 0.0536*** | 0.0555*** | 0.0516*** | 0.0516*** | 0.0548*** | 0.0541*** | 0.0587*** | 0.0579*** |
| | (0.00542) | (0.00534) | (0.00624) | (0.00665) | (0.00632) | (0.00647) | (0.00647) | (0.00644) | (0.00636) | (0.00657) | (0.00641) |
| Boundary Distance | -0.000109*** | -9.40e-05*** | -9.39e-05*** | -0.000124*** | -8.35e-05*** | -6.77e-05*** | -6.77e-05*** | -5.21e-05*** | -3.71e-05** | 4.71e-06 | 4.00e-06 |
| | (1.43e-05) | (1.42e-05) | (1.42e-05) | (1.48e-05) | (1.46e-05) | (1.48e-05) | (1.48e-05) | (1.47e-05) | (1.51e-05) | (1.58e-05) | (1.53e-05) |
| Boundary Distance * High Radon | 8.61e-05*** | 5.98e-05*** | 5.99e-05*** | 9.07e-05*** | 7.27e-05*** | 6.07e-05*** | 6.07e-05*** | 4.10e-05** | 5.28e-05*** | 1.00e-05 | 1.38e-05 |
| | (1.61e-05) | (1.59e-05) | (1.59e-05) | (1.67e-05) | (1.64e-05) | (1.66e-05) | (1.66e-05) | (1.66e-05) | (1.69e-05) | (1.77e-05) | (1.72e-05) |
| Basement | | 0.293*** | 0.304*** | 0.287*** | 0.255*** | 0.258*** | 0.258*** | 0.254*** | 0.210*** | 0.231*** | 0.233*** |
| | | (0.00308) | (0.00615) | (0.00639) | (0.00616) | (0.00629) | (0.00629) | (0.00626) | (0.00617) | (0.00701) | (0.00681) |
| **High Radon * Basement** | | | **-0.0148**** | **-0.0208***** | **-0.0199***** | **-0.0236***** | **-0.0236***** | **-0.0266***** | **-0.0403***** | **-0.0621***** | **-0.0629***** |
| | | | **(0.00682)** | **(0.00717)** | **(0.00691)** | **(0.00703)** | **(0.00703)** | **(0.00701)** | **(0.00691)** | **(0.00777)** | **(0.00756)** |
| Lot Size (SqFt) | | | | 1.05e-09** | 1.60e-09*** | 1.48e-09*** | 1.48e-09*** | 1.42e-09*** | 1.30e-09*** | 6.39e-10 | 4.30e-10 |
| | | | | (4.08e-10) | (5.56e-10) | (5.41e-10) | (5.41e-10) | (5.29e-10) | (4.76e-10) | (4.18e-10) | (3.96e-10) |
| Year Built | | | | | 0.00479*** | 0.00448*** | 0.00448*** | 0.00404*** | 0.00294*** | 0.00266*** | 0.00286*** |
| | | | | | (0.000109) | (0.000110) | (0.000110) | (0.000111) | (0.000112) | (0.000119) | (0.000117) |
| Number of Stories | | | | | | 0.137*** | 0.137*** | 0.122*** | 0.0787*** | 0.0261*** | 0.0252*** |
| | | | | | | (0.00685) | (0.00685) | (0.00616) | (0.00471) | (0.00571) | (0.00556) |
| Total Bedrooms | | | | | | | | 0.0409*** | 0.00664*** | 0.00522*** | 0.0105*** |
| | | | | | | | | (0.00128) | (0.00126) | (0.00159) | (0.00156) |
| Total Bathrooms | | | | | | | | | 0.172*** | 0.118*** | 0.122*** |
| | | | | | | | | | (0.00301) | (0.00879) | (0.00872) |
| Building Area (SqFt) | | | | | | | | | | 0.000145*** | 0.000144*** |
| | | | | | | | | | | (2.12e-05) | (2.09e-05) |
| Constant | 11.62*** | 11.51*** | 11.51*** | 11.55*** | 2.172*** | 2.624*** | 2.624*** | 3.423*** | 5.408*** | 5.886*** | 5.115*** |
| | (0.00467) | (0.00476) | (0.00529) | (0.00563) | (0.216) | (0.217) | (0.217) | (0.219) | (0.222) | (0.237) | (0.329) |
| Contains Sale Year Fixed Effet | NO | NO | NO | NO | NO | NO | NO | NO | NO | NO | YES |
| Observations | 381,645 | 381,645 | 381,645 | 315,323 | 269,837 | 260,281 | 260,281 | 259,506 | 254,369 | 212,908 | 212,908 |
| R-squared | 0.509 | 0.522 | 0.522 | 0.533 | 0.531 | 0.536 | 0.536 | 0.539 | 0.555 | 0.550 | 0.575 |

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

Notes: Progression of results of main specification at 1,000-meter bandwidth. Outcome variable is log selling price of home. All iterations include mile-segment fixed effects which are fixed effects for the nearest segment of the high/low radon boundary after the boundary is split into one-mile segments. High radon defined as area with over 4 pCi/L on average, drawn from KGS data. Sales and housing characteristics data from Zillow (2023).

The significantly positive effect of being in a high radon area is opposite the hypothesized effect. One explanation is that due to the fact that radon pools in basements, homes without a basement in high radon areas are less likely to test at a radon level sufficient to cause a reduction in home price. As discussed earlier there is potentially an upward bias in the high radon price estimates through some unobserved factor which is associated with selling price and a location in a high radon area. The generally more attractive homes in the high radon area of the sample would thus have a higher coefficient when accounting for the interaction term, as the non-interacted high radon term shows the coefficient for homes without a basement in a high radon area. While more work is needed to deal with potential omitted variable bias these results suggest that radon levels in homes without a basement are not high enough on average to manifest in a willingness to pay to avoid them. While this is contrary to my hypothesis it is generally consistent with the physical properties of radon which cause it to pool in basements and the fact that basements are exposed on 5 sides to radon release from soil. Additionally, I do not have any data on where the tests used in the KGS data come from, such as the percent that were conducted in basements. It is entirely possible that in the underlying test kit data that was aggregated by KGS the results of homes without basements are generally below the threshold while those above the threshold have basements.

As a robustness check I present the results of the general specification at various bandwidths between 5,000 and 100 meters of the boundary. As I narrow the bandwidth, I expect homes to become more similar on unobservable factors as I will eventually be comparing homes that are at most 100 meters away from each other, or 200 meters from their farthest comparison home. **Table 2.4** shows the progression of results as the bandwidth narrows. As the bandwidth narrows positive effect of being on the high radon side of the boundary moderates from 0.095 to 0.045 at the 100-meter boundary. These results support the results of the general 1,000-meter specification.

*Table 2.4* - General Model Results by Bandwidth Size

| VARIABLES | (1) 5000 Meters | (2) 2500 Meters | (3) 1500 Meters | (4) 1000 Meters | (5) 500 Meters | (6) 250 Meters | (7) 100 Meters |
|---|---|---|---|---|---|---|---|
| High Radon | 0.0690*** | 0.0825*** | 0.0646*** | 0.0579*** | 0.0398*** | 0.0274*** | 0.0116 |
| | (0.00581) | (0.00593) | (0.00619) | (0.00641) | (0.00715) | (0.00844) | (0.0114) |
| Boundary Distance | 6.64e-05*** | 3.05e-05*** | 5.59e-05*** | 4.00e-06 | -3.06e-05 | -7.62e-05 | 0.000499*** |
| | (2.93e-06) | (6.14e-06) | (1.12e-05) | (1.53e-05) | (2.85e-05) | (6.21e-05) | (0.000185) |
| Boundary Distance * High Radon | -6.23e-05*** | -3.46e-05*** | -4.54e-05*** | 1.38e-05 | 0.000112*** | 0.000285*** | -0.000238 |
| | (3.63e-06) | (6.84e-06) | (1.25e-05) | (1.72e-05) | (3.28e-05) | (7.34e-05) | (0.000226) |
| Basement | 0.257*** | 0.262*** | 0.246*** | 0.233*** | 0.217*** | 0.213*** | 0.214*** |
| | (0.00510) | (0.00572) | (0.00633) | (0.00681) | (0.00811) | (0.0102) | (0.0137) |
| **High Radon * Basement** | **-0.0949*** ** | **-0.101*** ** | **-0.0823*** ** | **-0.0629*** ** | **-0.0429*** ** | **-0.0422*** ** | **-0.0463*** ** |
| | **(0.00593)** | **(0.00642)** | **(0.00706)** | **(0.00756)** | **(0.00870)** | **(0.0104)** | **(0.0129)** |
| Lost Size (SqFt) | 4.02e-10 | 2.31e-10 | -5.02e-11 | 4.30e-10 | -6.11e-10 | -9.80e-10 | -4.69e-09** |
| | (2.80e-10) | (2.54e-10) | (3.58e-10) | (3.96e-10) | (5.99e-10) | (8.02e-10) | (2.25e-09) |
| Year Built | 0.00421*** | 0.00349*** | 0.00311*** | 0.00286*** | 0.00265*** | 0.00244*** | 0.00230*** |
| | (8.35e-05) | (9.36e-05) | (0.000106) | (0.000117) | (0.000152) | (0.000193) | (0.000295) |
| Number of Stories | 0.0354*** | 0.0400*** | 0.0272*** | 0.0252*** | 0.0198*** | 0.0344** | 0.0430** |
| | (0.00641) | (0.00633) | (0.00591) | (0.00556) | (0.00575) | (0.0159) | (0.0170) |
| Total Bedrooms | 0.00659*** | 0.00799*** | 0.0101*** | 0.0105*** | 0.0110*** | 0.0101*** | 0.0101*** |
| | (0.00118) | (0.00129) | (0.00145) | (0.00156) | (0.00184) | (0.00221) | (0.00315) |
| Total Bathrooms | 0.105*** | 0.115*** | 0.119*** | 0.122*** | 0.123*** | 0.121*** | 0.138*** |
| | (0.00708) | (0.00819) | (0.00856) | (0.00872) | (0.00982) | (0.0113) | (0.0112) |
| Building Area (SqFt) | 0.000202*** | 0.000182*** | 0.000161*** | 0.000144*** | 0.000121*** | 0.000109*** | 7.15e-05** |
| | (1.87e-05) | (2.00e-05) | (2.06e-05) | (2.09e-05) | (2.36e-05) | (3.22e-05) | (3.12e-05) |
| Constant | 2.239*** | 3.676*** | 4.594*** | 5.115*** | 5.527*** | 5.699*** | 6.516*** |
| | (0.170) | (0.199) | (0.244) | (0.329) | (0.448) | (0.641) | (0.652) |
| Observations | 366,773 | 308,727 | 251,815 | 212,908 | 145,723 | 93,411 | 49,236 |
| R-squared | 0.568 | 0.563 | 0.565 | 0.575 | 0.597 | 0.614 | 0.629 |

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

Notes: Regression results by bandwidth. Each column represents the results of a regression which includes observations within *x* meters of the high/low radon boundary. High radon defined as area with over 4 pCi/L on average, drawn from KGS data. Sales and housing characteristics data from Zillow (2023).

**Table 2.5** displays the results of the restricted sample, the preferred specification, which restricts the sample to only those mile long border segments which contain at least 100 observations within 1,000 meters of both the high and low side of the boundary. The results of the restricted sample are in line with those of the general model, providing further evidence that high radon potential and basements interact to produce a negative price effect. Comparing the linear combination of the interaction effects, a home with a basement in a high radon area sells for about 5% less than a comparable home with a basement in a low radon area.

*Table 2.5* - Restricted Sample Results

| VARIABLES | (6)<br>1000 Meters |
|---|---|
| High Radon | 0.0248* |
| | (0.0134) |
| Boundary Distance | 9.24e-05*** |
| | (2.59e-05) |
| Boundary Distance * High Radon | 9.70e-06 |
| | (4.66e-05) |
| Basement | 0.258*** |
| | (0.0192) |
| **High Radon * Basement** | **-0.0752*** ** |
| | **(0.0220)** |
| Lot Size (SqFt) | -9.40e-09*** |
| | (2.89e-09) |
| Year Built | 0.00357*** |
| | (0.000362) |
| Number of Stories | -0.0467** |
| | (0.0210) |
| Total Bedrooms | 0.000910 |
| | (0.00597) |
| Total Bathrooms | 0.183*** |
| | (0.0190) |
| Building Area (SqFt) | 0.000340*** |
| | (4.42e-05) |
| Constant | 4.113*** |
| | (0.757) |
| Contains Sale Year Fixed Effect | YES |
| Observations | 12,480 |
| R-squared | 0.511 |

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

Notes: Results of restricted sample. Sample restricted to only mile border segments that contain at least 100 homes on the high (over 4 pCi/L) and 100 homes on the low (less than 4 pCi/L) sides of the radon boundary, drawn from KGS data. Outcome variable is log selling price of home. All iterations include mile-segment fixed effects which are fixed effects for the nearest segment of the high/low radon boundary after the boundary is split into one-mile segments. Sales and housing characteristics data from Zillow (2023).

The results are notable given the cost of a radon mitigation system which ranges between $1,500 and $3,000 (Minnesota Department of Health, 2023). The price response is larger than the cost mitigation – which is quite effective at reducing radon levels. This suggests that sellers are experiencing a price penalty larger what would occur if they were to simply install a mitigation system before putting their home for sale. A possible explanation for the discrepancy is that buyers demand a further penalty beyond simply the cost of mitigation once a home has been discovered to be ‘tainted’ with high radon. Why do sellers not simply cancel the current sale, install a mitigation system, and relist their home? There may be frictions in the sale process that make this not cost effective for them, or they may be unaware that this may save them money. Alternatively, my results may represent an upper bound for the price penalty and future work would be well served to refine the estimates.

Due to the price penalty found in homes with basements in high radon zones the conclusions of this paper suggest that home buyers in Kentucky are aware of the dangers of radon exposure in homes with basements and seek to avoid the carcinogen. As radon is only detectable with a test it is unlikely that buyers are aware of radon levels without some source of information; barring some systematic difference in unobservables radon levels are the most likely driver of the price differential that I find. Likely sources of information are home radon tests done during a home inspection, the seller disclosure form statement of prior radon test levels, information from the EPA or state radon office, direct explanation from a home inspector or radon mitigation specialist, or a combination the above. This suggests that the current policy of voluntary testing, mandatory disclosure, and the licensing of radon mitigation professionals provides some level of information. Whether this level of information is adequate is beyond the scope of this paper, as I do not have information on individual test kits or radon mitigation systems. I am unaware of whether there are differentials in mitigation behavior by socio-economic status or whether buyers' homes with high radon levels even engage in mitigation post-purchase. Thus, if the policy maker is worried about residential radon exposure more research is needed to determine whether exposure is actually lowered. It is possible that buyers simply take the saving they receive and continue to live with high radon. What this paper provides is evidence that information is being transmitted to some buyers.

While homes with basements display the expected price penalty there is no negative effect for homes without a basement in high radon areas. This may be due to these homes not having radon levels above the mediation level, on average, or these homes may be treated systematically differently. For example, home inspectors may be less likely to suggest a radon test for homes without a basement. In this case policy intervention may be needed if homes without a basement are found to have elevated radon levels.

I assume in this paper that upon discovery of high radon individuals may negotiate down the price of a home. Other options such as the sellers giving cash to the buyers to facilitate the home sale, or installing a mitigation system and not adjusting the final sale price are also possible. The fact that alternative mechanisms that will not show up in the selling price of a home exist and there is still a price penalty is significant. Even with sales that have some negotiated settlement that is not reflected in the final sale price there is still a reduction in selling price of home with basements, on average.

The results provide evidence that on average there is a willingness to pay to avoid radon exposure. The independent variable – mean radon level – is itself an aggregate measure that is merely showing the radon levels that occur over a given geology *on average*, I have no information on the actual radon readings in a home. Radon levels are very prone to fluctuations based on weather, house features, and other factors. Short-term tests need to be conducted with windows closed because even a breeze can change radon levels in a home. The measure of radon levels is very imprecise and subject to a large amount of uncertainty. This combined with the aforementioned upward bias in the Zillow data suggest that these results are not a definitive conclusion. However, in all of the models run there is a consistent negative coefficient for the high radon-basement interaction term which is evidence that there is a price penalty for homes with basements in high radon areas. This finding is entirely consistent with the theory and literature on radon, as it pools in basements.

In order to address the shortcomings of this study, future work would be well served to get a richer data source for both radon and homes. The Zillow data is a great resource but due to the variance in county PVA data quality it ends up with systematic exclusions which may bias the results in the end. Data are not missing at random which introduces a degree of measurement error into the model. However, a more localized study in an area with more complete data would help fill in some of these gaps. Additionally, a project that directly uses radon test kit results would help alleviate the measurement concerns inherent to using aggregate data from KGS.

# CHAPTER 3. ECONOMIC INCENTIVES AND ENVIRONMENTAL OUTCOMES: STORMWATER UTILITY USER FEES AND IMPERVIOUS SURFACE COVER GROWTH

## 3.1 Introduction

In this study I examine the effect of municipal separate stormwater system (MS4) fees on the built environment using a stacked difference-in-differences design to examine whether the institution of a variable rate fee, based on the total impervious surface cover on a parcel, has the effect of lowering impervious surface cover using two outcomes – new residential construction and impervious surface cover growth rate in a stormwater utility (SWU) district. I do not find evidence to support my theory that impervious surface cover changes after institution of a variable rate fee in treatment SWUs compared to control SWUs. My results suggest that if municipalities wish to lower impervious surface cover within their boundaries, they may need to redesign fees or use other policy tools.

A municipal separate storm sewer system (MS4) is a type of SWU that is a series of publicly owned and constructed conveyances that transport rainwater from an urban area to a body of water. The usage and proper functioning of these systems may impact the health of surrounding ecosystems, human health, and urban development. At their best, they efficiently convey and purify stormwater and runoff – managing flooding and lowering pollution. At their worst, they increase the volume and velocity of floods and transport pollutants from dispersed urban areas to nearby surface waters, which has several negative effects. These systems are ubiquitous in the United States yet have received little attention from the policy community. I will use different funding mechanisms which have been instituted in response to federal regulations on MS4s to introduce and test a simple model of impervious surface cover.

I will first discuss why examining human changes to natural systems is important to policy scholars and society at large. Changes to natural systems cause negative effects at a scale that lead to externality problems, as the byproducts of a municipality do not stay within their borders. As an example, nitrogen runoff that exits municipal borders has effects not just on neighboring communities but also locations hundreds or even thousands of miles away. I will then discuss MS4s more broadly to establish the policy and administrative details that I plan to research. I will then introduce my theory of impervious surface cover change in response to MS4 fees before discussing my data, empirical strategy, and results.

### 3.2 Natural Systems

Humans have changed the Earth in innumerable ways during their existence on the planet – with many of the most profound changes occurring recently. These changes occurred on such a scale that geologists recently proposed that the Earth has entered a new epoch, the Anthropocene[1]. For geologists, the classification of epochs is a function of global-scale changes found in the geologic record; perhaps most famous is the meteor strike which is thought to have contributed to the extinction of 75% of life on Earth, including dinosaurs, and concurrently ended the Late Epoch, Cretaceous Period, and

[1] In geology, epochs are demarcations of time which are contained within periods which are in turn components of eras. For example, we are currently in the Quaternary Period of the Cenozoic Era which began about 2.6 million and 66 million years ago, respectively (Christopherson, 2003). Depending on who you ask we left the most recent epoch, the Holocene, within the last 60 to 400 years (Lewis & Maslin, 2015). The Holocene itself began about 11,650 years ago which means it likely contains the invention of written language, pottery, and continuous settlements.

Mesozoic Era (Renne et al., 2013)[2]. To motivate this paper, I will briefly outline the implications of largescale changes to the surface of the Earth that are inherent to urbanization.

3.2.1 *Urbanization & Impervious Surfaces*

Modern life invariably requires altering the natural landscape to support human habitation and activity – a process that transforms parts of a landscape from pervious to impervious. An impervious surface is defined as a surface of "any material that prevents the infiltration of water into the soil" (Arnold Jr & Gibbons, 1996). These surfaces include paved roads, houses' roofs, sidewalks, paved parking lots, and compacted soils.

In 2017, the percentage of impervious surface coverage within urban areas was 33.8% in North America and 26.5% globally, representing an increase of 0.7% and 1.6% from 2012, respectively (Nowak & Greenfield, 2020). There has been a steady increase in impervious surface cover throughout the 20th century, correlating with increases in urbanization (Shuster, Bonta, Thurston, Warnemuende, & Smith, 2005). Nowak and Greenfield (2012) examine impervious surface growth trends in cities using high resolution images[3] and estimate an average increase of 0.31% a year, suggesting that the trend has continued into the 21st century. Their study only examines 20 nonrandomly

[2] Another example is the eruption event which created the Siberian Traps in which volcanoes in current day Siberia erupted continuously for two million years, drastically heating the atmosphere, and likely contributing to the largest mass extinction event in planetary history with over 90% of all species going extinct (Saunders & Reichow, 2009).

[3] There are typically two approaches to estimating impervious surface coverage in an area: satellite and aerial photography. Satellite based approaches allow the classification of much larger areas up to and including global classifications. However, aerial photography has the advantage of being higher resolution than satellite imagery and thus can allow for more precise estimates albeit in smaller areas. Barring advancements in satellite imagery (or the declassification of ultra-high resolution satellite images) there will be a tradeoff between precision and scope.

selected cities in the United States, limiting the conclusions that we can draw, but it provides a reference for the growth of impervious surfaces.

Impervious surfaces are necessary for many of the amenities we value in society, such as a roof over our heads, roads to drive on, places to park our cars, and sidewalks to make walkable neighborhoods. On the other hand, environmental scientists have found that impervious surfaces contribute to degraded water quality, hotter cities, and more destructive flooding (Chithra, Nair, Amarnath, & Anjana, 2015) and have used impervious surface cover as an indicator for environmental quality for decades (Arnold Jr & Gibbons, 1996). Any level of impervious surface cover alters the natural landscape and reduces the ability of natural systems to remove pollutants from water, which is associated with negative effects. However, research generally finds 10% to 15% impervious surface cover in a watershed as when ecosystem health shows a sharp decline, such as increased water temperatures and pollutant levels (Moglen & Kim, 2007). As impervious surface cover increases runoff increases and infiltration of water into soil drops.

When impervious surfaces prevent rainwater from infiltrating into soil, the result is both higher volume and higher velocity of runoff. Stormwater runoff accumulates substances that are present on the surfaces over which it flows. Runoff sweeps up anything on the ground – lawn fertilizers, oil, spilled chemicals, particulate matter from factories and automobile exhaust –and finds its way to a nearby body of water, generally making its way into the ocean or an underground aquifer (Frazer, 2005). Artificial conveyance of stormwater by impervious surfaces bypasses the natural pollutant filtration, which soil, wetlands, and other natural ecosystems provide, concentrating pollutants. Higher velocity runoff causes increased erosion, which destroys natural systems and transports sediments. The accumulation of pollutants in runoff exemplifies nonpoint source pollution – pollution which does not originate from any single point, such as a factory smokestack, but instead results from many diffuse points coming together. This type of pollution is a major contributor to environmental degradation but is difficult for governments to address due to its diffuse nature among other factors (Xepapadeas, 2011). Lower water quality affects the environment itself, recreational opportunities, and drinking water. More polluted water can strain water treatment systems resulting in lower drinking water quality (Sjerps, Kooij, van Loon, & Van Wezel, 2019), increased costs to maintain prior quality levels (Chen, Haunschild, Lund, & Fleenor, 2010), and increased greenhouse gas emissions from water treatment (Zouboulis & Tolkou, 2015). The list of pollutants carried by runoff and their effects on environmental and human health and wellbeing is not the focus of this paper. However, in order to provide an accounting of pollution dangers please see **Appendix A** for a review of the detrimental effects of one of the most common pollutants, nitrogen.

### 3.3 Municipal Separate Storm Sewer Systems (MS4s)

The chief water quality legislation in the United States, the 1972 Clean Water Act (CWA) and its amendments, does not allow for nonpoint source pollution regulation. This lack of regulation results from the understanding of the issue at the time, the relative ease of regulating point source pollution compared to nonpoint, and a decision to avoid imposing regulatory burdens on farmers (Laitos & Ruckriegle, 2012). The CWA successfully lowered pollution from point sources, but without a mechanism to address nonpoint pollution, the nation's waterways continued to be polluted to a level that concerned voters and Congress enough to pass additional legislation.

Congress amended the CWA in 1987 to require, among other things, the regulation of storm discharge in urban areas under the already established National Pollutant Discharge Elimination System (NPDES) permitting program[4]. The EPA has regulatory authority over separate stormwater sewer systems. In effect, the EPA declared that by taking nonpoint source discharge (runoff from parcels) and conveying the runoff in a built system, the runoff becomes is then a point source which the federal government has the authority to regulate. These systems are known as MS4s (Municipal Separate Storm Sewer Systems)[5]. 40 CFR 122.26(b)(8) broadly defines MS4s as "a conveyance or system of conveyances (including roads with drainage systems, municipal streets, catch basins, curbs, gutters, ditches, man-made channels, or storm drains)" (Stormwater Discharges, 1990).

Two factors contributed to the NPDES program's extension to MS4s and federal involvement in the issue. The first is the previously mentioned recognition nonpoint source pollution's contribution to environmental degradation, and the second is the

[4] Following the 1987 CWA amendment, the EPA worked to develop an extension of NPDES permitting requirements to MS4s. The EPA requires NPDES permits for any entity that discharges pollutants from a point source directly into a water of the United States. Originally NPDES regulations focused on industrial waste following the focusing event of the 1969 Cuyahoga river fire[4] which in addition to providing popular support for the passage of the CWA also helped lead to the creation of the EPA (Solid Waste Agency of Northern Cook County v. United States Army Corp of Engineers, 2001) and helped shift government focus from maintaining navigability on rivers to protecting water quality (Duchesne, 2004).

[5] MS4s exist in contrast to two other systems: sanitary and combined systems. Sanitary sewer systems convey wastewater from buildings through pipes to a treatment plant. Combined sewer systems are a combination of both with wastewater from buildings and stormwater in the same conveyance. However, governments have not built new combined systems since the first half of the 20th century due to their tendency to become overwhelmed during storm events and discharge wastewater onto city streets, homes, overwhelm treatment plants, and heavily pollute nearby ecosystems (National Pollutant Discharge Elimination System, 2018). Combined sewer systems and sanitary sewer systems are not subject to the regulations of interest for my study.

externalities imposed on downstream municipalities by other MS4s. The original focus of stormwater management was to control flooding and remove stormwater in the most efficient manner possible. The focus on flood control by stormwater systems led to runoff in natural water systems that multiple municipalities share, imposing costs on these municipalities, and raising jurisdictional issues as there was little city-to-city recourse. The federal government, on the other hand, is the level of government best suited to regulate cross-border jurisdictional issues and Congress passed the CWA amendments to require cities to recognize these costs (NAFSMA-USEPA, 2006). Essentially, the boundaries which demarcate a shared watershed generally do not align with administrative boundaries. Many municipalities may exist in the same watershed and their pollution will in turn affect all users of a common watershed. Additionally, water flows downstream, and the pollution of upstream municipalities is not stationary and will eventually end up in another jurisdiction.

To roll out the NPDES program to entities subject to MS4 permitting requirements MS4s, the EPA split them into two groups based on population – Phase I and Phase II – with each required to obtain an NPDES permit by a different date. Phase I permittees are split into medium and large MS4s based on their population. Large MS4s are cities or counties with over 250,000, residents while medium had between 100,000 and 250,000. Phase II, or small MS4s, are any MS4s within an urbanized area, with the designation extended every ten years when the Census Bureau updates urbanized area designations. Phase II MS4s also include public entities beyond municipalities such as universities, hospitals, and prisons (NPDES, 2018). The EPA required Phase I entities to apply for an NPDES permit with a stormwater management program by November 1992 for large MS4s and May 1993 for medium MS4s. Phase II MS4s did not receive a final rule until 1999 and the EPA did not require them to apply for an NPDES permit until March of 2003 (Government Accountability Office, 2007)[6]. Per data provided to me by the EPA, there are 7,069 regulated MS4s as of 2014, 744 of which are Phase I and 6,325 are Phase II. Of the 7,069 MS4s 1,214 are other public entities such as universities, hospitals, and prisons. My proposed research will focus exclusively on the city and county MS4s and not other public entities.

### 3.3.1 *MS4 Funding Mechanisms & Stormwater Utilities*

Descriptive work by Warren Campbell, a civil engineering professor at WKU who has been conducting an annual survey of MS4 funding mechanisms since 2007, finds that municipalities fund their stormwater programs in three ways: general revenue, flat stormwater fees, and variable stormwater utility fees[7]. Campbell (2020) finds 1,807 non-general revenue funded MS4s in the United States, about 31% of MS4s. The use of stormwater fees has been increasing since 2007, though he points out that legal barriers

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[6] The EPA follows a maximum extent practicable (MEP) standard to reduce polluted discharge from MS4s into surface waters in NPDES permits. The MEP standard is ambiguous and has been subject to litigation and clarification by courts over the years. However, it recognizes that meeting the specific water quality standards outlined in the CWA may not be practical due to budgetary, feasibility, or other concerns. Thus, regulated entities must institute best management practices to address pollution concerns (California State Water Resource Control Board, 2004). The EPA outlines six specific areas that must be addressed:

1. Public education and outreach
2. Public participation/involvement
3. Illicit discharge detection and runoff
4. Construction site runoff control
5. Post-construction runoff control
6. Pollution prevention/good housekeeping for municipal operations

(Stormwater Phase II Compliance Assistance Guide, 2000)

[7] The jargon on stormwater utilities in the world of MS4s warrants clarification. Stormwater utilities includes all user fee funded systems. Within stormwater utilities there are flat fees and variable fees based on usage of the stormwater system. Practitioners and researchers in the field refer to the variable fees as stormwater utility programs while the flat rate systems are stormwater fee programs (Kea, Dymond, & Campbell, 2016).

exist to the imposition of fees in some states (Campbell, 2020). It is important to note that while Campbell's data is the best that exists publicly, he does not claim to document every MS4 in the nation. He estimates that there are around 2,000 stormwater utilities and that his dataset is likely missing smaller, nonmunicipal systems.

There are two types of flat fee systems. One is a flat rate for every parcel of land in a municipality, while the other is a tiered system where different classifications of parcels pay different flat rates. In the latter, single family homes may be $2, apartment complexes $10, and commercial parcels $15. The key to these systems is that there is no change in fee based on the stormwater system's calculate use or any scalable factor in any of the tiers. Of 1,807 systems 227 have a flat fee system as of 2020.

Stormwater utility fee systems vary more, but all share the common feature of having some sort of variation in the fee that scales based on use of the system. The National Association of Flood and Stormwater Management Agencies classifies use-based funding schemes into four categories: "impervious area, combination of impervious area and gross area, impervious area and the percentage of imperviousness, and gross property area and the intensity of development" (NAFSMA-USEPA, 2006). All these methods in some way attempt to quantify the contribution of each parcel to stormwater runoff. **Figure 3.1** describes the most common fee structures.

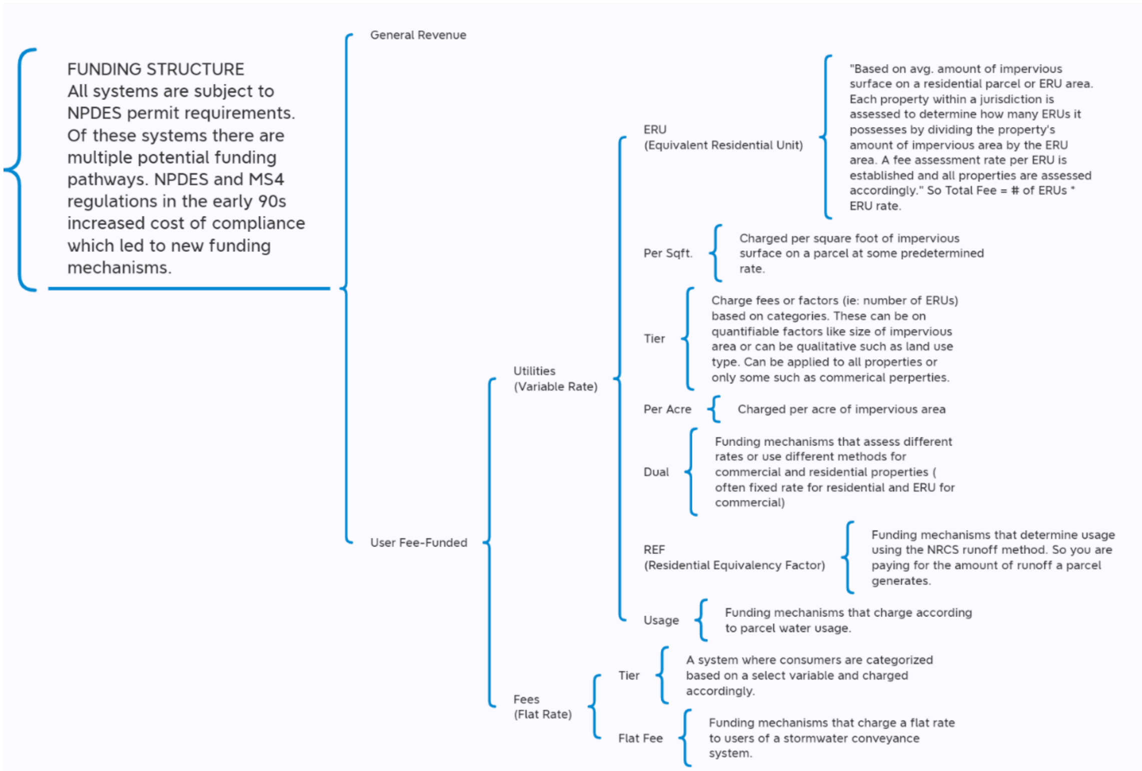


*Figure 3.1* - Funding Mechanisms for MS4s

Nearly 50% (864) of fee-funded MS4s use the equivalent residential unit (ERU) system, making it by far the most common fee-based funding mechanism as of 2020 (Campbell, 2020). The ERU system calculates the average impervious surface area of residential parcels in a jurisdiction. Then, the stormwater authority compares each parcel to this number in determining the specific user fee. The ERU is the total residential impervious surface cover divided by the number of residential parcels and the fee is the number of ERUs on a specific parcel multiplied by the ERU fee (ERUs on parcel * rate per ERU = fee).

The proliferation of stormwater fees of all types in the last thirty years is due at least in part to compliance costs. The requirements of the CWA are an unfunded mandate and raise costs for MS4s as they implement new practices and integrate new technologies which require perpetual upkeep into their water systems. Stormwater management agencies have shifted their mission and funding strategies over the years. The National Association of Flood and Stormwater Management Agencies described these changes in 2006, stating, “the stormwater function has evolved from a basic capital construction and maintenance program supported primarily by local taxes, to a program of integrated water resource management, environmental enhancement, and recreational services requiring a multi-faceted benefit-based financing system” (NAFSMA-USEPA, 2006). In addition to evolution in stormwater agency mission, changing weather patterns caused by global warming and aging infrastructure also contribute to increasing costs to MS4s operators as peak intensity of rainstorms increases, overwhelming previously functional stormwater systems (Kea et al., 2016; Zhao, Fonseca, & Zeerak, 2019). A question arises about how exactly municipal governments pay for the increased costs imposed by MS4 regulations and increased strain from climate related hydrological events.

Jerch (2021) examines how local governments finance environmental mandates by looking at how jurisdictions responded to the CWA’s passage in 1972. They find that rather than decreasing spending in other areas or raising taxes jurisdictions tended to fund new water quality investments through user fees. The response to the original CWA is similar to how some municipalities responded to the CWA amendments 15 years later. From the perspective of stormwater managers, dedicated fees are a preferred funding mechanism in that they provide a consistent revenue stream exclusively allocated for the use of the stormwater program. One additional advantage of fee-based funding is that tax-exempt property is not exempt from fees; for stormwater programs these properties, such as universities, military bases, and state-owned property, can be large contributors to stormwater related issues (NAFSMA-USEPA, 2006).

Outside of the water science world, which tends to examine the technical aspects of stormwater management, and case studies, little research on MS4s and stormwater fees exists. In a study on the diffusion of stormwater fees, Chalfant (2018) finds that state and federal regulation associates with fee imposition, as fee enactment spikes in the years after the rollout of NPDES Phase regulations. They also find that some states have statutory barriers to fees and that fees again spike after the legislature or new case law relaxes these barriers. Kea, Dymond and Campbell (2016) also find that fees appear to correlate with the rollout of MS4 regulations. The authors go further than Chalfant (2018) and examine correlations between fee type and municipal characteristics with a couple of notable findings. The authors theorize that denser areas are more developed and have higher stormwater costs, but they suggest these areas may also have more personnel that can conduct the calculations necessary for variable rate fees. Meanwhile, small towns may face lower costs due to less development and have less technical ability to set a variable fee. The results are not clear; municipalities that use flat fees tend to be smaller and less dense than those with a variable rate, but the range of population size is small. On the other hand, denser areas tend to use variable fees, but the range is quite large, and both small and large municipalities have variable rate systems.

The authors also find that areas with higher home values associate with variable rates while lower value areas tend to impose flat fees. The home value analysis raises some equity concerns, but unfortunately the authors do not examine the issue in much depth. Flat fees in a less low-income municipality may be regressive if poor residents pay a larger share of their income while consuming less impervious surface area than their wealthy peers in the same municipality. Future research needs to examine how the impervious surface cover of poor areas compares with that of their wealthier peers and whether less advantaged residents tend to pay a higher proportion of their income on stormwater management fees.

With the background on impervious surfaces, a discussion of some of the harms from stormwater runoff, and an overview of MS4s established I will I propose an in-depth examination of the relationship between stormwater fees and impervious surface cover (with a goal of examining water quality in future work).

**3.4 Theory**

It is an open question whether stormwater fees induce behavioral responses by forcing property owners to internalize the cost they impose upon the stormwater system through the individual generation of runoff or whether they are economically neutral and correspond to little behavioral change. Economic neutrality is a principle of taxation (Denison & Facer, 2005) but in the case of a stormwater fee minimizing behavioral response may not be the goal. A recent review of research on stormwater fees highlights the question of behavioral change due to fee structure as an area in need of further research (Zhao, et al., 2019). A study of two Virginia cities on the theoretical revenue raising capability of different fee structures also highlights the same question as a research opportunity (Fedorchak, Dymond, & Campbell, 2017).

I argue that MS4s are a common pool resource due to their low excludability[8] and rivalrous nature. One cannot be feasibly blocked from runoff leaving their property over nonpayment, but the system's use does affect the ability of others to use the system. For example, a factory with facilities and parking areas which increase the total runoff generated in the town can overload the system, which will result in flooding and pollutants spreading across the community through floodwaters. Additionally, this same hypothetical factory can contribute polluted runoff which cannot be effectively managed by the MS4, leading to a depletion of groundwater resources, recreational activities, and biotic diversity in drainage basins and nearby surface waters. The common pool nature of water systems, fisheries, and drainage basins is accepted in the field of environmental policy (Ostrom, Gardner, Walker, Walker, & Walker, 1994).

Under a conventional theory of common pool resources each property owner maximizes their own utility and possesses complete information. In the context of stormwater this means that a property owner will maximize the impervious surface cover of their parcel until the private marginal cost of a unit of impervious cover equals the private marginal benefit. Under this framework a market failure occurs if the social marginal cost or benefit is not aligned with the private marginal cost or benefit (Ostrom, 2002). Thus, the socially optimal amount of impervious surface cover on an individual's parcel may be lower than the amount provided in the absence of regulation. A social planner may wish to impose fees to move the private cost towards the social cost.

[8] There is *some* degree of excludability as in theory development of a parcel could be blocked by a government.

The imposition of fees is one method of recognizing social costs. Depending on the structure, they can serve to finance operations, change behavior, or both. In the case of financing operations, fees are often broad and flat. When changing behavior, fees are based on use and must be sufficiently large to incentivize privately adjusting the factor used to calculate the fee. The only decision businesses or resident makes with a flat fee is whether to locate in the jurisdiction to begin with, while a user can lower variable fee payment by removing impervious surface cover or building less. As examples, the use of relatively low universal fees on drug manufacturing plants helps finance the FDA but does not impose high enough costs to significantly affect decisions on plant operations. On the other hand, large fees on the manufacture of CFCs were successful in virtually eliminating the production of ozone depleting CFCs at the end of the 20th century (USDA-ERS, 1999).

According to surveys, MS4 operators view fees primarily as a dedicated revenue stream to finance operations – while also recognizing that impervious surface cover is the predominant factor in system use (Zhao, et al., 2019). In my research I have yet to come across a source which states a municipality imposed a fee type with the goal of lowering impervious surface cover. However, municipalities do use fees to change behavior in other instances such as road fees to lower congestion (Yang, Purevjav, & Li, 2020) Some may argue that the intention is irrelevant, but a lack of intentionality supports the argument that municipalities pick fee structure independent of potentially unobserved factors that also influence impervious surface cover. For example, if a stormwater manager is an impervious surface cover zealot, they may package a variable rate fee in with other efforts to lower impervious surface cover. However, the lack of intentionality in changing behavior may suggest that they do not view fee structure as a method to change the built environment in an MS4.

The fact that impervious surfaces are costly to remove suggests that we may not see an overall reduction in impervious surface cover in a municipality. Instead, a resident or commercial entity may change their future behavior such as reducing the footprint of future home expansions or new construction in response to the fee. This theory suggests that we may see a reduction in the growth rate of impervious surfaces in the years following a fee.

I propose a simple model of the relationship between fee structure and impervious surfaces:

Impervious surfaces are a function of fee type, fee amount, property type, date of construction.

The above discussion suggests that fee type (variable vs. flat), fee amount (does the imposition of costs outweigh the benefits from cover), property type (residential vs. nonresidential), and date of construction (before vs. after imposition of fee) may all play a role in changing behavior. This leads me to two hypotheses that I will test:

H1: *Imposition of a variable rate fee will lead to lower impervious surface cover in new construction after the institution of the fee*

H2: *Imposition of a variable rate fee will lead to lower district-wide impervious surface cover growth after the institution of the fee*

Hypothesis one examines whether residential construction firms or consumers change their behavior when faced with a variable rate fee. If firms and consumers are responsive to the fee I expect to see a lower average footprint size post-fee. The second hypothesis takes a broader look at impervious surface cover and examines whether the rate of impervious surface cover growth changes overall. Parking lots and other paved surfaces may be cheaper to either reduce post-construction or more responsive to variable fees. Because the first hypothesis looks only at residential building footprints it would miss out on this variation. Taken together the two hypotheses allow a multifaceted look at whether impervious surface cover changes as a result of policymaking. I will exploit variation in fee type, impervious surface cover, timing of fee imposition, and building footprint to test my hypotheses.

Consider the following hypothetical example to help illustrate my hypotheses. Municipality A and B are neighboring jurisdictions that are broadly similar. Municipality A institutes a variable rate fee on residential properties. Homeowners in municipality A are now subject to $100 per ERU in their parcel. As a reminder, this is the amount of impervious surface cover on a parcel and is calculated by dividing the total amount of residential impervious surface cover in a SWU by the total number of parcels. Homeowners have some ability to lower their ERU around the margins such as replacing a driveway; however, I cannot see this directly in my data. Another avenue to impervious surface cover reduction is through changes in the construction of homes. Homes may get built up rather than out to reduce impervious surface cover and lower the fees a home is subject to. Similarly, firms can respond to the imposition of a variable rate fee by removing or reducing impervious surfaces such as vacant buildings, parking lots, and private roadways. We may see businesses build smaller parking lots post-fee imposition. This will lead to a lower growth rate in Municipality A after fee imposition when compared to Municipality B.

### 3.5 Data

Data for SWUs are drawn from the previously discussed Campbell (2020) SWU survey. This is the only national dataset that contains information on SWU fees, imposition dates, and locations. In order to link these data with my other sources I geocoded all SWUs contained in the survey, which includes cities, counties, and unique districts. Cities and counties follow the respective boundaries and were linked in ArcGIS using Census shapefiles and FIPS codes. Unique districts do not conform to established administrative districts. For each of these districts I either found the boundary on the SWU website or contacted the SWU directly to request a shapefile and was able to obtain a shapefile for each unique district. This left me with 1,777 SWUs in total of which 733 have a variable rate fee. My empirical strategy will exploit variation in the timing of fee institution only in variable rate fee SWUs which are displayed in **Figure 3.2.** County, city, and unique SWUs can be seen across the United States.

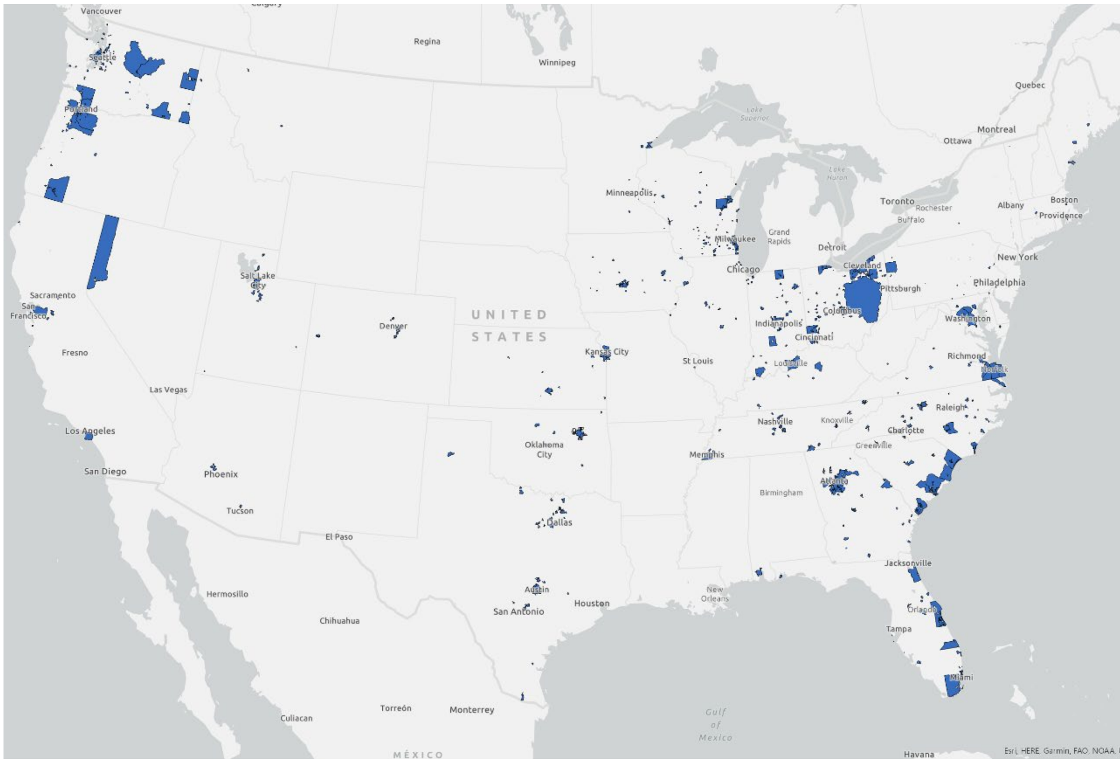

*Figure 3.2* – Variable Rate SWUs in the United States, 2020
Notes: Data compiled by author using ArcGIS and Campbell (2020) SWU survey. Blue shading indicates an SWU with a variable rate fee.

Impervious surface cover data come from the United States Geological Survey's Multi Resolution Land Characteristics Consortium National Land Cover Database (NLCD) imperviousness datasets. NLCD imperviousness datasets divide the country into 30-meter pixels and use high resolution satellite imagery, geospatial modeling, and machine learning to calculate a total percent impervious figure for each pixel in the country. There are releases for the years 2001, 2004, 2006, 2008, 2011, 2013, 2016, 2019, and 2021. The 2011 NLCD impervious surface data – the most recent release year for which studies are available - is accurate within 1.5% when compared to geographically limited but higher-resolution impervious surface datasets[9] (Wickham et al., 2018). One

[9] In order to assess accuracy these studies use the mean absolute deviation between the NLCD data and the high-resolution data (NLCD %IS – High-Res %IS). High-resolution data use 1-meter squares compared to 30-meter squares for NLCD data.

caveat is that accuracy is lower in smaller, urbanized census block groups, however the smallest areas I use are census places which are within not in agreement with high-resolution data by 5.7% on average (Wickham et al., 2020). Importantly older years in the dataset are reprocessed using the same techniques as newer data which allows for cross-time, apples-to-apples comparison of impervious surface cover (Yang et al., 2018). In order to get an MS4-level measure of impervious surface cover I use ArcGIS to aggregate every pixel within an MS4 boundary and get the mean impervious surface cover in an MS4. This gives me the average percentage of impervious surface cover by MS4 and year from which I can calculate the average growth rate of impervious surface cover by MS4.

I utilize the Zillow ZTRAX dataset (2023) of home assessments as another measure of impervious surface cover. This dataset contains data on home characteristics including location and square footage. Some states and municipalities contain a measure of building footprint which is an indicator of how much physical space the building covers, however due to the low availability of this data I instead utilize square footage of the home. In order to proxy for home footprint, I divide the square footage by the number of stories in the home. This introduces some amount of measurement error as one can imagine a building with a smaller top floor than ground floor, but it is the most accurate measure available to me and allows me to examine a different potential pathway of change than the NLCD data. Some observations are missing data across states and years in which case these variables are dropped from my dataset. Observations that are missing year built, square feet, or stories are all dropped from the dataset. Additionally, the square feet designations for non-residential assessments have values which are both unrealistically high and low and appear less reliable in general. In order to avoid introducing further measurement error I restrict my sample to single family residential homes. I use ArcGIS to spatially link every home assessment to the MS4 the home is in to get a dataset of home footprint.

Overall, my two measures of impervious surface cover allow me to approach change in impervious surface cover from two different angles. Each measure has some degree of measurement error but by utilizing two very different datasets I can get a more accurate picture of potential effects than I would from one dataset. The NLCD data examine the potential effect of variable rate fees on the entirety of impervious surface cover in an area while the Zillow data examine a narrower pathway through the construction of new homes.

In addition to my explanatory and response variables I link a set of economic, demographic, and political covariates. The covariates I include are per capita income, percent of the area comprised of black residents, total population, and percentage of the vote for the Democratic candidate in the most recent election. Population and black population share are drawn from the American Community Survey, elections data come from the MIT Elections Data Lab, per capita income comes from the Bureau of Economic Analysis. Per capita income captures the relative wealth of an area which may be related to both home size and impervious surface cover growth, though all specifications have been run using median household income drawn from the ACS from 2010 to present and from the Decennial Census in 2000 as an alternate measure of wealth and are robust to this specification. Per capita income is included in the main specifications due to the data being available yearly between 2000 and 2010 while median income is only available in 2000 and then yearly from 2010 onward.

For covariates that are only available at the county level I assign municipalities to a county based on the county that the majority of the MS4 lies in. For unique MS4s that contain many counties I sum all counties where they cover at least 50% of the area of the county. While this technique introduces a degree of measurement error, I do not rely on covariates in my model as all results are robust to their inclusion. In the future I plan to use weights to get more accurate measures for non-county MS4s.

My completed dataset spatially links MS4s, impervious surface cover, and a range of covariates. This dataset is a contribution to the literature itself as to my knowledge it is the first national dataset of impervious surface cover and MS4s and among the first to examine impervious surface cover in a policy context. Additionally, there are new data projects on the horizon that may help improve the accuracy of impervious surface measures, such as the Bing Building Footprint Inventory.

**Table 3.1** provides an overview of select descriptive statistics of variable rate SWUs included in the final dataset while **Figure 3.3** displays mean impervious surface cover in these same SWUs. The variable rate SWUs is mid-size city, though the population ranges from small towns to the over 9.5 million resident of Los Angeles County.  These areas lean republican with a small black population and a per capita income that outpaced the national average of $31,548 in 2001 but by 2021 per capita income is lower than the $64,430 average. Other than per capita income the summary statistics remain largely consistent across the timeframe of the study.

*Table 3.1* - Select Descriptive Statistics on MS4s

| | Population | | | Democratic Vote Share | Percent Black Residents | County Per Capita Income |
|---|---|---|---|---|---|---|
| Year | Mean | Min | Max | | | |
| 2001 | 429,589 | 7,100 | 9,626,034 | 43.79 | 10.31 | $37,799.00 |
| 2021 | 513,895 | 7,386 | 9,811,842 | 43.41 | 11.79 | $60,601.00 |

Note: Mean impervious surface cover is the average impervious surface cover percent of all 30m pixels wholly within a municipal boundary. Population numbers drawn from 2000 and 2020 census. Population is based on census designed place or county. Vote share and per capita income are at the county level for all MS4s.

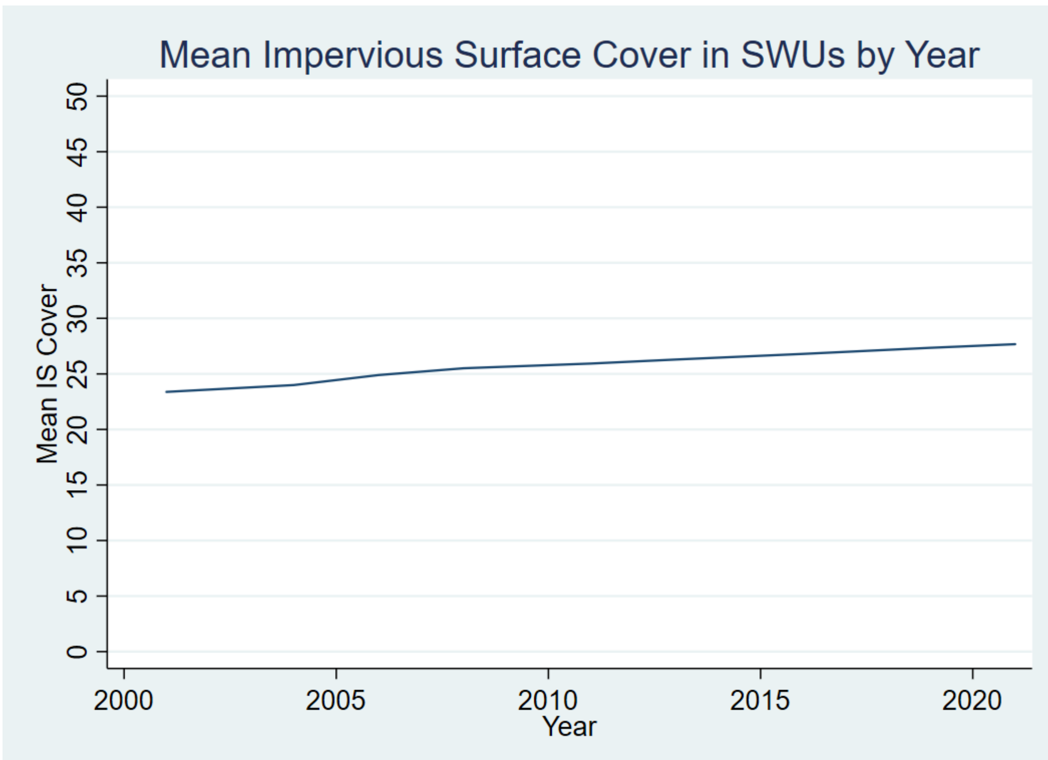


*Figure 3.3* - Mean Impervious Surface Cover by Year
Note: Mean impervious surface cover based on NLCD impervious surfaces data and SWU boundaries as linked by the author. Mean impervious surface cover is the average impervious surface cover percent of all 30m pixels wholly within a municipal boundary.

Overall, these statistics show that cities of all sizes and densities institute these fees, but the typical municipality for both fee types is not large. It also gives a sense of what a typical amount of impervious surface cover looks like. Referring to the discussion of the environmental impact of impervious surface, the mean cover percentage in the dataset seen in **Figure 3.3** is well above the 10% to 15% threshold used to demarcate sharp declines in ecosystem health. There has been a slow and steady increase in impervious surface cover in these areas over the course of the $21^{st}$ century.

### 3.6 Empirical Strategy

In order to examine my first hypothesis, I limit my examination to stormwater utilities that institute a variable rate fee on residential construction during or after the year 2000. 2000 is chosen due to the NPDES rules being finalized in 1999 which marked the end of the period of uncertainty surrounding NPDES regulation. This gives twenty years of home construction to examine. I exclude fixed rate fees and locations that never adopt a fee due to concerns that these areas may be different on unobservables than a utility that decides to implement a fee based on impervious surface cover. For example, these locations may have resident who both push back on the institution of a variable rate fee and have a preference for high levels of impervious surface cover. I exclude utilities that impose a fee only on non-residential properties due to the previously mentioned concern with the building footprint data for these properties. These restrictions mean I cannot conduct a traditional difference-in-differences design where I have a treatment group which adopts a variable rate fee and a comparable control group which does not adopt the fee as every SWU in my model eventually adopts a variable rate fee.

With this in mind, I utilize a stacked difference-in-differences design wherein I use variation in the timing of fee institution rather than variation in the occurrence of fee institution to estimate an average treatment effect. Separate DiD experiments are created for each MS4 that has a fee introduced and that MS4 is the treatment group for that experiment and those utilities that do not have a fee and do not institute a fee within the post-period serving as the control group. Each MS4 can be thought of as its own experiment which is its own dataset, and these experiments are compiled into one dataset and run together. Therefore, the same utility may be in the dataset multiple times as a control for different MS4s. By design nearly every utility in my model will be treated at some point, with the exception being those utilities that adopt a variable rate fee sometime during the window of the final fee years and do not have enough post periods for inclusion. The main specification examines three pre and post periods which allows time for to examine parallel trends and time for construction to adjust to the new policies. Results are robust to a five-year window. With the stacked data and use of only variable rate fee SWUs I end up with a sample size of 4,709,533 observations wherein each observation is a home in a SWU.

My approach for hypothesis two is similar to that of hypothesis one. I use a stacked design to examine all MS4s which impose a variable rate fee at some time between 2001 and 2021. The stacked NLCD dataset has 14,670 observations where each observation is a SWU itself. The NLCD model uses three pre and post periods which allows for a wide range of year of implementation due to only having NLCD data for nine years between 2000 and 2021. Four periods would allow only those MS4s which institute a fee in 2011 and 2013 to be included as treatment, while two periods do not allow for an examination of potential delayed effects of fee institution. With the main specification MS4s that instituted a fee between 2008 and 2016 are included in the treatment group.

To test whether the timing of variable rate fee institution is plausibly exogenous I ran a regression of observable characteristics on the timing of fee imposition (**Table 3.2**).

While a handful of characteristics are statistically significant, they largely are not practically significant. The strongest predictors of timing of fee imposition are white population share and overall population, with whiter areas tending to be early adopters and more populous areas being later adopters. Both of these variables are included as controls.

*Table 3.2* - Timing of Fee Institution for All Variable Rate Fee MS4s

| | (1)<br>Year Created |
|---|---|
| Log of Total Residential Buildings | -0.247** |
| | (0.102) |
| Democratic Vote Share | -0.006 |
| | (0.008) |
| Percent White | -1.825*** |
| | (0.437) |
| Log of Per Capita Income | 0.691 |
| | (0.508) |
| Log of Total Population | 1.605*** |
| | (0.427) |
| | |
| Observations | 3,584 |
| R-squared | 0.016 |

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

My main equation takes the following form:

$$y_{ismf} = \sum_{j=-3}^{3} \delta_j(T_{isf} * 1(TSE_{isf} = j)) + TSE_{isf} + \alpha_y + \alpha_{sf} + \varepsilon_{ismyf} \quad (1)$$

Where outcome *y* is either average footprint size of new residential home *i* in SWU *s* in county *m* in year *y* and stack/experiment *f* or it is impervious surface cover growth rate in SWU *s* in county *m* in year *y* and stack/experiment *f*. T is a binary treatment indicator for whether a unit (home or MS4) is treated in the stack. TSE is the time since fee imposition for a home with year zero omitted. The variable of interest is $\delta_j$ which is TSE times treatment. Fixed effects calendar year and SWUxStack are included.

Overall, the stacked approach allows me to examine the implementation of a variable rate fee in the DiD event study framework with variable timing and comparing only those units which have a variable rate fee instituted at some point. The key driver of this is the desire for more power in results and the fundamental difference between areas that choose a variable rate fee versus those that choose a fixed rate.

### 3.7 Results

**Figure 3.4** displays the results of the main specification for hypothesis one, which examines changes in average home footprint size pre- and post-fee implementation, without covariates. The main specification examines a three-year band around the time of fee implementation. As can be seen the direction of the coefficient is consistently negative but never rises to a level of significance, which is suggestive but not convincing evidence that the imposition of a variable rate fee does not have an effect on the size of new homes. The consistently negative direction of the sign before implementation could be taken as evidence that the treatment and control groups are not exhibiting parallel trends, while the smaller confidence intervals and negative signs post implementation suggest treatment groups may have a reduction in building footprint. In order to examine the relationship more closely the same model is run using covariates that may be associated with our outcome of interest. In this case I control for demographic, economic, and political factors of the MS4.

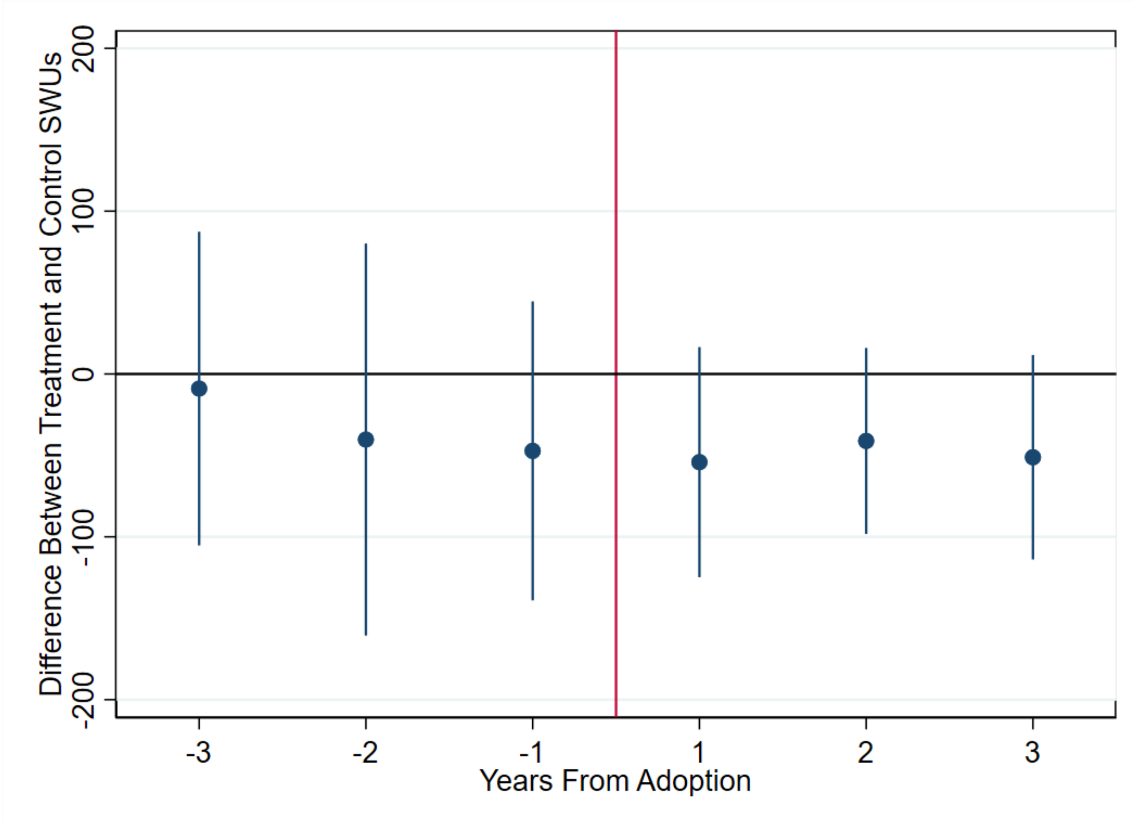


*Figure 3.4* - Difference in Average Footprint of New Residential Homes Before and After Variable Rate Fee Imposition. Footprint data from Zillow (2023). No control variables.

Results of the model with control variables included can be seen in **Figure 3.5.** The inclusion of covariates moderates the magnitude of the outcome and tightens the confidence intervals. The coefficients generally move towards zero in the years immediately before and after fee introduction. Trends in the years immediately before fee introduction suggest that the comparison groups are exhibiting parallel trends before in the time before introduction as the coefficients move around zero. Post-fee introduction the coefficients generally reduce in economic significance as the confidence intervals tighten. Taken with **Figure 3.4** these results provide further evidence that the introduction of variable rate fees does not have an effect on new home size.

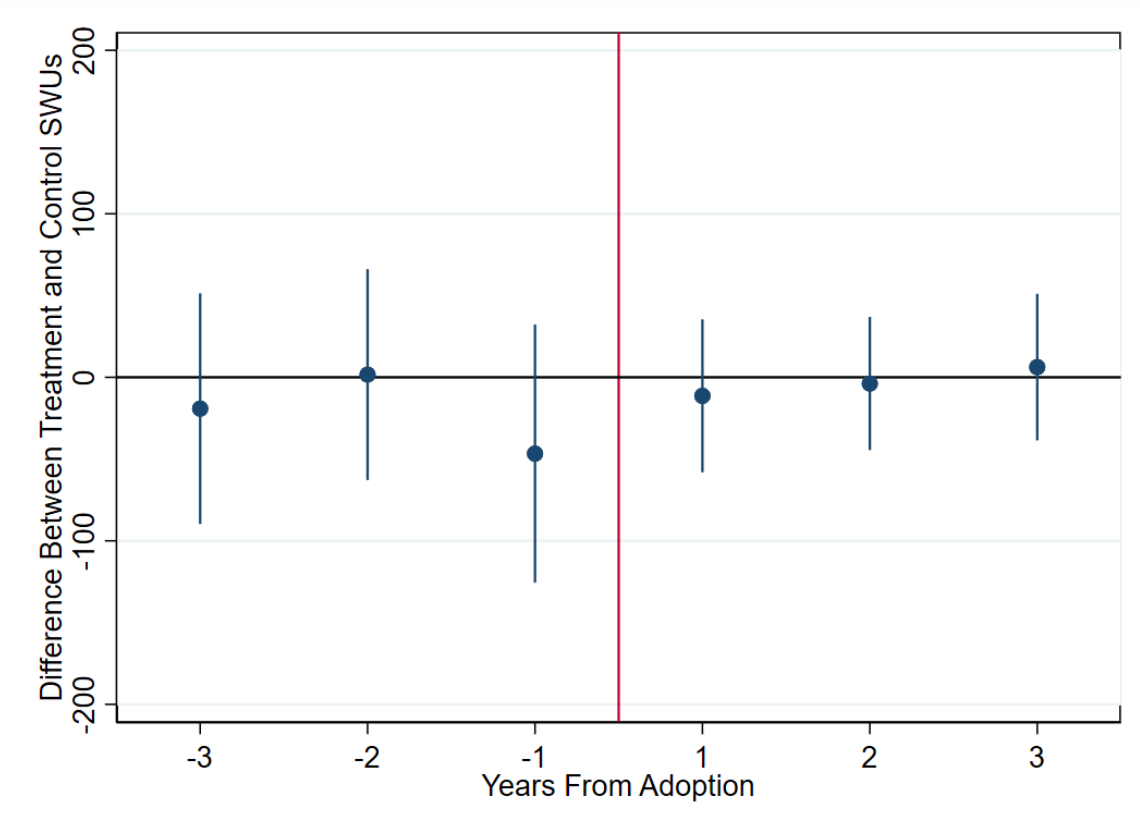


*Figure 3.5* - Difference in Average Footprint of New Residential Homes Before and After Variable Rate Fee Imposition. Footprint data from Zillow (2023). Control variables included.

The results of the first model provide evidence that fee imposition does not have an effect on the built environment through the pathway of new home construction. However, due to limitations with the dataset and the construction of the footprint variable itself there is room for further exploration of this outcome. A more robust dataset using proprietary data from a private GIS service could provide a better answer and should be explored in the future.

The results of the second model, which examines total impervious surface cover growth in an MS4, are displayed in **Figure 3.6** and **Figure 3.7**. **Figure 3.6** does not include covariates while **Figure 3.7** includes covariates. The results for impervious surface cover growth are consistent across both specifications and show that treatment and control MS4s exhibit parallel trends in growth before implementation of the fee and do not diverge in post-fee growth. In addition to each coefficient not rising to statistical significance they are also consistently economically insignificant with coefficients ranging from 0.002% growth to -0.003% growth. This can be compared with the average growth rate of 0.021% in included MS4s over the time period studied (2000-2021). These results reinforce the footprint size results seen in **Figures 3.4 and 3.5** and suggest that variable rate fees do not result in a change in impervious surface cover.

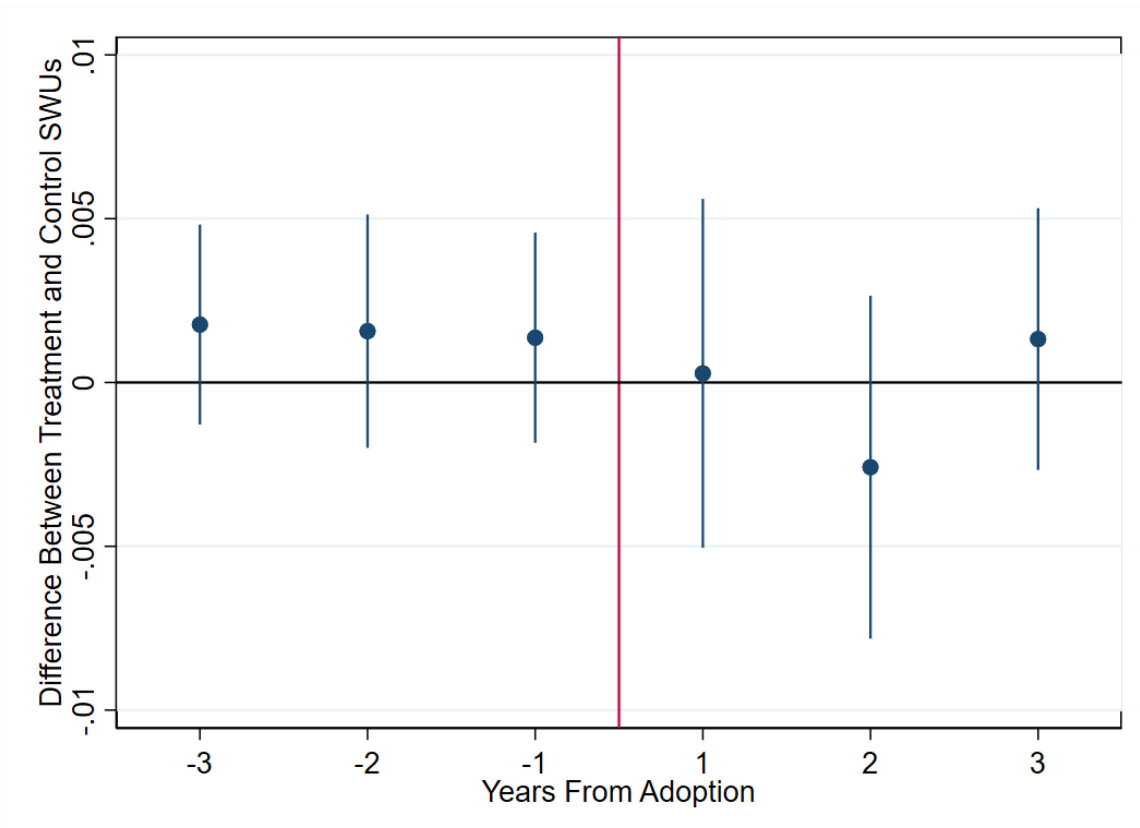


*Figure 3.6* - Difference in Impervious Surface Growth Rate between Treatment and Control MS4s. Growth data from NLCD. No control variables.

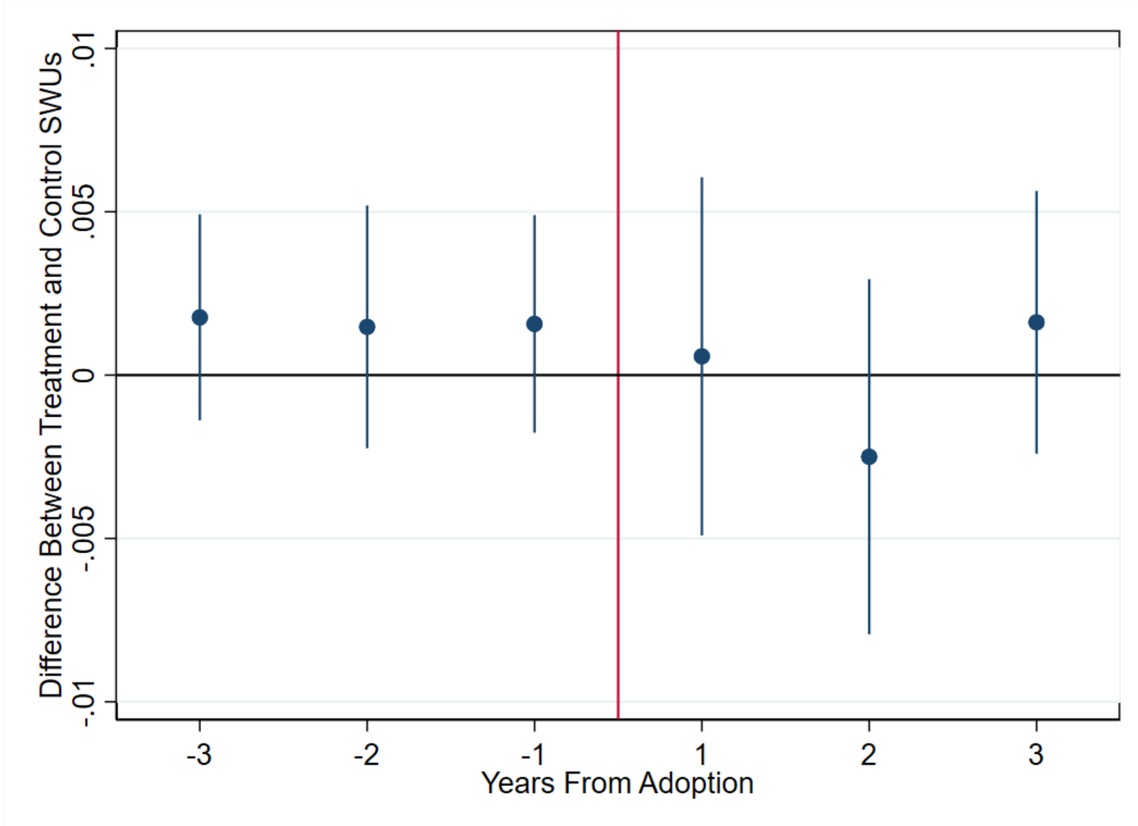


*Figure 3.7* - Difference in Impervious Surface Growth Rate between Treatment and Control MS4s. Growth data from NLCD. Control variable included.

As discussed previously the main specification uses three pre and post periods due to the limited number of years for which the NLCD is available. Three pre and post periods allows the most potential treatment MS4s while also allowing an adequate number of years post-implementation to examine lagged effects of the fee. However, the results are robust to both two and four pre/post periods.

**3.8 Discussion**

Taken together both models do not provide evidence to support either hypothesis and suggest that the imposition of variable rate fees does not have an effect on the built environment. This study is an examination of one potential side effect of a variable rate fee structure which can help inform policymakers when they are working to implement a fee. The discovery of an effect on impervious surface cover would have signaled a positive externality from variable rate fees which could inform future policymaking decisions. Fees are not explicitly designed to lower impervious surface cover but rather to fund efforts to mitigate the negative effects from impervious surface cover. The reduction in total impervious surface cover was a hypothesized positive side effect from variable rate fees. Importantly, the overall trend of the SWUs studied show impervious surface cover that is high and growing – leading to resultant negative effects.

Of the two models the NLCD model provides the cleanest evidence of no effect, insignificant coefficients which consistently hover around zero, and the underlying data itself is more accurate. NLCD data have been peer reviewed and carefully constructed for use cases such as this study. The Zillow data, on the other hand, are overall less reliable but were the best data available for examining the size of new construction.

There are a few potential explanations of why there was no effect found. Fees may not be high enough to elicit a response. User fees may be imposed to a level meant to adequately fund mitigation efforts but that do not rise to the threshold of changing behavior. A fee that is high enough to change behavior may face political and popular pushback. The present study was unable to examine differences in fee amount due to a lack of data, but future work should examine variation in impervious surface cover growth based on fee amount.

Another explanation is that users may be unaware of the fee. If users are unaware that their yearly fee could be lowered with less impervious surface cover, they will not change their built environment to realize these savings. This question could be examined with survey work in areas that have stormwater utility fees by asking residents if they are aware of them and asking about the mechanics of a variable rate fee. If this is a cause of the lack of response to the fee one solution could be information campaigns to educate residents on the fee and how it works.

A takeaway for policymakers is that a variable rate fee itself does not seem to change behavior. Issues that come from impervious surface cover will continue to be an issue post-fee implementation. If policymakers which to lower impervious surface growth rates or even reduce total impervious surface cover they will need to explore alternative policy solutions. Potential policies could be to educate users on the negative effects of impervious surface cover or a fund or tax credit system that incentives residents and businesses to reduce impervious surface cover or replace impervious surfaces with permeable or semi-permeable surfaces. An example of this is Stormwater Quality Projects Incentive Grant Program in Lexington, Kentucky. The Water Quality Fees Board uses money raised from the stormwater fee to fund stormwater mitigation projects including the installation of permeable surfaces and restoration of wetlands (Mabson, 2023). This more direct policy may be better suited to change behavior than the indirect effects examined in this paper. Policymakers would be well served to implement some policies that address the steady increase in impervious surface cover as our waterways, health, and wellbeing are all affected.

Future efforts in this area would be well served to refine the examination of the size of new construction post-fee. The Zillow dataset has the benefit of being both large and covering many years, but the data itself is somewhat unreliable and the construction of a build footprint variable adds another layer of assumptions. Future work would be well served to make use of datasets which have a more accurate measure of building size.

Additionally, a more granular examination of areas such as parking lots, sidewalks and driveways may reveal effects that are not captured from examining the entire MS4 using the NLCD. Also missing are data about the range of alternatives to impervious surfaces that engineers have developed such as semi-permeable parking lots. One potential avenue of exploration could be to look at a smaller set of MS4s but ones that have more robust and reliable data.

# CHAPTER 4. GALLOWAY IN THE 21st CENTURY: LOCAL MITIGATION INCENTIVES AND FEDERAL DISASTER RELIEF

## 4.1 Introduction

How does federal disaster relief and recovery spending affect incentives for local disaster mitigation? Floodplain managers, engineers, and policymakers have been asking this question at least since the release of the Galloway Report in 1994. The Galloway Report, formally known as the Report of the Interagency Management Review Committee, was commissioned by President Clinton in response to widespread flooding in the Midwest in 1993 and is the first government document to suggest federal post-disaster programs, largely established in the 1950s, may induce moral hazard by lowering local government incentives to avoid risk, stating "through the provision of disaster assistance … the federal government may in fact be reducing incentives for local governments to be more prudent in their actions" (Interagency Floodplain Management Review Committee, 1994). In the time since its publication there has been little scholarly effort to empirically examine the effect of federal post-disaster assistance on local government behavior. The difference between post-disaster aid and pre-disaster mitigation is the key distinction in this paper, both are authorized by a presidential disaster declaration, but they have different goals. Pre-disaster mitigation is defined as actions taken before the occurrence of a disaster that reduce the damages or risk of future disasters while disaster relief or recovery is defined as actions taken in the aftermath of a disaster to rebuild or recover to a pre-disaster state. Post-disaster aid programs are for relief or recovery works to return an area to "normalcy" and not necessarily to reduce future risk (FEMA, 2016). This paper is an effort to push the conversation forward, over thirty years after the Galloway Report was first issued.

In the United States, funding for disaster relief comes primarily from the federal government through a system of grant programs authorized at the discretion of the president – FEMA programs alone, only one portion of US disaster spending and not inclusive of emergency supplemental appropriations[10], have an estimated yearly average expenditures of $12 billion between 2004 and 2019 (Painter, 2019). A presidential disaster declaration authorizes general disaster relief for post-disaster activities such as reconstruction, unemployment insurance, and individual housing. In addition to direct aid to disaster-stricken areas, a disaster declaration generally authorizes hazard mitigation grants for the entire state – not just the affected area. Hazard mitigation grants differ from general disaster relief in that they are used for projects that mitigate against the harm from future disasters, not to fund the recovery of the current disaster.

In this paper I perform an analysis of how local governments interact with federal disaster spending and in future work hope to examine the causal effect of federal aid on public mitigation as well as other outcomes such as private insurance take up, migration, and floodplain construction. I first outline my motivation and the background of federal disaster assistance, highlighting changes in FEMA policy which is key to understanding mitigation but has largely been ignored by the literature. I then describe my general theory of the moral hazard from federal aid, before presenting an analysis of local government take up of federal disaster aid and finally examining moral hazard arising in local government pre-disaster mitigation though a simple regression model. Overall, I find heterogeneity in local government behavior based on disaster type, with suggestive

[10] Hurricane Katrina, for example, received $120 billion in supplemental appropriations (Kousky & Shabman, 2012).

evidence showing local governments are less likely to mitigate against future disasters if they receive disaster recovery funds for non-hurricane disasters. When a county experiences a hurricane they spend significant sums on pre-disaster mitigation, which is measured by their use of Hazard Mitigation Grants.

**4.2 Motivation**

Scientists are increasingly confident in the attribution of climate change to the increase in the frequency and intensity of a variety of natural hazards such as tropical storms (Bender et al., 2010), extreme rainfall (Knutson et al., 2014), ice and snow storms (Klima and Morgan, 2015), and wildfires (Yue et al., 2013). Natural scientists have historically been quite cautious with attributing anthropogenic climate change to the increase in natural hazards seen in recent decades, but their confidence has been growing as more data becomes available and models are refined (National Academies of Science, Engineering, and Medicine, 2016). Disaster spending has been steadily increasing over the last 60 years (**Figure 4.1**) and if this trend continues spending on these programs will continue to grow absent any major political or policy change, as will the importance of rigorously examining adaptation and mitigation aspects of climate change, as avoidance of the effects of warming is now likely impossible (IPCC, 2018).

In **Figure 4.1**, large spikes can be seen post-2000 due to Hurricanes Katrina (2005), Sandy (2012), Harvey (2017), and Covid-19 (2020-2021) – though the general trend is an increase even in years without a major disaster riving spending. While hurricanes have driven noticeable yearly spikes, they are not the only disasters causing major damage. According to the National Centers for Environmental Information (NCEI) data on billion-dollar disasters[11], hurricanes are 14.5% of the billion-dollar disasters since 1980 but 56.6% of the costs. However, the overall number of billion-dollar disasters has been steadily increasing since data became available from an average of 3.3 a year in the 1980s. 5.7 in the 1990s, 6.7 in the 2000s, before jumping to 13.1 in the 2010s. There were twenty-eight separate billion-dollar disasters in 2023 alone. There were more billion-dollar inland floods in the 2010s than in the years between 1980 and 2009. It is not just the costs, which can be driven by disasters striking developed areas such as New York City or Houston, but the number of deaths associated with these disasters has also steadily increased from 299 a year in the 1980s to 523 a year in the 2010s (NCEI, 2024).

An extensive literature exists on how natural disasters negatively impact people. Areas studied include long-run effects of fetal exposure to hurricanes (Karbownik and Wray, 2019), short and medium-run effects of Katrina on income (Deryugina et al., 2018), effects on private homeowners' insurance markets (Born and Viscusi, 2006), and poverty effects (Rodriguez-Oreggia et al., 2013). In the presence of such a rich literature on the effects of disasters themselves and individual responses to disaster aid there has been relatively little research done on federal post-disaster relief spending on local government behavior[12].

[11] NCEI defines billion-dollar disasters as natural disasters which cause at least a billion dollars in damages in 2024 adjusted dollars.

[12] In the context of disaster management mitigation refers to "the effort to reduce loss of life or property by lessening the impact of disasters" (such as through the construction of flood barriers or tornado shelters) while relief is "the process of responding to a catastrophic situation" (Lindsay, 2012)

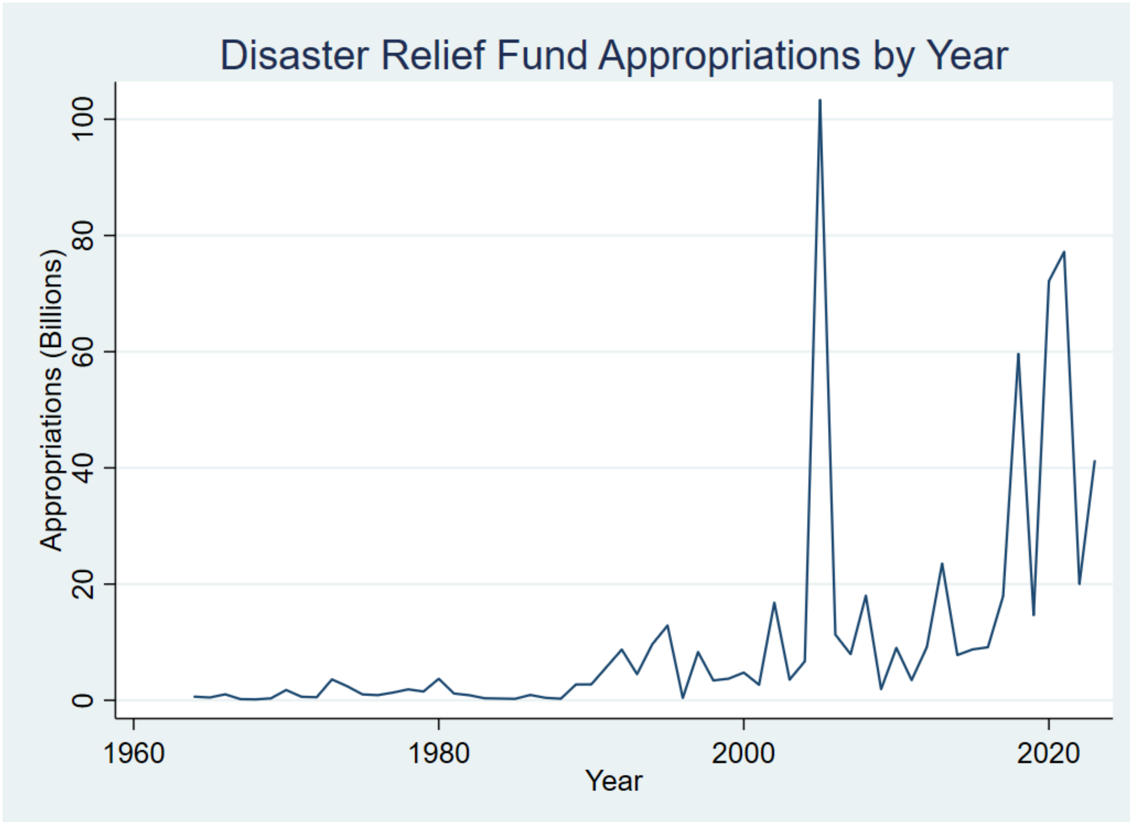


*Figure 4.0.1* - Disaster Relief Fund Appropriations by Year, 1964-2022
Notes: Figure represents total appropriation by year to Disaster Relief Fund. All data are in 2023 dollars. Data from Congressional Research Service 2023.

Endogeneity concerns are barrier to causal examination of federal disaster relief and local mitigation, as there are likely omitted variables which affect both a disaster declaration and future mitigation. For example, private mitigation activity, which may lessen the damages from a weather event and lower likelihood of a disaster declaration, is also likely to be associated with demand for public mitigation activity. While the current analysis is not causal, future work will explore the causal link between disaster funding a local government mitigation activity and this paper lays the foundation for that research by providing the first examination of local government response to federal disaster policy since the mid-1990s. This is an important topic due to the increase in disaster costs, one way to bend the cost curve down is to incentivize local governments to engage in mitigation efforts that will pay dividends down the line.

In this paper I push forward the topic of local government mitigation and moral hazard by analyzing the mitigation behavior of counties which receive a disaster declaration and those in the same state that do not receive a declaration, some of which are potentially affected by the disaster either through direct impacts or media exposure. When a disaster declaration is made for a state, post-disaster aid is authorized for specific counties, while general disaster mitigation grants are unlocked for the entire state – even areas not affected by the declared disaster. Two facets of federal disaster policy are key to my research design 1) for much of the history of FEMA direct disaster aid was not allowed to be used for mitigation and 2) when disaster aid is authorized for specific counties, the entire state becomes eligible for mitigation grants. I will leverage this design to examine short-term changes associated with a disaster declaration, as my outcome is mitigation funding available statewide, regardless of county declaration status, which becomes available immediately following a disaster.

### 4.3 Background

For much of the history of FEMA the policy design of disaster aid may have had the effect of both lowering the incentives for disaster-stricken areas to engage in pre-disaster mitigation and inhibiting local pre-disaster mitigation efforts. This is because until policy changes the availability of pre-disaster mitigation funds from the federal government was largely tied to a disaster declaration and local governments faced restrictions on the use of disaster relief funds for mitigation. The following section will outline the history of disaster aid in the modern era while highlighting mitigation policy.

A presidential declaration is the primary means of unlocking funding for disaster aid in the United States and is statutorily authorized and defined by the 1988 Stafford Act. In order to formally request a disaster declaration, a governor must submit a letter to the president through FEMA which states the counties the declaration will cover and the specific aid programs that are being requested; this letter includes county-level preliminary damage assessments conducted by state and regional officials. The relevant FEMA field office will review the request with special consideration paid to statutorily defined categories before making an approval or denial recommendation. FEMA headquarters conducts a final review and makes a recommendation to the president to approve or deny the disaster. The president has sole authority to approve or deny a declaration request, though a governor may appeal a denial. A declaration will typically grant relief to specific counties and unlock mitigation funding for the entire state.

A declaration unlocks funds for one or all of the following: Individual Assistance (IA), Public Assistance (PA), and Hazard Mitigation Grants (HMGP) programs. PA is designated to support state and local governments while IA is directed towards helping individuals and households recover from a disaster. PA funds emergency work which is temporary, such as debris removal, and permanent work which is repairing physical structures. Importantly, PA permanent work requires that a structure be rebuilt to the *same* specifications as before the disasters. Before 1998 there was a uniform ban on mitigation efforts through PA, but in 1998 guidance was modified to allow PA funds to be used for mitigation, known as section 406 mitigation funding. However, projects need specific approval from FEMA to engage in PA mitigation and the mitigation efforts can *only* be performed the part of structure which was damaged (FEMA, 2023). A counties mitigation efforts under section 406 have more leeway to perform mitigation but the extent of mitigation is still tied directly to where the damage happened to occur, drastically limiting the overall extent of mitigation under section 406 compared to HMGP mitigation.

The key takeaway is that even as the use of PA funds for mitigation have been relaxed, restrictions still mean that a local government will need to seek other funding sources to address vulnerabilities and engage in mitigation. As an example, imagine a county which has forty miles of road, and a two-mile section is washed out during a flood. The president declares a disaster and authorizes public assistance for the county and hazard mitigation grants for the entire state. Under current policy, the county can use PA funds to restore the road to its previous state and can be authorized to mitigate future damage by building a culvert *only on the damaged two-mile section*. The remaining thirty-eight miles of road are not eligible for mitigation with PA funds and remain vulnerable to future flooding. This scenario raises the question of whether local governments use PA funds for mitigation.

There is limited data to answer this question, as FEMA does not have any publicly available data on the use of PA funds under section 406. Based on a Congressional Research Service report which provides the extent of limited publicly available information, the use of mitigation funds for PA appears to have been low. **Table 4.1** shows the percentage of PA funds per fiscal year that were spent on mitigation. These data suggest that although some mitigation activity occurred under section 406 prior to 2013 the vast majority of work was not mitigation. The largest mitigation activity occurred in the same fiscal years as Hurricanes Katrina (2005) and Sandy (2013).

In 2013 the federal government further relaxed the restrictions on mitigation with PA funds with passage of section 428 in the Stafford Act Amendments. Section 428 is intended to increase the flexibility of FEMA to use Section 406 funds by establishing the Public Assistance Alternative Procedure (PAAP) Pilot Program. This program removed the notice of rulemaking requirement for changes to PA mitigation procedures and instructed FEMA to develop a program to expand the use of PA funds for mitigation (Brown and Richardson, 2015). A 2022 FEMA OIG report found that PAAP led to an increased use of PA funds for mitigation among participants in the pilot program by reducing costs, lessening reporting requirements, and expanding eligible work. Additionally, FEMA officials work with local governments post-disaster to increase mitigation by identifying projects that can be mitigated with PA funds, and when they cannot FEMA encourages the use of HMGP funds for these projects (DHS OIG, 2022). Unfortunately, there is no publicly available data on how extensive mitigation activities with PA funds is after 2013 and the OIG report is the only source of information on PA funds used for mitigation under the pilot program. Due to this data limitation and the enactment of Section 428 I will examine whether response changes with the inclusion of a post-2013 indicator in my model.

*Table 4.1* - PA Spending and PA Mitigation Spending in Millions, 2003-2013

| Fiscal Year | PA Mitigation | PA Total | Pct. Mitigation |
|---|---|---|---|
| 2003 | 42 | 1092 | 3.85% |
| 2004 | 101 | 3464 | 2.92% |
| 2005 | 258 | 21395 | 1.21% |
| 2006 | 88 | 852 | 10.33% |
| 2007 | 132 | 1566 | 8.43% |
| 2008 | 279 | 6118 | 4.56% |
| 2009 | 83 | 1713 | 4.85% |
| 2010 | 84 | 1552 | 5.41% |
| 2011 | 202 | 3701 | 5.46% |
| 2012 | 24 | 985 | 2.44% |
| 2013 | 2052 | 16999 | 12.07% |

Notes: PA spending based in millions. Data drawn from publicly available FEMA data on yearly disaster aid. PA mitigation spending totals drawn from CRS report based on data they obtained from FEMA (Brown and Richardson, 2015). 2013 highlight represents the year that new executive order relaxing rules on mitigation spending through PA program went into effect. In this year $2,002,000,000 of overall PA mitigation spending was on Hurricane Sandy. Of this over $500,000,000 was on a single project for the NYU Langone Medical Center.

Contrary to PA, HMGP is designed to fund mitigation with an aim to reduce the cost of future disasters through actions such as floodproofing utilities, purchasing properties that experience chronic flooding, or the construction of community tornado shelters. The program is authorized for the entire state when a disaster is declared, not just affected counties. This means that non-damaged counties have the ability to learn from the experience of damaged areas in the state and engage in mitigation to reduce their risk before a disaster occurs. HMGP funding is based on the total amount of post-disaster assistance distributed to a state ranging from 15% of the first two billion dollars in aid to 7.5% of aid up to thirty-five billion dollars. States with enhanced hazard mitigation plans receive 20% of funding up to thirty-five billion. Overall 47% of FEMA appropriations through the disaster relief fund[13] between 2000 and 2013 went towards PA, 25% towards IA, and 6% towards HMGP, with the rest of the money split between administrative and technical costs (Brown and Richardson, 2015). The authorization of HMGP through a disaster declaration means that the largest source of federal spending on hazard mitigation requires a disaster to occur. This link between post-disaster relief with statewide pre-disaster mitigation funding is key to my empirical strategy.

Congress has more recently introduced legislation to help sever the link between the occurrence of a disaster and the availability of pre-disaster mitigation funding with the passage of the Disaster Recovery Reform Act of 2018. This legislation established the Pre-Disaster Mitigation fund, into which the President is authorized to set aside the amount of 6% of the previous year's disaster funding. These funds are available to FEMA for use for a pre-disaster mitigation grant program called Building Resilient Communities and Infrastructure (BRIC) program that is not directly tied to a disaster declaration. States are eligible to apply for BRIC grants if they have had a federally declared disaster within the last seven years (Horn, 2022). This new program may help encourage pre-disaster mitigation by establishing a permanent fund and loosening the restriction of funds to a disaster declaration, but research is needed on its efficacy. Perhaps owing to the timing of the creation of this program with the Covid-19 pandemic and the lengthy cycle of grant application and selection I have seen no research on these programs. My data ends before the implementation of the BRIC program but future work would be well served to examine this area.

[13] The disaster relief fund represents yearly appropriations intended to cover disasters that occur in a given fiscal year. This figure is not inclusive of emergency or supplemental appropriations.

The limited studies that utilize HMGP funding to proxy for mitigation efforts ignore the use for section 406 PA funds for mitigation. One of the only studies which uses HMGP funds, Ji and Lee (2021), use HMGP funding between 2010 and 2015 to study whether counties which engage in mitigation activities incur lower future damages from disasters, finding that use of HMGP funds is associated with lower future disaster damages. Ji, Yeo, and No (2022) examine the association between different types of non-profits and HMGP use between 2010 and 2016. In their justification of using HMGP funding to measure mitigation activity they cite Ji and Lee (2021).

The use of HMGP funding is not a reason to discount research or invalidate results entirely but researchers need to be aware of the existence of this form of mitigation funding. We know that section 406 mitigation is only authorized for damaged structures and systems which provides a boundary on how widespread the use is. Unfortunately, researchers do not yet know how widespread the use is for these damaged facilities or how PAAP may have changed the use of both section 406 and HMGP. I am working to receive 406 funding data through FOIA requests which can be shared with the broader disaster research community. Overall, there is a complex policy web when it comes to federal mitigation funding which has changed several times over the last few decades. I hope that by highlighting this area researchers will examine section 406 and BRIC in future work.

### 4.4 Moral Hazard in Disaster Aid

Moral hazard introduced through the design of U.S. disaster policy has been studied to varying degrees by economists and political scientists. Both literatures ask whether and to what degree disaster aid may reduce incentives to optimally prepare for future disasters and suggest it as a cause of steadily increasing disaster expenditures. The ready availability of aid to victims of a disaster, regardless of whether and to what degree individuals and governments take precautions pre-disaster to mitigate the severity of damage or reduce the probability of loss, embodies a textbook example of moral hazard. As stated in the Galloway Repot, "through the provision of disaster assistance … the federal government may in fact be reducing incentives for local governments to be more prudent in their actions" (Interagency Floodplain Management Review Committee, 1994).

Federal and state governments act as de facto insurers and take on a large share of the financial risk of a disaster from local governments and individuals[14] who are directly impacted by a disaster and who have the most direct ability to engage in risk reduction activities. The majority of disaster assistance comes from the federal government, but Pew Charitable Trusts has recently undertaken the first comprehensive examination of state disaster financing mechanisms. They find that 42 states employ either commercial disaster insurance or self-insure. However, between 2008 and 2018 insurance covered only 28% of the repair costs to damage state infrastructure (Pew, 2021). They do not examine the degree to which local governments employ insurance. State disaster relief funding may be necessary due to low-scale disasters which do not meet the federal disaster threshold or because states must often cover upfront costs before being reimbursed by the federal government. According to Pew, state disaster funds are generally used to cover state cost share for federal aid, further reinforcing the federally

[14] The government does not take on all risk as individuals are still exposed to physical, psychological, and a degree of financial risk.

dominated nature of disaster aid. Thus, while the state government can be seen as the insurer for individuals and local governments the federal government is the insurer of last resort and I make the assumption that they are the drivers of the moral hazard.

The foundations of moral hazard in disaster studies can be traced back to Lewis and Nickerson (1989) who present a model of self-insurance against natural disasters in the face of government assistance. Their model suggests that due to truncation on the right-hand side of the loss distribution for individuals, essentially a guarantee that individuals will not face large losses due to a natural disaster, there is a divergence between the optimal level of private self-insurance and level which minimizes government expenditures. A key assumption underpinning their analysis is that due to political and social constrains the government cannot credibly commit to not providing disaster relief. The history and current status of government disaster relief discussed suggests that this is an accurate assumption (See: Bea, 2010; Davis, 2013; Davis, 2014; Lindsay and Murray, 2011). Especially relevant is Platt's (2012) analysis of the evolution of disaster policy into what can now be thought of as an entitlement program, as long as an area or individual meets certain criteria they are entitled to disaster relief.

Kelly and Kleffner (2003) further extend theory surrounding disaster aid through a formal model of optimal mitigation in a system with a monopolistic disaster insurer and government assistance. They show that post-disaster government assistance lowers the level of mitigation performed by individuals, suggesting that one solution to alleviate this outcome is government subsidized mitigation assistance. In their model the monopolistic insurer is a profit maximizer which is applicable for only the private U.S. disaster insurance market such as earthquake and wildfire insurance, however their results still support the idea that government aid reduces the incentive for individuals to perform mitigation. Federally subsidized mitigation assistance is mainly provided through HMGP and the new Building Resilient Infrastructure and Communities (BRIC) program.

Work in fiscal federalism tends to emphasize institutional design and the tradeoff between centralized and decentralized decision making. Centralized systems are better able to reduce externalities while decentralized systems can more efficiently match actions to the preferences of constituents (Oates, 2008). In a fully decentralized system Tiebout sorting would suggest that individuals would sort into the community that provides their optimal level of disaster relief. It appears that the current system is one in which neither of these benefits are fully realized, as it is characterized by centralized post-disaster relief and decentralized pre-disaster mitigation.

Wildasin (2008) connects this literature with disaster funding in the United States, discussing the implications of different levels of government being responsible for pre-disaster mitigation efforts and the reality of post-disaster federal relief efforts. He describes the problem in terms of externalities and institutional design. In theory, local governments are best able to determine the benefits and costs associated with different mitigation options, without federal intervention the entirety of net benefit accrues to the locality. When the federal government assumes responsibility for reimbursing costs, they lower the net benefit that the locality receives, some of the benefits that arise from a reduction in damages go to federal taxpayers rather than the locals. This is a clear externality issue where local governments in charge of mitigation policy do not internalize the costs of their mitigation decisions.

The ideal solution to the issue, in Wildasin's formulation, lies either in an assignment of total mitigation responsibility to the federal government or a removal of the federal government from disaster relief. Recognizing the implausibility of the federal government ending all involvement in disaster relief he suggests a partial solution with the creation of mandatory disaster funds that acts as a rainy-day fund and must be drawn down before the federal government will aid. An idea along these lines, a 'disaster deductible' was proposed by FEMA during the Obama administration in which states would be required to pay a disaster deductible before receiving federal aid; however, it was not adopted (Kousky, Lingle, and Shabman, 2016).

In the political science literature Burby (2006) describes moral hazard as a potential driving force behind what he termed the local government paradox, which is the tendency for local governments to not take adequate precautions to protect their constituents. Moral hazard is one possible explanation for this paradox, Burby emphasizes the short-term electoral considerations faced by local officials. These considerations coupled with the long-term nature of disaster planning may reduce incentives for pre-disaster mitigation. Any money spent on disaster preparation, an expenditure which by its very nature is designed to *avoid* visible effects, is less money that can be spent on areas which may be more immediately visible to the voting populace such as economic development. One paradox of hazard mitigation is that if money is well spent voters should not see the effects, it is only when mitigation fails that voters become aware.

There is an extensive literature on individuals' moral hazard due to government disaster insurance, with recent work generally supporting the contention that government aid is associated with moral hazard, though ambiguities remain (See: Brunette, Cabantous, Couture, and Stenger, 2008; Kousky, 2017; Kousky, Michel-Kerjan, and Raschky, 2018; Raschky, Schwarze, Schwindt, and Zahn, 2013). A large gap in the literature exists in empirical work on how disaster aid affects state and local government action. One study, conducted in the early 1990s, found a positive correlation between PA receipt and future flood mitigation compared to governments that did not receive aid (Burby, 1991). This study surveys a sample of governments asking whether they received PA and whether they engaged in mitigation activities afterwards. Without any attempts at controlling for other factors this is an obvious result, governments that did not report PA may not be at significant risk of flooding.

In a recent work, Miao, Shi, and Davlasheridze (2020) examine the association between fiscal decentralization and mitigation by examining flood loses, finding that states with more fiscal decentralization have higher losses from flood events. They do not directly examine mitigation spending, as their measure of interest is the totality of state spending on natural resources which also includes flood mitigation, but their study provides evidence that decentralization is associated with higher flood loses which can be driven by suboptimal mitigation efforts. They identify both the Burby electoral considerations and moral hazard driven by federal relief as possible contributing factors.

Based on theory discussed above I expect to see counties that receive a disaster declaration and subsequent aid to have a lower level of mitigation activity, measured through the use of HMGP funds and the total amount of HMGP funding used, than comparable governments that do not receive aid within a disaster. While moral hazard is a large part of the story the Burby local government paradox also comes into play. When a disaster occurs in a nearby county the incentive for local politicians to engage in visible mitigation efforts may be increased. In the short term these officials may seek to secure the federal mitigation funding that is available in the immediate aftermath of a disaster.

**4.5 Data**

For my analysis I utilize the universe of major disaster declarations which authorized public assistance and hazard mitigation grants, public assistance funded projects, and hazard mitigation projects between 1998 and 2019. 1998 is the starting year due to data on hazard mitigation funds not being available before 1998 while 2019 is the end year due to the Covid-19 pandemic. The pandemic led to massive increases in declarations and FEMA funding across the entire country and marks a different period for disaster management. This also coincides with the introduction of the BRIC program and the permanent pre-disaster mitigation fund.

There were 1,274 total presidential disaster declarations between 1998 and 2019 of this there were 1,236 authorized both PA and HMGP funds, leaving about 97% of declarations in the final dataset. **Figure 4.2** displays the count of major disaster declarations by county between 1998 and 2019. There is a notable spread in the total number of declarations with heavy concentrations in New England, Florida, the Great Plains or 'Tornado Alley', and the Appalachian region in Kentucky, West Virginia, Ohio, and Tennessee. Parts that show a notable absence of disasters are Michigan, the rust belt, and the Rocky Mountain region. These regions experience snowstorms which are more likely to authorize Individual Assistance, which includes home heating assistance, and more likely to be Emergency Declarations, which is for disasters that do not rise to the threshold of a major disaster and fund things such as short-term snow removal.

Importantly, there is a large degree variation both geographically and by number of disasters by county.

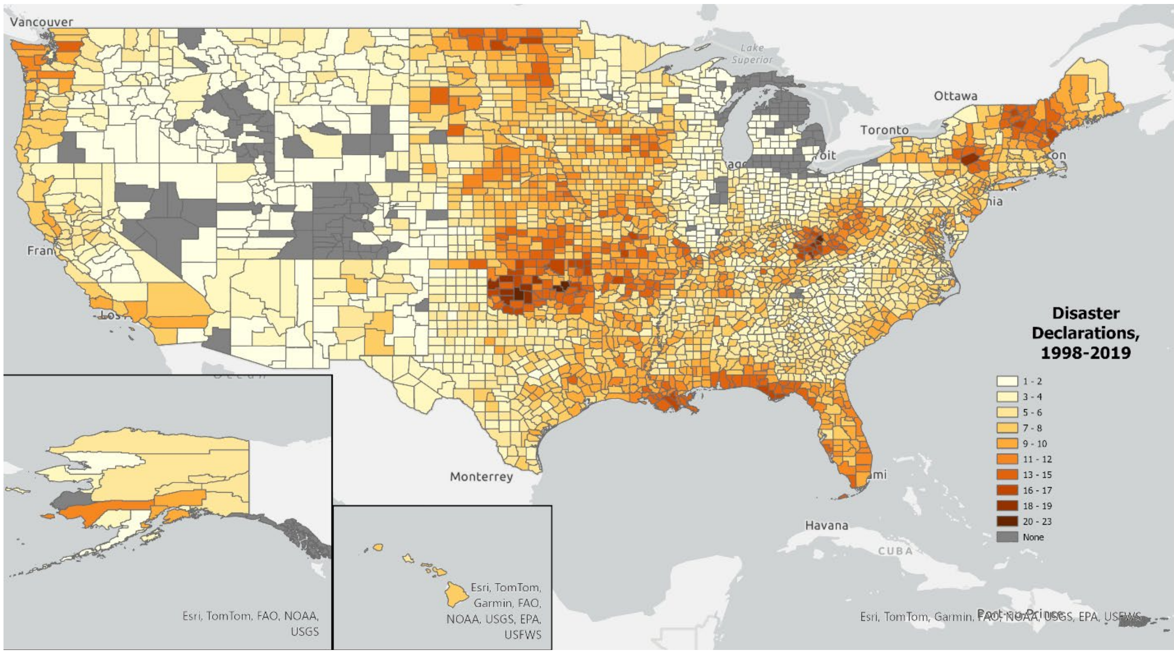


*Figure 4.2* - Disaster Declarations by County, 1998-2019
Notes: Map displays the count of major disaster declarations by country, drawn from FEMA data. Only disasters which authorized PA and HMGP funds are included. Darker shades represent more total disasters. Figure created by author using ArcGIS.

**Figure 4.3** displays the total number of severe weather events between 1998 and 2019 that caused at least $10,000 in non-crop property damage or at least one death, drawn from the NOAA weather events database. This serves as a proxy of the intensity of weather events throughout the country and helps to provide a sense of areas that are most affected by the types of events likely to lead to a disaster declaration. Notably, crop damage is excluded which is the likely cause of the relatively low number of events throughout the Great Plains. When compared to the map of disaster declarations there is a high intensity of events throughout the South and extending up Appalachia into the Midwest and Northeast. These areas may be more exposed to severe weather and thus more likely to utilize HMGP funds when available. There is a notable difference between the two maps due to the fact that **Figure 4.3** incorporates many events that cause damage but do not rise to the level of having a disaster declaration. The two figures taken together highlight that counties are exposed to many damage causing events which do not lead to an authorization of HMGP. **Table 4.2** displays the correlation matrix between use of HMGP and the number of NOAA events within the last 1, 2, 3, and 5 years. There is a positive correlation between the number of damaging events and the use of HMGP which suggests that counties may learn from past events and will use HMGP funds as they become available. Without including past non-disaster declaration events as a control, the model may be prone to omitted variable bias. This research is among the first to incorporate NOAA events in a study of disaster policy.

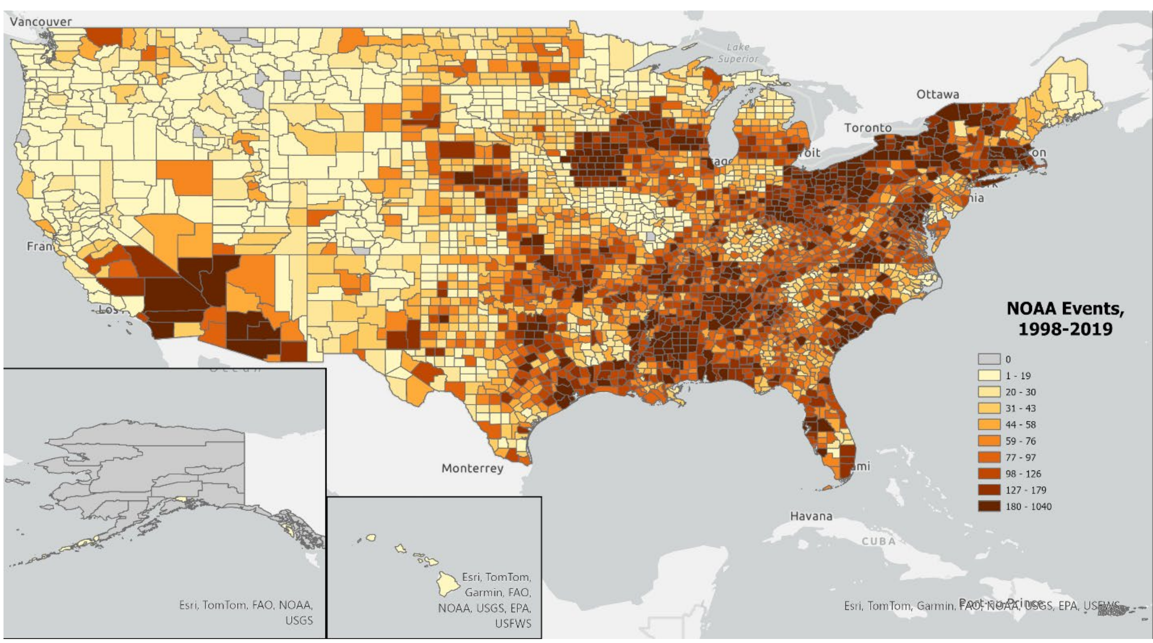


*Figure 4.3* - NOAA Events, 1998-2019
Notes: Displays the count of severe weather events that caused at least $10,000 in non-crop property damage or at least one death, by county. Events drawn from the NOAA Storm Events Database. Figure created by author using ArcGIS.

*Table 4.2* - Correlation Matrix, HMGP Use and Number of Damaging Weather Events, 1998-2019

| | Correlation |
|---|---|
| 1 Year | 0.1112 |
| 2 Years | 0.1374 |
| 3 Years | 0.1467 |
| 5 Years | 0.1543 |

Notes: Displays correlation coefficients between use of any HMGP funds for eligible counties and events in the NOAA Storm Events Database which caused at least $10,000 in non-crop property damage or at least one death in a county.

In total there are 2,988 counties which received PA funds between 1998 and 2019, while 2,680 used HMGP funds in the same time period. **Figures 4.4 and 4.5** display PA and HMGP funds by county, respectively. These are the two programs which are examined in this paper and these figures highlight both the geographic variation as well as the relative lack of uptake up HMGP when compared to PA. There are high levels of PA funding along coastal areas affected by hurricanes, but also throughout the West, Midwest and Northeast. Especially notable is the lack of PA in large swaths of Michigan and the Mountain West. When compared to **Figure 4.4**, Michigan has a handful of counties which use HMGP funds but have not had a declared disaster or used PA funds. The other notable takeaway from **Figure 4.4** is the lack of HMGP use in areas which have a relative higher number of declarations and events throughout Missouri, Indiana, Tennessee and parts Appalachia. Moral hazard is one possible explanation for the discrepancy between HMGP authorization and HMGP use and the explanation that this paper explores.

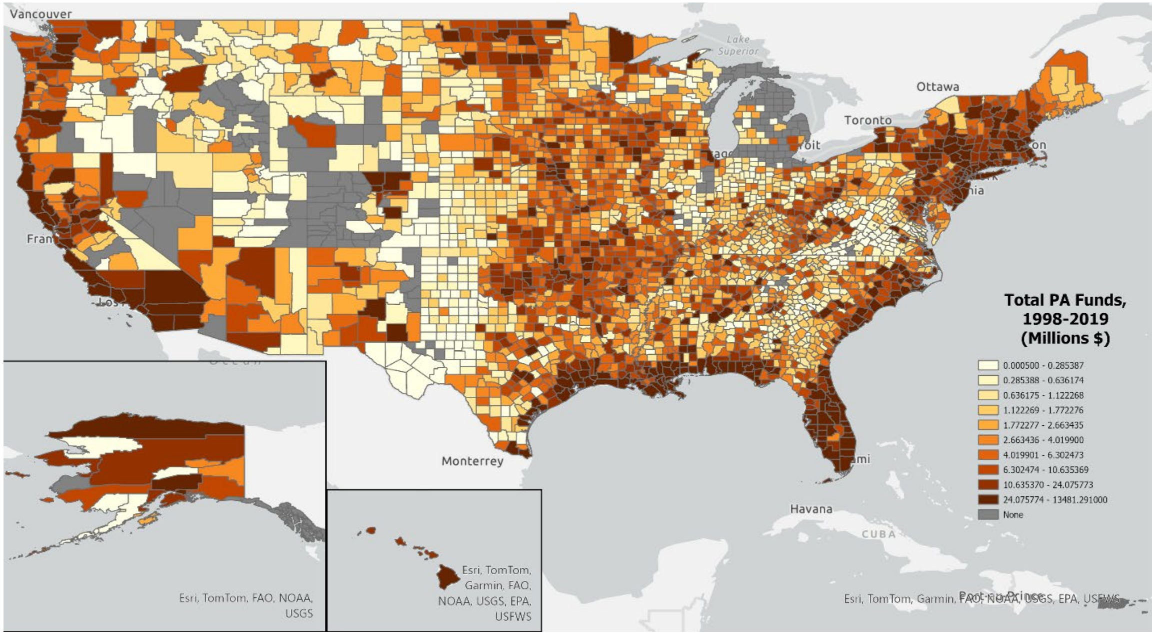


*Figure 4.4* - Total PA Funds in Millions, by County, 1998-2019
Notes: All data are from FEMA Public Assistance Dataset. Data displayed in deciles, with relatively darker shares representing relatively higher level of funds. Figure created by author using ArcGIS.

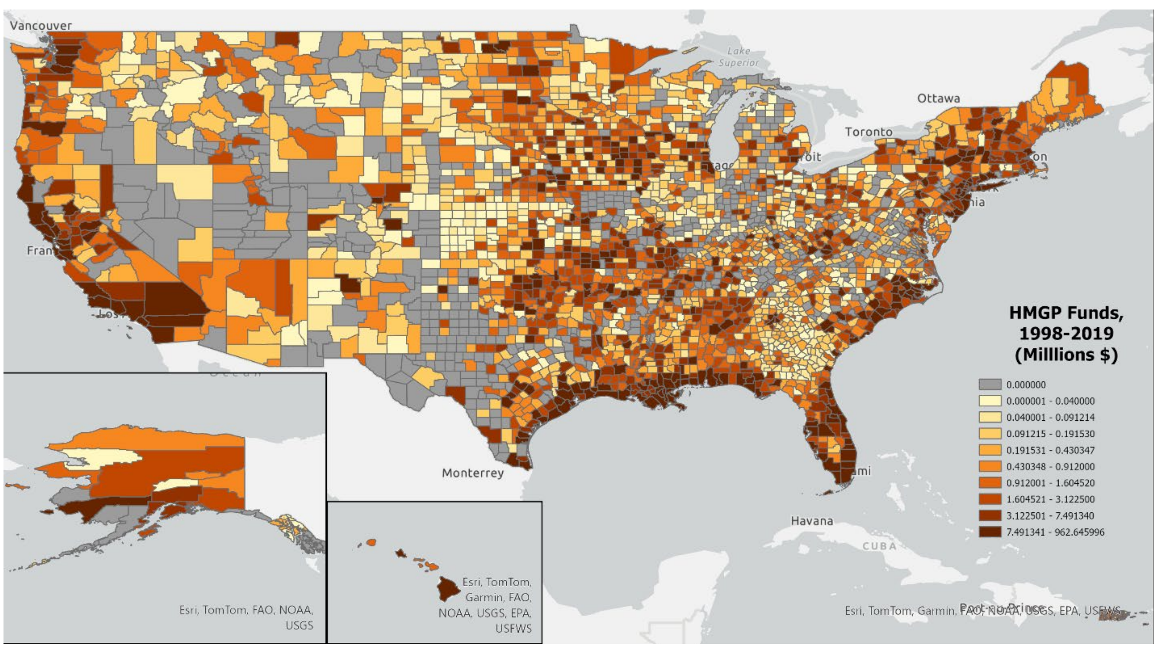


*Figure 4.5* - Total HMGP Funds in Millions, by County, 1998-2019
Notes: All data are from FEMA Hazard Mitigation Assistance Dataset. Data displayed in deciles, with relatively darker shares representing relatively higher level of funds. Figure created by author using ArcGIS.

The previous maps help inform the variation in geography and intensity of the main variables included in the study and give a sense of the shape of disaster aid in the United States while highlighting the lack of mitigation uptake in some eligible counties. One important facet of disaster aid is the amount of funding which is tied to hurricanes. Hurricanes in the United States drive overall spending in the time period studied through a handful of especially costly events. **Figure 4.6** displays total PA funding by whether the incident is a hurricane or all other categories of disaster[15]. As can be seen, the hurricane spending in FY 2005, 2013, and 2017 dwarf the total spending in all other years. These destructive hurricanes cause high levels of damage in concentrated areas such as New Orleans (2005), New York/New Jersey (2012), and Houston (2017). These hurricanes cause vast destruction and authorize the spending of very high sums of PA and HGMP which may lead to differential behavior among affected counties. As such, all models will be run both with and without hurricanes included to see whether behavior changes.

[15] An HGMP chart looks the similar due to the fact that total HMGP funding is a percentage of PA funding.

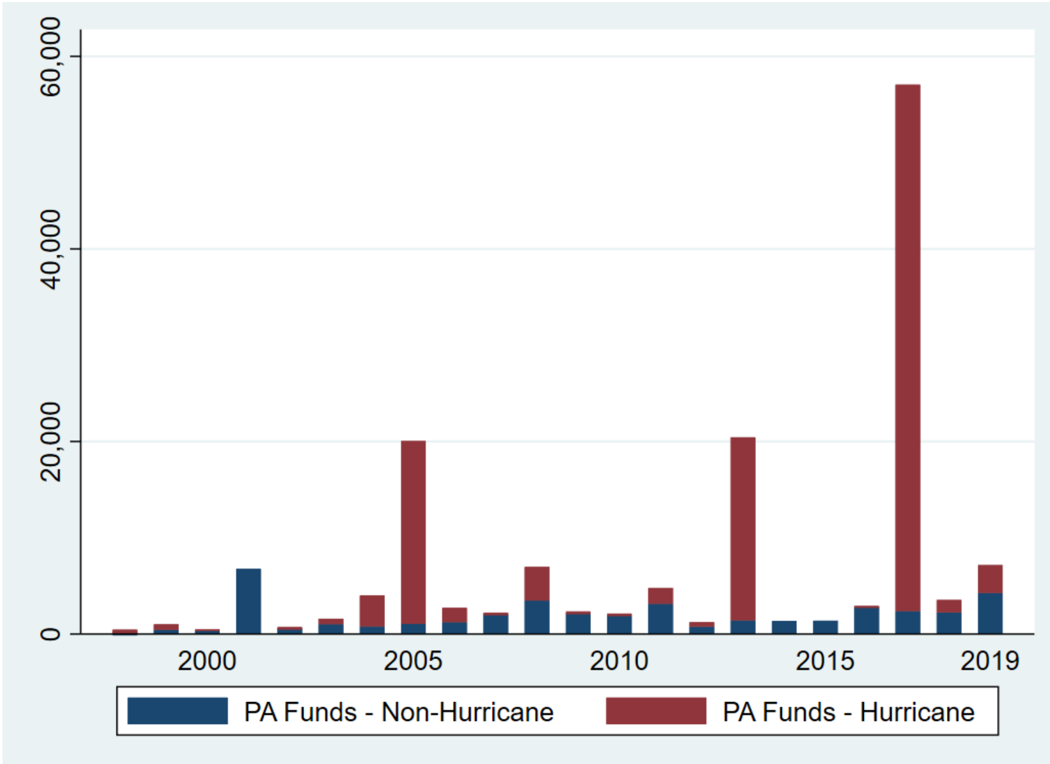


*Figure 4.6* - Total Public Assistance by Hurricane/Non-Hurricane Status, 1998-2019
Notes: Data are drawn from FEMA Disaster Declarations Database and Public Assistance Database. Figure created by author in STATA.

## 4.6 Methodology

I estimate the relationship between disaster declarations and pre-disaster mitigation using the following equation:

$$Y_{itd} = \beta_0 + \gamma D_{itd} + d_t + d_d + \varepsilon_{itd} \qquad (1)$$

where *Y* is mitigation in county, *i,* in year, *t*, tied to disaster¸ *d*. The mitigation outcomes are HMGP funding and a dummy variable of using only HMGP funds, both within *d*. The variable of interest is dummy variable, *D*, for if a disaster was declared in a county for in that disaster declaration. This coefficient is interpreted as the relationship among eligible counties, which are generally all counties in a state which receives a disaster declaration, between being in a county that receives a disaster declaration compared to a county that does not receive a disaster declaration for either using any HMGP funds or the amount of HMGP funds utilized. Additionally,

I also run each equation with controls to account for potential endogeneity using the following equation:

$$Y_{itd} = \beta_0 + \gamma D_{itd} + \beta_1 M_{it} + \beta_2 C_{it} + d_t + d_d + \varepsilon_{itd} \quad (2)$$

*M* is county-level disaster controls which are time lags for PA and HMGP funds over the prior five years and total number of severe weather events over the prior five years which are defined in the data section. The time lags control for prior recovery and mitigation spending which may influence current mitigation spending, while the severe weather events control for the previously explored relationship between prior events and use of HMGP. *C* is county-level economic political, and demographic controls. Political and economic controls are the share of the vote for the Democratic candidate in the most recent presidential election, per capita income and unemployment rate. Demographic controls are county population, population density, and the percentage of country residents that are Black. The political, economic, and demographic controls are included because the makeup and characteristics of a county may be associated with both preference for mitigation and administrative capacity for a county to receive mitigation funding while also being associated with the likelihood of having a disaster declared. As an example, wealthier counties may be more likely to receive a level of damage which receives a disaster declaration due to a higher total monetary value to be harmed while wealthy counties may also have a mix of residents who have a higher preference for mitigation. All of the included controls attempt to isolate the explored relationship to the act of a county receiving a disaster declaration in order to examine the question of moral hazard. I also include year fixed effects. All specifications include disaster fixed effects in order to examine within disaster variation.

To mitigate concerns that PA money is being used in declared counties to fund mitigation projects, which would mean I incorrectly conclude that declared counties are not mitigating, I run my model with an indicator for two time periods. The first is 1998-2013, which covers the period in where we have information on the amount of PA funding used under 406 and it is relatively low as seen in **Table 4.1**. The second will cover 2013-2019 which will cover the period of revised section 406 mitigation funding and the expansion of mitigation through PA with section 428. There is a still a concern that counties with a disaster declaration may lower HMGP take-up due to performing mitigation with PA funds, but we know empirically that this uptake largely remained low (**Table 4.1**).[16] Additionally, even with expanded PA funding, mitigation projects have a more limited scope when compared to projects eligible under HMGP. The expanded specification is as follows, without controls (3) and with controls (4):

$$Y_{itd} = \beta_0 + \gamma D_{itd} + \rho(D \times P)_{itd} + \beta_3 P_{itd} + d_t + d_d + \varepsilon_{itd} \quad (3)$$

$$Y_{itd} = \beta_0 + \gamma D_{itd} + \rho(D \times P)_{itd} + \beta_1 M_{it} + \beta_2 C_{it} + \beta_3 P_{itd} + d_t + d_d + \varepsilon_{itd} \quad (4)$$

where $\rho$ is the additional change in outcome measure $Y$ associated with a disaster which occurs after 2013.

Lastly, I run all specifications for the five most frequent types of disaster declaration between 1998 and 2019: severe storm, flood, hurricane, snowstorm, and tornado. In particular, hurricanes may cause such vast destruction and result in high levels

[16] I am currently working with a FOIA officer at FEMA to obtain specific data on section 406 and 428 mitigation funding by county and will utilize these data in future work.

disaster spending, as seen in **Figure 4.6**, that they may lead to differential outcomes compared to more common disasters such as flooding, tornados, and severe storms. It is important to see how the response of local government may change depending on the type of disaster.

### 4.7 Findings

**Table 4.3** displays the estimates for equations (1) and (2), with each column representing a different outcome measure and section A showing coefficients without controls and section B including controls. In the first column we see that across all specifications a county that has a declared disaster is significantly less likely to utilize HMGP funds than an otherwise eligible county within the same disaster that did not receive a disaster declaration. This suggests that on the extensive margin counties are less likely to engage in pre-disaster mitigation efforts if they receive funds that allow them to repair public infrastructure. It is important to reemphasize that HMGP funds are by far the most common funds used for pre-disaster mitigation. Even under section 406 funding the only mitigation work that can be performed without HMGP funds is in the damage parts of a structure or system.

When looking at HMGP funds utilized, a county that receives a declaration uses an economically significantly higher amount of HMGP funds than a non-declared county when looking at all incident types. On the intensive margin, declared counties that do opt to use HMGP funds are using significantly more funds than non-declared counties. This result raises the question of the difference in characteristics between those declared counties that utilize HMGP funds and those that do not. Future analysis should examine the characteristics of counties that do and not utilize HMGP funding. Additionally, the coefficients increase by about $250,000 when including controls. The controls were chosen to control for potential omitted variables and when included we see that declared counties are spending nearly $400,000 more per disaster than non-declared counties. The key takeaways from **Table 4.3** are that declared counties are less likely to use HMGP funding and that they use a higher level of funding compared to non-declared counties.

*Table 4.3* - Estimates of HMGP Outcomes - Disaster Declaration Relationship, 1998-2019

| | Use HMGP | HMGP Funds (Thousand $) |
|---|---|---|
| | | |
| A. No Controls | | |
| Outcome | -0.701*** | 132.696 |
| | (0.007) | (150.992) |
| | | |
| B. Controls | | |
| Outcome | -0.680*** | 397.551** |
| | (0.008) | (165.217) |

Notes: Results from each column and row are from separate estimates. HMGP funds are in thousands of dollars. Covariates not displayed. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

**Table 4.4** displays the results of equations (3) and (4), which estimates how the introduction of section 428 changed the HMGP-declaration relationship. Looking at the first column, the likelihood of using hazard mitigation funds for declared counties remains consistent with and without controls and the post-13 relationship slightly decreases the coefficient. The results in the second column, concerning funding amount, are more muddled. Without controls the sign flips and a declared county uses less overall funding than a non-declared county. However, the model with controls is the preferred specification and the results there indicate that there was still a moderation in the total amount of funding post-2013 but a declared county remained likely to use a significantly higher amount of mitigation funding. This further reinforces the results of **Table 4.3** and suggests that declared counties are less likely to use HMGP funds but that they use a higher total amount. In terms of the introduction of 428 and the PAAP pilot program, there is no strong evidence of changes post-2013. The relationship on use of HMGP remains similar, while the coefficient on HMGP funds is not significant. This is not to say that there is no change from the introduction of revised section 406 and PAAP but if data become available it would be wise to examine actual participation in PAAP.

*Table 4.4* - Estimates of HMGP Outcomes - Disaster Declaration Relationship Pre- and Post-2013, 1998-2019

| | Use HMGP | HMGP Funds (Thousand $) |
|---|---|---|
| A. No Controls | | |
| Outcome | -0.688*** | 229.276 |
| | (0.009) | (178.768) |
| | | |
| Outcome X Post-13 | -0.045*** | -336.981 |
| | (0.016) | (333.924) |
| | | |
| B. Controls | | |
| Outcome | -0.666*** | 451.795** |
| | (0.008) | (165.217) |
| | | |
| Outcome X Post-13 | -0.046*** | -176.829 |
| | (0.016) | (356.582) |

Notes: Results from each column and row are from separate estimates. HMGP funds are in thousands of dollars. Covariates not displayed. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

There may be heterogeneity in response based on disaster type, as different disasters cause different magnitudes of damage and have different possible mitigation measures. **Table 4.5** displays the relationships based on disaster type. There is clear heterogeneity among response based on the type of disaster. The biggest takeaway is that hurricanes are the major driver of the use of HMGP funds by declared counties. The coefficient for hurricanes dwarfs all of the other coefficients combined. With the exception of flooding, which is the only disaster type not to have statistical significance, in all other disaster types a declared county uses fewer overall funds than a non-declared county. Taken with **Figure 4.6**, these results highlight just how much hurricanes have driven disaster spending over the last two decades.

The results suggest that declared counties that experience floods also use more HMGP funds, even though the coefficient is not statistically significant. This is an interesting result because flooding has similarities with the damage caused by hurricanes. Both types of flooding can be mitigated with control measures such as flood walls and culverts, and both can result in property buyouts of repetitive loss properties. Perhaps these types of disaster readily lend themselves to mitigation efforts compared to other disaster types. One way to examine this in the future will be to analyze the specific type of mitigation project associated with each disaster type and declaration status.

*Table 4.5* - Estimates of HMGP Outcomes – Disaster Declaration Relationship by Disaster Type, 1998-2019

| | No Controls | | Controls | |
|---|---|---|---|---|
| | Use HMGP | HMGP Funds (Thousand $) | Use HMGP | HMGP Funds (Thousand $) |
| A. Severe Storm | | | | |
| | -0.738*** | -274.872*** | -0.727*** | -228.075*** |
| | (0.009) | (27.357) | (0.011) | (34.836) |
| B. Hurricane | | | | |
| | -0.589*** | 2,804.757*** | -0.525*** | 5,667.433*** |
| | (0.024) | (1,065.279) | (0.029) | (1,445.567) |
| C. Flood | | | | |
| | -0.733*** | -64.672 | -0.702*** | 94.102 |
| | (0.020) | (133.541) | (0.023) | (171.835) |
| D. Snowstorm | | | | |
| | -0.634*** | -317.937*** | -0.627*** | -333.618*** |
| | (0.023) | (47.356) | (0.029) | (54.849) |
| E. Tornado | | | | |
| | -0.689*** | -119.636 | -0.671*** | -15.307 |
| | (0.044) | (79.216) | (0.062) | (130.713) |

Notes: Results from each column and row are from separate estimates. HMGP funds are in thousands of dollars. Covariates not displayed. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

**4.8 Discussion**

This paper contributes to the literature in a few ways. First, it is among the first to empirically look at local government incentives for mitigation from the design of federal disaster aid and moral hazard. The results paint a muddled picture of moral hazard in federal disaster funding. On the one hand, declared counties are consistently less likely to utilize HMGP funding overall, but they generally use a higher amount of funds. Hurricanes appear to drive high mitigation spending in affected counties, which fits with the high level of damage caused by hurricanes. In general, there is not conclusive evidence to support or dismiss the moral hazard theory, as the two outcomes point in different directions. This research shows that the question of moral hazard is worth pursuing and I plan to examine the question with a causal framework in the future. One possibility is to utilize a spatial first difference which will compare damaged counties with their immediate neighbors that are likely to be similar based on unobservable characteristics.

A key takeaway is that there is significant heterogeneity based on disaster type. The magnitude of the difference between hurricanes and other disaster types in HMGP spending for declared counties is quite large which highlights the devastation that hurricanes can cause and shows that some affected counties are engaging in large mitigation efforts. Similarly, flooding is the only other type of disaster with a positive, albeit small, coefficient. This suggests that these types of disasters may lend themselves more to mitigation than other types of disasters. Going forward I plan to examine the actual projects being funded by both HMGP and PA funds to determine how mitigation varies based on disaster type.

Another key contribution for future research is that programmatic design is important and the PA and HMGP funds are more complicated than current research takes into account. Research has not considered section 406 PA mitigation funds as well as the new pre-disaster mitigation fund and BRIC program. The good news for current research is that my results do not show a change in response post-2013 that would invalidate prior results. However, due to data limitations I am unsure how much PA funding was used for mitigation or which counties/states participated in the PAAP pilot program. In general researchers need to take the nuances of the program into account.

Finally, this paper integrated the NOAA storms database into the dataset to control for the general intensity of weather events in a county. To my knowledge no other policy research on federal disaster funding uses the NOAA storms database. However, I showed that the prior number of events an area receives is correlated with mitigation behavior. It is likely correlated with independent variables that may be used in disaster research, and as such should be included in models to avoid omitted variable bias. As an example, more events may lead a higher preference for mitigation which may lead to private mitigation activity and is correlated with lower damages and a lower likelihood of a disaster being declared, while also being correlated with a higher likelihood of using mitigation funds when available due to the preferences of the population.

During the entire time period studied, PA funds could not be used to build mitigation measures that were not on damaged parts of a structure. This means that even section 406 PA funds can only repair the parts of structures that happened to be damaged in a disaster and cannot be used to fund mitigation measures on structures vulnerable to future damage but left untouched. Future work should examine the relationship between HMGP funds and PA funds within counties at a project level. For example, are HGMP funds being used for mitigation on ineligible parts of building or structures that are being mitigated with PA funds?

One of the central questions of this paper is whether federal disaster policy induces moral hazard. The results show that declared counties are less likely to use

HGMP funds at all, supporting moral hazard theory, but they also use higher amounts overall, which does not provide evidence of moral hazard. Additionally, when broken down by disaster type the largest drivers of higher HMGP use is hurricanes, with floods also contributing. Moral hazard may arise based on the type and magnitude of disaster. The conclusion from these results is that there is evidence both for and against the moral hazard theory and more research is needed. The takeaway for policymakers is that currently it does not appear that disaster policy introduces moral hazard for hurricanes and floods, but that it may for other types of disasters.

To fix issues with the current project I intend to introduce a causal model to examine moral hazard. This model will use a spatial first difference which arranges all counties with their neighbors. By doing this I can construct a model which compares declared counties with their immediate neighbors which were exposed to the disaster but did not receive a declaration. This will help to construct a credible 'but for' scenario which accounts for unobserved factors. This paper is the first step towards establishing a strong research agenda in federal disaster policy. For the next steps I am working with a FEMA FOIA officer to receive more detailed information on section 406 funding, detailed disaster damages estimates, and more data on the projects that are funded with PA and HMGP.

Beyond a causal model this research has highlighted the need for more basic research on HMGP use. Research needs to examine the characteristics of counties that are associated with HMGP use. Additionally, research needs to examine the types of projects that counties fund with grants based on both county characteristics and disaster type. A possible scenario is that certain counties or states have HMGP projects ready to go and are simply waiting for a disaster to authorize funds. If this is the case the type of incident may not even matter.

This paper was a first step in research agenda on the examination of moral hazard in local governments and of the use of HMGP funds. The results lead to the conclusion that there is considerable heterogeneity by disaster type and that while declared counties are less likely to utilize HMGP funding than non-declared counties, they are likely to use more of the funding overall. This suggests that based on the type of disaster there may be a degree of moral hazard introduced through the design of federal disaster policy. These results are a good first step in my broader research agenda.

**Appendix A. NITROGEN**

Nitrogen is a key chemical for plant growth and for this reason is a primary component of fertilizers. For much of human history nitrogen was a limiting factor in farming as it was relatively uncommon in non-gas form – even though it is by far the most common gas in Earth's atmosphere. For nitrogen gas to become usable for most living organisms it requires the breaking of three covalent bonds, an energy intensive process called nitrogen fixation. Organisms in soil and lightning are the primary sources of nitrogen fixation in the natural world (Raymond, Siefert, Staples, & Blankenship, 2004). Researchers overcame this limitation in the early 1900s by developing the Haber Bosch process to artificially fix nitrogen into ammonia which enabled the synthetization of fertilizer chemicals from atmospheric nitrogen (Stein & Klotz, 2016). The widespread use of synthetic fertilizers in the $20^{th}$ century "has altered the global nitrogen cycle so fundamentally that the nearest geological comparison refers to events about 2.5 billion years ago" (Lewis & Maslin, 2015).

The proliferation of synthetic nitrogen has been an unambiguous success in terms of feeding the world. According to science journalist Charles C. Mann, synthetic nitrogen has allowed humans "to extract an addition 3 billion people's worth of food from the same land" (Mann, 2018). However, this incredible benefit does not come without environmental and human costs. I will highlight a selection of environmental and human effects that are not exhaustive but are pertinent to my study.

Just as nitrogen induces plant growth when used in farming it also induces growth when introduced to the natural environment. Increased nitrogen levels contribute to the process of eutrophication, in which an increase in nitrogen in a water system leads to increased algae growth. These algae can be directly and indirectly harmful to humans and other life. When these algae die their decomposition extracts oxygen from the water which kills off animal life and creates what is known as a dead zone – an area of water devoid of both oxygen and life. Agricultural runoff from farms in the Midwest is a major factor in the Gulf of Mexico dead zone which can extend thousands of square miles. Eutrophication can also be a major issue in small water systems and can lead to a loss of biotic diversity, recreation activities, harm economic potential, and hurt power generation (Khan & Ansari, 2005). Algae blooms in Lake Erie have prompted the shutdown of the water supply for the city of Toledo (Steffen et al., 2017). The algae blooms themselves can cause sickness and death upon consumption. Researchers have linked cholera outbreaks to algae blooms (Colwell and Huq, 2001). Increases in nitrogen in water systems can lead to overall biotic diversity loss through the disruption of natural balance of these systems.

As mentioned, the proliferation of nitrogen as fertilizer has had profoundly beneficial effects on human life. The increase in food production since the 1960s has led to a decrease in starvation and malnutrition around the world. Poor distribution networks are now more likely to drive food insecurity than an inability to produce (Smil, 2000). Additionally, better diets help lower vulnerability to infectious diseases and parasites leading to better quality of life and health outcomes for vulnerable populations around the world (Townsend et al., 2003). Townsend and coauthors review the literature on the negative effects of nitrogen on human health. They highlight that direct ingestion of nitrates through drinking water can have negative health effects. The Safe Drinking Water Act requires nitrates in drinking water to be under 10 ppm – a figure which studies suggests up to a fifth of groundwater sources may exceed. Direct health effects noted in the Townsend paper include “reproductive problems, methemoglobinemia, [and] cancer” (Townsend et al., 2003). In addition to these direct health effects Townsend et al. discuss the link between increased nitrogen levels in groundwater and insect borne disease such as malaria and West Nile virus.

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**Vita**

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**Education**

| | |
|---|---|
| 2017 | **Master of Public Policy**<br>University of Kentucky |
| 2013 | **B.S. in Public Affairs**<br>Indiana University |

**Publications**

Darolia, R., Owens, S., & Tyler, J. (2022). The opioid crisis and educational performance. *The ANNALS of the American Academy of Political and Social Science*, *703*(1), 188-233.

**Professional Positions**

| | |
|---|---|
| 2022 – Present | **Tennessee Department of Human Resources**<br>Senior Data Analyst |
| 2021 – 2022 | **University of Kentucky**<br>Course Instructor |
| 2015 – 2022 | **University of Kentucky**<br>Research Assistant |

**Honors, Scholarships, and Grants**

- Commissioner's Excellence Award, 2024
- Department Fellowship, 2017-2019
- Academic Scholarship 2017-2020
- Outstanding MPP Student, 2017
- Pi Alpha Alpha National Honor Society, 2017